REACTOR DESIGN FOR PRODUCTION OF FERMENTABLE SUGARS FROM EMPTY FRUIT BUNCH

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ABSTRACT

Bioethanol is a fuel produced from sugar fermentation process that used bio-based renewable sources as feedstock. As the second largest producer of oil palm, Malaysia has abundant of empty fruit bunch (EFB) waste. Despite of tremendous experimental studies done on effectiveness of using EFB for production of bioethanol, the process implementation in industry is still discouraging. This is due to lack of proven technology and high capital cost of investment. Hence, there is a need to find a straight-forward and cost effective process with a promising glucose yield. From previous experimental work, it has been proven that combination of low pressure steam heating (LPSH) and dilute acid pretreatment (DAP) able to gain a glucose yield of 78.6%, which is comparably higher than other pretreatment methods. In this present study, a block flow diagram was developed based on the data provided in the experimental work. The analysis then continued with mass balance calculation of process operation. With a scale up feedstock to ratio of 10 (to 100g of EFB), both pretreatment and hydrolysis process unit operations were modelled in Aspen Plus simulator for production of fermentable sugars. The reactors were based on RStoich and RYield reactor block due to unavailability of kinetic rate of reactions. Mass balance results from both experimental and simulation were compared and the difference was found to be around 0.73% to 0.85%. This indicated that the assumptions in simulation modelling were almost accurate to the actual experimental works. The reactor was sized based on the largest unit operations volume, which was determined to be 0.01791 m^3. Detailed reactor's mechanical design was illustrated using Microsoft Visio. Using bare module cost technique, the cost estimated to build this fermentable sugars reactor was around RM 111 000. This design work could be considered as a significant progress in the effort to bring the experimental works to industrial application.

ABSTRAK

Bioetanol adalah bahan api yang dihasilkan daripada proses penapaian gula yang menggunakan sumber yang boleh diperbaharui sebagai bahan mentah. Sebagai negara pengeluar kedua terbesar kelapa sawit, Malaysia mempunyai banyak sisa tandan kosong. Walaupun banyak kajian eksperimen telah dilakukan ke atas keberkesanan penggunaan tanda kosong terhadap pengeluaran bioethanol, pelaksanaan proses ini dalam industri masih tidak menggalakkan. Ini adalah disebabkan oleh kekangan teknologi dan kos modal pelaburan yang tinggi. Oleh itu, terdapat keperluan untuk mencari satu proses yang mudah dan berbaloi dari segi kos, di samping menjanjikan hasil glukosa yang baik. Hasil dari kerja eksperimen sebelum ini mendapati bahawa gabungan stim pemanasan tekanan rendah dan prarawatan asid cair berjaya menghasilkan glukosa sebanyak 78.6%, yang mana antara lebih tinggi berbanding dengan kaedah prarawatan yang lain. Dalam kajian ini, gambar rajah blok telah digambarkan berdasarkan data yang disediakan dalam kerja eksperimen. Analisis ini diteruskan dengan pengiraan imbangan jisim terhadap proses operasi. Dengan menggunakan bahan mentah yang telah diskalakan kepada nisbah 10 (sehingga 100 g EFB), unit-unit operasi proses prarawatan dan hidrolisis dimodelkan di simulator Aspen Plus simulator untuk pengeluaran gula beragi. Reaktor yang dipilih adalah berdasarkan blok RStoich dan RYield kerana ketiadaan kadar kinetik tindak balas. Hasil keputusan pengiraan imbangan jisim dari kedua-dua eksperimen dan simulasi dibandingkan dan didapati berbeza sekitar 0.73% hingga 0.86%. Ini menunjukkan bahawa andaian dalam pemodelan simulasi hampir tepat kepada kerja eksperimen yang sebenar. Saiz reaktor dikira berdasarkan jumlah operasi unit yang terbesar, iaitu 0.01791 m^3. Reka bentuk mekanikal reaktor yang terperinci telah dilukis menggunakan Microsoft Visio. Dengan menggunakan teknik kos modul terdedah, anggaran kos untuk membina reaktor ialah sekitar RM 111 000. Kerja-kerja mereka bentuk ini boleh dianggap sebagai peningkatan besar dalam usaha membawa kerja-kerja eksperimen kepada kegunaan industri.

