Jurnal Teknos-2k Vol. 15, No. 2, Juli 2015

Design of a Small Scale Biofuels Plant for Internal Combustion Engine

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Abstract

The concern of finding an alternative fuel to replace the gasoline is demanding due to the price increment and environmental aspects. Choosing the alternative fuel became a controversial subject since many considerations, methods, cost and continuous improvement are essential. Three well known processes in production of ethanol are; pre-treatment, fermentation and post-treatment. The design of a portable bio-fuels plant will be presented with all the design equations and selected materials. Considering scaling down the plant requires conceptualizing the procedures and integration the units since the plant is meant to fit in a truck or mobile platform. Integration of units raises the need for knowing that some of processes will be merged to a single unit. The overall dimensions are 6 m by 3 m in term of length and width respectively. The plant contains three storage tanks, two fermentation reactors where the integration of units takes place pervaporation and pure ethanol tank. All the dimensions will be provided as each part will be elaborated.

***Keyword**: bio-fuels, portable plant, biomass, renewable energy.*

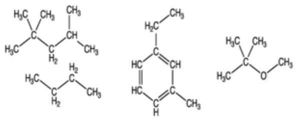
1. Introduction

The world can be simulated as a device that is run by crude oil. Without it enormous chaos will occur since no vehicle or machine can run without it. Since scientists are arguing that crude oil is a finite liquid. There was a need to look for an alternative fuel that can run relatively as crude oil.

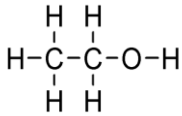
Moreover, a voice of environmental concern is dramatically rising since the global warming is taking a place. So, environmental and economical factors gathered to enhance the necessity of finding a substitutional fuel.

Ethanol is an alcoholic fuel, one of the most important renewable fuels because of its contribution to the reduction of negative environmental emission generated by worldwide utilization of fossil fuel. Ethanol (CH_3CH_2OH) is considered a common high alcohol since it's a first generation biofuel routes and it became an interested fuel when it was found that it can run an internal combustion engines (Pfromm *et al*., 2010). Antoine Lavoisier described ethanol as a compound of carbon, hydrogen, and oxygen which is the same main compound of gasoline, Figure1, so it can be considered as a replacement to gasoline.

The transformation of such biological resources energy rich product, example sugar cane, cassava or lignocellulosic, is complicated. It requires the right pre-treatment of the biomass for the fermentation organisms to transform them into pure ethanol. A hydrous ethanol will be obtained and it has to be concentrated for the dehydration process in order to be utilized as oxygenate for gasoline that's why mostly ethanol is used in transportation sector (Cardona and Sa´nchez, 2007).



(a)



(b)

Figure1. Fuel compounds, (a) gasoline compound; (b) ethanol compound

However, the complexity of the production process explains why ethanol didn't consider a prior fuel comparing to gasoline before the crisis. But, the increasing of the crude oil price and the unbelievable demands urged the researchers to find a fuel that can replace gasoline. This project will focus on designing a small scale ethanol plant. All the processes including integration possibility will be discussed with proper yeast for the fermentation process.

2. Lignocellulose biomass

Lignocellulose represents the most abundant biopolymer on the earth as well as constitutes the main components of the various industrial wastes. It can be found in profuse biological materials such as wood, grass, paper, vegetable peels and empty fruit bunch (EFB). This biomass will contribute in production a valuable biofuel like bioethanol. Economically, lignocellulosic biomass is preferable over other agriculturally biofuels feedstocks due to its ability to be produced quickly and at significantly lower cost than food crops. Lignocellulosic biomass is an important component of the major food crops; it is the non-edible portion of the plant, which is currently underutilized, but could be used for biofuel production (Millati *et al.*, 2000). Ultimately, considering the production of ethanol as biofuel from lignocellulosic biomass is the most promising feedstock according to its wide availability and low cost.

2.1 Palm oil Empty Fruit Bunch

In this project EFB (Figure 2) is selected to be the main considerable feedstock due to firstly, its wide availability and secondly because it accumulates a large amount of lignocellulosic waste.