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LIST OF ABBREVIATIONS

AFEX	-	Ammonia Fiber Explosion
ASL	-	Acid Soluble Lignin
ASME	-	American Society of Mechanical Engineering
CEPCI	-	Chemical Engineering Plant Cost Index
CHEMEX	-	Changhae Ethanol Multiexplosion
DAP	-	Dilute Acid Pretreatment
EFB	-	Empty Fruit Bunch
EOS	-	Equation of State
HPST	-	High Pressure Steam Pre-Treatment
LPSH	-	Low Pressure Steam Heating
NaOH	-	Sodium Hydroxide
NREL	-	National Renewable Energy Laboratory
NRTL	-	Non Random Two Liquid
PSD	-	Particle Size Distribution
US	-	United State

LIST OF SYMBOLS

a	-	Stoichiometry coefficient of component a
A	-	Acceptable
A_i	-	pre-exponential constant
$A_{polymer}$	-	xylan, glucan, arabinan, galactan, mannan, lignin
b	-	Stoichiometry coefficient of component b
B	-	acceptable up to 30°C
B_1	-	constant for vertical process vessel
B_2	-	constant for vertical process vessel
$B_{monomer}$	-	xylose, glucose, arabinose, galacton, mannose, ASL
c	-	Stoichiometry coefficient of component c
C	-	Caution
C_{acid}	-	Acid concentration (%w/w)
C_{BM}	-	Bare module cost
C_p^o	-	Equipment purchase cost for base condition
d	-	Stoichiometry coefficient of component d
D_i	-	Internal vessel diameter
E	-	Fractional weld efficiency
E_i	-	activation energy
F_{ai}	-	Final amount of component A in product stream
F_{ao}	-	Initial amount of component A in feed stream
F_M	-	Material factor
F_p	-	Pressure factor
H_2SO_4	-	Sulfuric acid
k_i	-	kinetic rate constant
K_1	-	constant to calculate cost of vertical agitated and jacketed process vessel

K_2	-	constant to calculate cost of vertical agitated and jacketed process vessel
K_3	-	constant to calculate cost of vertical agitated and jacketed process vessel
L	-	Length of reactor
N	-	Not recommended
P_d	-	Design pressure
P_o	-	Operating pressure psig
R	-	Gas Constant
S	-	Maximum allowable stress
T	-	Temperature
t_p	-	Wall thickness
W	-	Reactor weight
X	-	Conversion
Δn_i	-	Number of moles of component i (consumed or produced)
ρ	-	Density of carbon steel
π	-	pi (=3.143)

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CHAPTER 1

INTRODUCTION

1.1 Overview

In this chapter, general background knowledge of the present study will be introduced. Key important issues, objectives, scope as well as the significant of study will also be presented.

1.2 Background of Study

World energy consumption rate is increasing tremendously each day. Due to this, there has been rising concern on the energy sources. Energy sources can be classified into two types; non-renewable and renewable sources. Example of non-renewable source is fossil fuels. As the fossil fuel sources are going to deplete, people starts to look at other alternative renewable energy sources such as solar, wind, water and biomass. Bioenergy could benefit us in terms of economy, environment and energy security (Balat, 2011). From economy point of view, renewable energy will contribute to the sustainability, fuel diversity and reducing the dependency on imported petroleum. As for the environment, the emission greenhouse gases can be reduced and at the same time, the usage of bioenergy material can contribute to higher combustion efficiency and reduce the air pollution impact. Besides that, bioenergy will also give advantage on the energy security of a nation, as it would reduce the dependency of fossil fuel (Balat, 2011).

Bioethanol is an example of renewable energy derived from several biomass feedstock. Bioethanol can be blend with gasoline to be used as transportation fuel. The suffix "bio" only signifies that it is produced from fermentation of biomass sources. In terms of chemical compound, it is exactly the same as synthetic ethanol, C_2H_5OH. Currently, United State (US) is the leading producer of ethanol with 57% market share, follow by 28% market share in Brazil and 5% Europe. Most of the ethanol produced from US is imported to Canada (31%), Brazil (15%) and China (8%) (Renewable Fuels Association, 2016). Figure 1.1 shows the market distribution of ethanol.

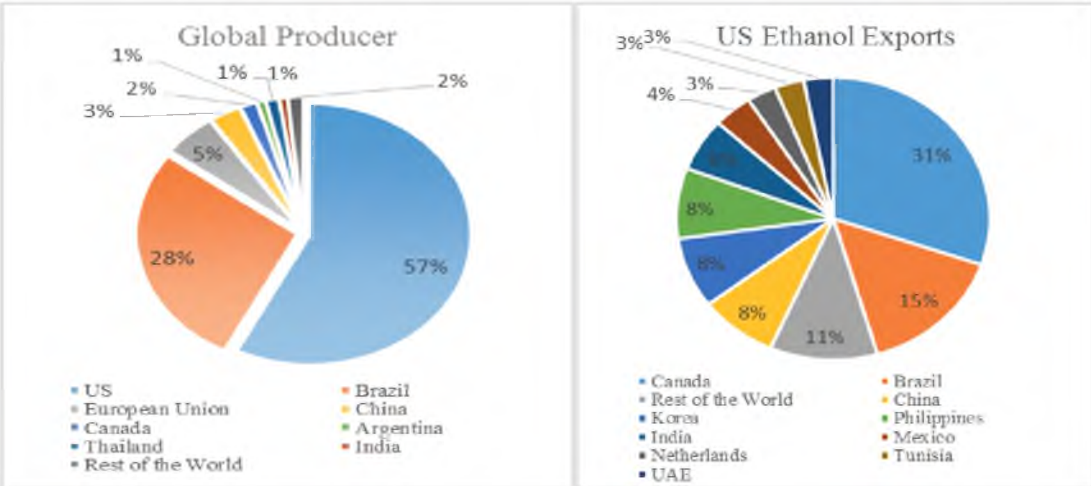

Figure 1.1 Global Ethanol Production and Top US Ethanol Exporter in 2015 (Renewable Fuels Association, 2016)

Besides promote to decrease the greenhouse gases emission and reduce the dependency on petroleum, another key important benefits of ethanol usage is its octane rating of 113. Octane rating is a measure of fuel's ability to resist knocking, which is the burning of fuel in engine's combustion chamber. Higher fuel's octane number would resulted in better engine performance, increase fuel efficiency as it is more resistant to knocking, and eventually help to decrease greenhouse gases (Renewable Fuels Association, 2016). According to US Department of Energy and Sources, ethanol's octane rating is the second best after methanol; which has an octane rating of 115 (Renewable Fuels Association, 2016). In addition, the price of ethanol is also relatively cheaper than other key octane sources as observed in Figure 1.2.