Currently, the common usage of this biomass is to be burned for steam and power generation for factories as a disposal method. However, the existing method led to an enormous environmental issue, example pollution, as a result of incomplete combustion and produced ash particles. Therefore, the utilization of such by-products by converting it to a useful product is a great importance. One of the beneficial utilization is producing bioethanol from the contained lignocellulosic is such waste. The main interest in conversion of this biomass to ethanol is their consistent availability. EFB could consist of cellulose in a considerable percentage, 44%, while the rest found in form of hemicellulose and lignin, can be noted in Table 2 (Piarpuza´n *et al*., 2011). In order to convert this biomass it is necessary to have it in fibers form so it can be ready to progress with the conversion procedures, Figure 2(c).

Table 1. Average composition of EFB (Cardona and Sa´nchez, 2007)

	Content (wt.%)		
	EFB		PPF
References	[2][a]	[3]	[4]
Component			
Cellulose	46.77	15.47	24.00
Hemicellulose	17.92	11.73	14.40
Lignin	4.15	7.14	12.60
Ash	–	0.67	3.00
Oil	–	–	3.48
Moisture	–	65.00	40.00
Others	–	–	2.52

a Dry basis.

a) Fruit bunch b) Solid EFB c) Fiber EFB

Figure 2. Empty fruit bunch

3. Process Description

First of all, EFB comes in long fibers that need to be reduced to an average particle size of 2 cm by grinding it. After that in pre-treatment the raw material needs to be mixed with 2% of sodium hydroxide solution at room temperature at a solid ratio of 10% (volumetric base) then this mixture comes to a carbon steel stirrer at 30^{o}C and after this the fibers is sent to the fermentation process. In the fermentation process the cellulose is converted into glucose while the inhabitants are removed. The sugar is assimilated by the yeast sacerevisiae in the fermenter and converted into ethanol (Wallner *et al*., 2009). Due to size limits and optimization simultaneous saccharification and fermentation (SSF) process will be implemented and an additional integration will carry on as SSF is coupled with pervaporation as separation process. According to Table 2 it was determined that this reaction-separation integration can yield a high substance conversion 60-90% with final ethanol concentration within 3 to 7 days.

4. Concept of Design

The overall plant will be 6 m length, 3 m height and 3.5 m width and the layout shown in Figure 3. These dimensions were determined after designing the tanks and reactors with extra space for maintenance and cleaning purposes. The numbers of storage tanks were suggested to be three in order to make sure that there will be enough pretreated biomass supplied to the fermentation reactor which will be operating as batch fermenting method. The first tank will be placed at back of the

Table 2. Reaction-Separation Integration comparison (Cardona and Sa´nchez, 2007)

Technology	BioagentUunit Operation	Feedstock/Medium	Remarks	References
Continuous SSF coupled with pervaporation	*S. cerevisiae* + *Trichoderma reesei* cellulases/silicate membrane	Cellulose	Modeling based on kinetic approach; yield 0.44 g/g; EtOH conc. 248.3 g/L in permeate and 4.1 g/L in broth; reduced product inhibition effect; residence time of 72 h; 60–99% substrate conversion	Sánchez et al. (2005)
Batch fermentation coupled with membrane distillation	*S. cerevisiae*/capillary polypropylene membrane	Sucrose-containing medium	2–3 d cultivation; periodic flow of broth through membrane distillation module during 5–6 h per day or continuous coupling to bioreactor; yield 0.47–0.51 g/g; EtOH conc. 50 g/L in broth; productivity 2.5–5.5 g/(L.h)	Gryta (2002, 2001) Gryta et al. (2000)
Continuous fermentation coupled with membrane distillation	*S. cerevisiae* and *S. uvarum*/ polypropylene and poly(tetrafluoro-ethylene) membranes	Glucose and molasses solutions	430–695 h cultivation; EtOH conc. 60 g/L in broth and 200–400 g/L in cold trap; high concentrated medium (316 g/L molasses)	Calibo et al. (1989)

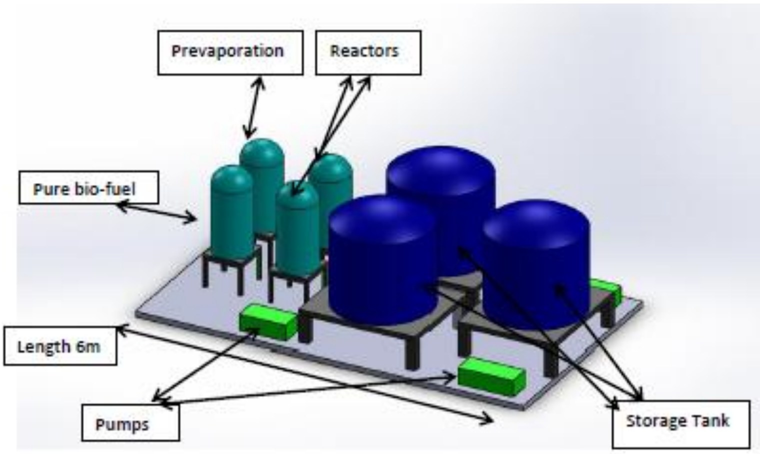


Figure 3. Plant layout

plant and will be in charge of supplying the other two with the feedstock. Likewise, two fermentation reactors will be placed in front of the storage tanks where the mixture will be sterilized by an impeller. It's essential to emphasize that each tank and reactor will be 70% filled to avoid over flood as well as for safety purposed because an experiment was conducted in the automotive lab and it was found that filling the reactor over 70% the vortex will be created causing the mixture to fall over the reactor. For the literature it was suggested that the material recommended to be used is stainless steel since it has a strong endurance for corrosive materials and ability to sustain relatively high temperature. To obtain the optimum temperature a heat exchanger was designed in order to elevate the temperature of the reactor when it's required as well as cool it down when it is necessary. Inside the fermenter four impellers will be added to sustain a uniform stirring and certain the movement of the mixture as whole to allow the yeast to interact with the biomass. Lastly, pervaporation, post-treatment, will be attached to the fermenter in order to obtain pure bioethanol with high concentration.

5. Design Development

For the storage tanks, Figure 4(a), it has been suggested that three tanks will be allocated to store the biomass before and after pretreated. One of the tanks will contain the required chemicals, sulfur dioxide, SO_2, as it will be pumped into the second tank where the biomass will be poured in and the biomass as mentioned has to be in 2-4 mm size and pretreated with high pressure. Then, the mixture will be exposed to a steam of 160-290^{o}C for few seconds and then drop the pressure from range of 0.69-4.85 MPa to atmospheric pressure.

The diameter of the storage and reactor tank has been determined from Equation 1. The liquid volume was set to be 1790 liter and the height to diameter ration is 1. Additionally, the power was found from Equation 3. Since various reactions will occur inside, it's essential to select the right material as such it was found that Carbon Steel ASIS 1020 is the best option due to its endurance of bearing high temperature and pressure drop.

$$D = \sqrt[3]{\frac{4V}{\pi R}} \text{ m} \qquad (1)$$

$$H = D \text{ x } R \qquad (2)$$

$$P = \frac{5xVx0.2641}{1.341} \text{ W} \qquad (3)$$

Secondly, the most important part of the plant is the reactor, Figure 4(b), since the fermentation process will take place in it, therefore it has to be detailed in order to obtain a high bioethanol concentration. Thus, specific equations are being employed from (Bergman *et al.*, 2013) where the dimension, height and power will be determined. It is set that the liquid volume inside the reactor will be 112 liter filled 70% only of the tank as it has been mentioned earlier. Using Equation 1 provided us with the diameter of the reactor which was found to be 0.6 m and height to diameter ratio was 2. Subsequently the height is twice the diameter.

For the baffle, the spacing from the walls was 0.47 m with a width of 0.05 m and distance from the bottom equal to 0.3 m from the following Equations, all measurements are in meter unit.

$$\text{Baffle spacing} = \frac{\pi D_t}{4} \qquad (4)$$

$$W = \frac{D_t}{12} \qquad (5)$$

$$\text{Distance from bottom} = \frac{D_t}{2} \qquad (6)$$

where W is the width of the baffle.