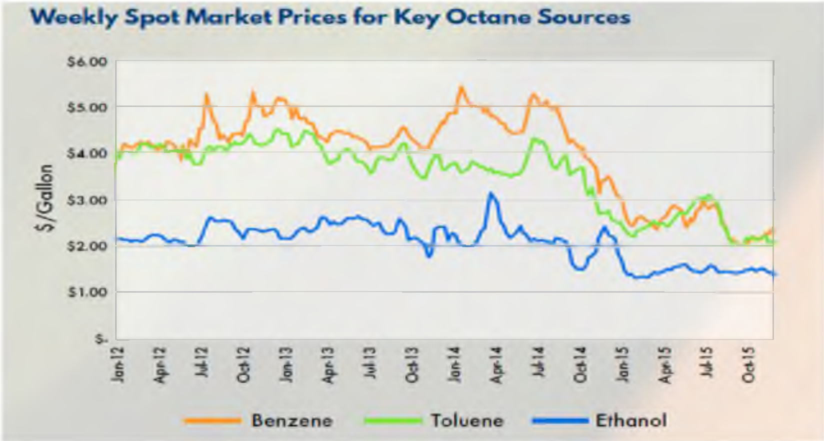

Figure 1.2 Ethanol price trend as compared to Toluene and Benzene (Renewable Fuels Association, 2016)

Bioethanol can be produced from either sucrose-rich crops, starch-rich crops or lignocellulosic materials (Balat, 2011). The lignocellulosic materials, which also known a second generation materials, are more preferable compared to the other biomass feedstock because they are non-edible raw materials, and thus, they will not affect the food-supply chain. The sequence of general operations in lignocellulose-based bioethanol production is illustrated in Figure 1.3.

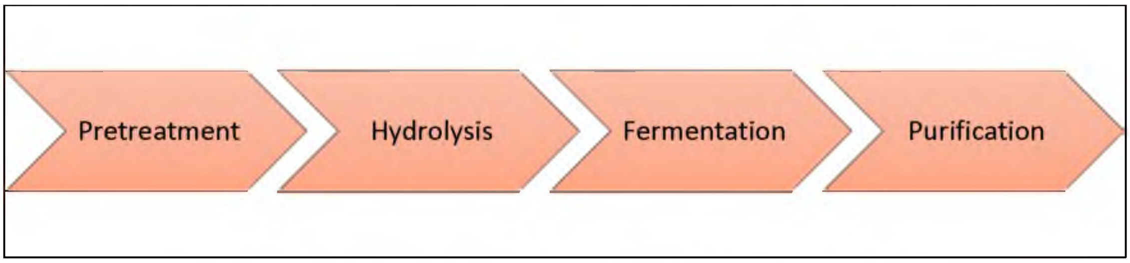

Figure 1.3 Four major processes in production of bioethanol

Referring to Figure 1.3, biomass feedstock will first go through pretreatment process to break the biomass recalcitrant structure and enhance digestibility for the next process; hydrolysis. In hydrolysis process, cellulose, hemicellulose and lignin will decompose to simpler compounds through either chemical reaction with H^+ ions or using enzymatic hydrolysis technique. The output of hydrolysis process is known as fermentable sugars as they are ready to be fermented and later on produce bioethanol. Finally, the bioethanol obtained from fermentation process will be purified to increase the final bioethanol's product quality.

Globally, Malaysia is the largest exporter and second largest producer for crude palm oil. Latest data from Malaysian Palm Oil Board recorded that there was an increment 46% of total planted oil palm area in year 2015 as compared to year 2014. This has made the total area covered for oil palm planted area by December 2015 to be 5.64 million hectare (Choo, 2016). It was also reported that amount of crude palm oil produced throughout 2015 was 19.96 million tonnes, an increase of 1.5% from previous year (Choo, 2016). Hence, there are abundant of expected waste generated based on the statistic in the report. One of massive waste generated from the production of crude palm oil is empty fruit bunch (EFB).

Various studies on pretreatment technology have been conducted to explore the best method to improve the glucose yield from the palm's EFB. These include pretreatment using chemical (acid/alkali), physio-chemical (steam, liquid hot water, ammonia fiber explosion) and also biological approach. As the second largest producer of palm oil, Malaysia has huge potential for production of bioethanol as it has an ample amount of lignocellulosic materials. Currently, the EFB is being burnt as feedstock for boiler to generate energy. This activity could lead to air pollution. Thus, converting these lignocellulosic materials into renewable energy such as bioethanol would be a better option in terms of sustainability and environmental concern.