As the mixture is being pumped to the reactor there will be four impeller rotating to ensure that a uniform mixed between the biomass and the added chemicals, yeast sacerevisiae. The temperature will be controlled to be in range of 60-70^{o}C and a heat exchanger will be used to heat up the reactor. Equations from (7) were used to design the impeller. Consequently, the diameter, distance from the bottom, jacket, width and height were determined from Equations 7-11, all measurements are in meter unit. The reason of using four baffles is to avoid the formation of swirling and vortex as it was suggested in (Bergman *et al.*, 2013).

$$D_a = \frac{D_t}{3} \quad (7)$$

$$E = \frac{D_t}{3} \quad (8)$$

$$J = \frac{D_t}{12} \quad (9)$$

$$W = \frac{D_a}{5} \quad (10)$$

$$L = \frac{D_a}{4} \quad (11)$$

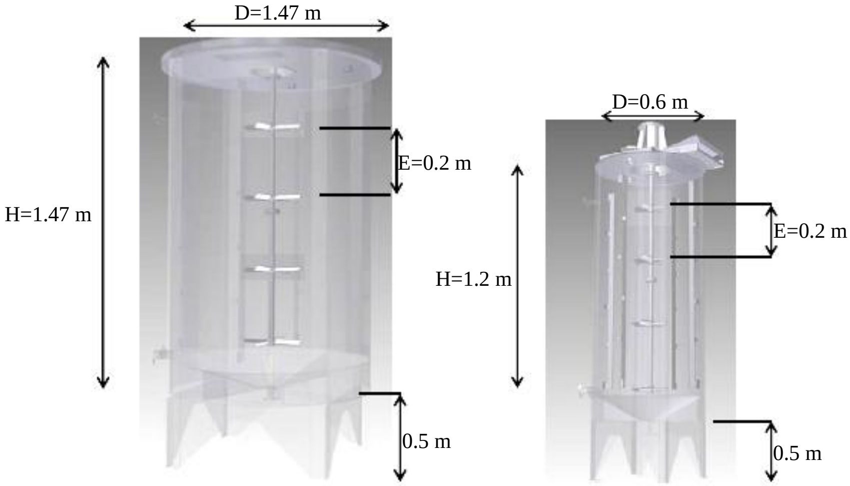
According to Cardona and Sanchez, keeping this reaction for 72 hours will convert all cellulose into ethanol reaching 90-95% conversion of the final yield. Furthermore, coupling it with the pervaporation will yield higher concentration.

Shell and tube heat exchangers have been chosen as type of heat supply. This heat exchangers are suitable when dealing with potentially fouling material such as biodiesel and biofuels. The material of construction for all heat exchanger units were decided to be carbon steel 304 as the literature recommended.

The condensation within the tubes was assumed to be vertical up flow. This geometry was recommended as method of condensation in literature as the preferred arrangement for refluxing hot condensate. Standard reflux condensers usually alter between 2 to 3m in length. For a mobile plant, a horizontal arrangement with only a slight vertical gradient was presumed for installing the condensers. The vertical gradient will guarantee that the condensate is returned to the distillation column by gravity. In addition, the near-horizontal arrangement minimizes the overall heights of the distillation unit.

6. Result and Discussion

The design of the tanks, reactors, impellers and baffles has been achieved. Furthermore, an analysis of the mass flow rate variation with regards to the required power and time has been conducted for the aim of reducing the electrical supply when the reactor reaches a stable condition because the water flow rate was recommended to incline to a level of maintaining the desired temperature. From the results obtained, the required power was determined according to the variation in mass flow rate. Such a result will be beneficial when the heat exchanger is running in a relatively constant temperature over the operation time and therefore the power required will reduce as the mass flow rate decreases, Figure 5. Additionally, this finding was supported by the result obtained in Figure 6 where the power declined over the operation time since the operation will run under a relative steady state temperature. Thus, as the temperature within the reactor reached a range of 60-70^{o}C, which is suggested operation temperature, the mass flow rate will decrease as shown in Figure 7. Ultimately, the tanks were designed by the aid of the equations provided in section 5 and the specifications were determined and summarized in Table 3.