Based on the recent Malaysia Annual Biofuel report from United State Department of Agriculture, the production of biodiesel is forecast to increase from 359 million liters to 537 million liters annually (Wahab, 2015). Production of biodiesel in Malaysia has shown positive growth from year to year. However, there is still no significant production of bioethanol in commercial quantities yet in Malaysia. The commercialization of the process is still discouraging as there is limited or known proven industrial scale technology developed from laboratory scale. There are five major phases in designing a chemical process industry. Standard process flow in building a chemical plant starts with research and development phase, then preliminary process design phase, followed by basic engineering, detailed engineering, construction and start-up, plant operation, retrofit, and finally decommissioning phase (Kidam, 2012). The experimental works are considered as part of research and development (R&D) stage in the chemical plant design. This is the fundamental basis to the conceptual preliminary design. Recently, the sequence process of combined method of low pressure steam heating (LPSH) and dilute acid pretreatment (DAP) has been successfully developed. In the study, the glucose yield was increased from 30.1wt % to 78.6 wt% (Hamid, 2015). This is in fact among the highest glucose yield that could be obtained from EFB feedstock. Due to the positive potential seen from this developed method, an initiative has been attempted to advance this method into a mini-pilot scale with a better reactor configuration.

1.3 Problem Statement

Some of the issues that have made the bioethanol project in Malaysia became unfeasible include high capital investments, lack of advance technology and difficulties to have a constant supply of feedstock (Wahab, 2015). The LPSH and DAP pretreatment methods are chosen not only because its ability to produce high glucose yield but also because of process simplicity (Hamid, 2015). Hence, this present work will focus on designing a scale up mini-pilot reactor that apply these two methods; LPSH followed by DAP for fermentable sugars production. One challenge in this work is the absence of kinetic rate of reactions. The reactor will be designed based on conversion factor or yield instead of the rate of reactions. This actually limits the user to perform process optimization from simulation study as the output is fixed. Another challenge will be choosing an appropriate scale up factor for the preliminary design. Various literature sources has to be gathered to ensure a reliable simulation results. As the feedstock contains majority of cellulose, hemicellulose and lignin, it will also be a challenge to define these lignocellulosic materials as solids in simulation study. These challenges were taken into the consideration when designing the fermentable sugars reactor.

1.4 Objectives

In general, the aim of this project is to design a reactor for production of fermentable sugars from EFB using combined methods of low pressure steam heating and dilute acid pretreatment. With this aim, the objectives of the present study were divided as follows;

i. To develop process block flow diagrams based on experimental data and perform mass balance on both current and scale up process operations.

ii. To simulate scale up pretreatment and hydrolysis process unit operation models in Aspen Plus by employing integrated LPSH and DAP methods. The simulation results and experimental results shall be validated in term of fermentable sugars yield.

iii. To perform preliminary sizing, illustrate mechanical design using Microsoft Visio and costing for fermentable sugars reactor.

1.5 Scope of Study

In order to achieve the stated objectives of this study, the scope is limited to:

- Only covered until hydrolysis process where fermentable sugars are produced.
- The process simulation in Aspen Plus will used an EFB feedstock of 100g, which scaled up to a factor of 10 from the initial experimental data (10g).
- Equipment selection, preliminary sizing and costing will only be done for reactor. Sizing of other process unit operations and auxiliary equipment are not included.

1.6 Significant of Study

This study presents a preliminary design of a reactor for production of fermentable sugars from EFB. Data from laboratory work which contributed to the highest glucose yield was chosen as the base case for this study. With the Aspen simulation, one will be able to determine whether it is technically feasible to develop the similar LPSH and DAP concept for scale up amount of raw EFB feedstock. The development of Aspen simulation model for pretreatment and hydrolysis processes is another significant contribution of this work as it can be used for future improvement studies. This preliminary design work is part of the motivation to bring experimental works for industrial application by taking the advantage and huge opportunities for the country, Malaysia, as the largest exporter and second largest producer of crude palm oil.

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