(a) Storage tank (b) Reactor tank

Figure 4. Tanks

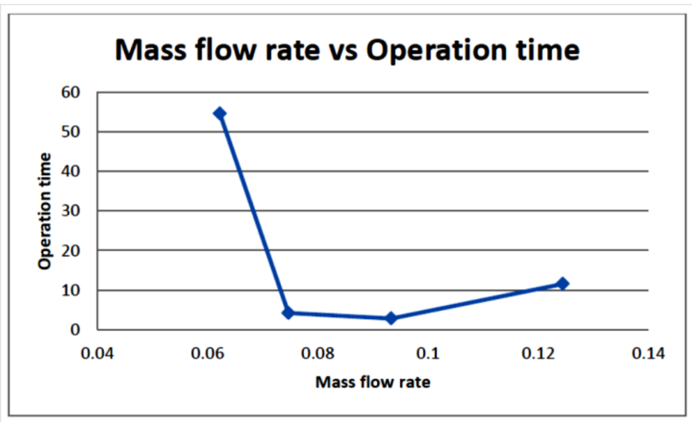


Figure 5. Mass flow rate variation with operation time

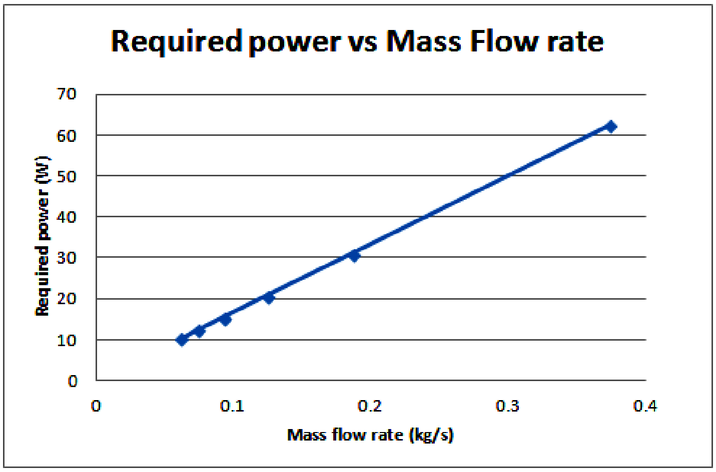


Figure 6. Required power with the variation of mass flow rate

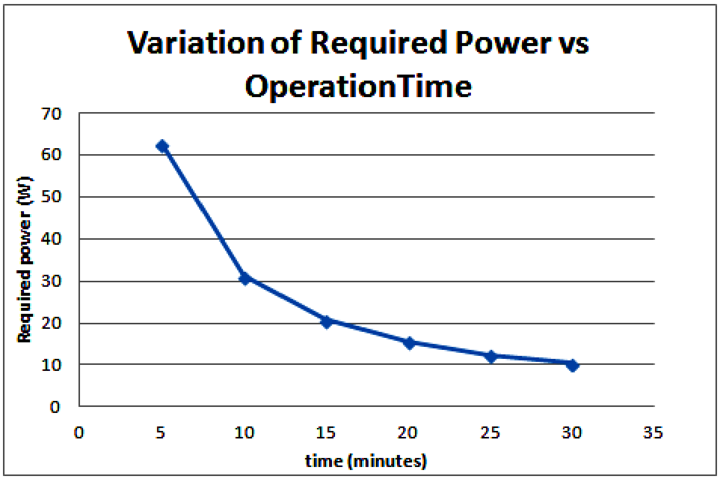


Figure 7. Variation of required power with operational time

Table 3. Tank specifications

Specifications	Storage Tank	Reactor Tank
Liquid volume (m^3)	1790.5	112
Tank height to diameter ratio	1	2
Percent filled (%)	70	70
Tank volume (m^3)	2.5	0.3
Tank diameter (m)	1.47	0.6
Tank height (m)	1.47	1.2
Tank material	Carbon steel AISI 1020	Stainless steel AISI 304

7. Conclusion

Ultimately, it can be said that the objective of the project is achieved. A detailed design has been provided to yield high and pure bioethanol fuel with the recommended unit's integrations in order to compromise the space and production cost. Furthermore, a great care must be given to the process conditions since any variation of ph value, temperature and concentration will influence the concentration of the biofuel.

Acknowledgement

The author gratefully acknowledge the financial assistance by Ministry of Higher Education (MOHE) of Malaysia through Universiti Teknologi Malaysia (Research University Grant: Q.J130000.2509.08495) since July 2014.

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