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Preliminary study of FCC design for palm-based biofuel production through heat balance analysis

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Abstract. Fluid Catalytic Cracking (FCC] is playing a big role in oil refinery industries and it has been used for producing most of the fuel around the world. FCC has also a great potential for producing biofuel derived from palm-based bio oil. However, it takes a complex calculation to design the overall FCC system. This paper offers the design simplification of FCC through heat balance analysis in two main components, that is riser section and regenerator section. The objective of this study is to estimate the appropriate amount of fuel for a given amount of feed. It is obtained that the required amount of fuel is greater as amount of the given feed increased.

Keywords: fluid catalytic cracking, palm oil, biofuel, heat balance

1. Introduction

FCC is playing a big role in oil refinery industries and it has been used for producing the majority of fuel around the world [1]. FCC is first used commercially in 1942 where in that era, the clay-based catalyst remains to be used [1]. Since then, the research on FCC was developed greatly. For example, the development of catalyst materials with a higher activity level, such as synthesized SiO2-Al2O3-based catalyst, synthesized SiO2-MgO-based catalyst [1,2], and microporous aluminosilicates (Zeolites) catalyst[1]. In addition, the research also includes the development on kinetics model of reaction rates of catalytic cracking through lumping technique. The first kinetic model proposed consist of 3 lumps [3]. Then, the model is developed into a higher number of lump, such as 4-lumps [4], 5-lumps [5,6], and 6-lumps [7–9]., and 10-lumps kinetic model [10].

FCC conversion technology is also utilized for producing biofuel derived from bio-oil materials. In 2010, P. Bielansky *et al.* conducted an experiment to compare the use of palm oil, rape seed oil,

and soy bean oil as a feed materials in FCC [11]. It is obtained from the experiment that the palm oil gives the best result due to its high fatty acid chains. Furthermore, Ma, et al performed an experiment to evaluate the use of mixed raw-bio oil and oil kitchen waste as feed materials in FCC [12]. Furthermore, Ibarra *et al.* had carried on a study of the effect of catalyst variation and RCO in producing a biofuel through FCC [13]. Hence, it can be implied that for the FCC technology has a promising capability for converting palm oil into biofuel.

Currently, Zero Energy Building Research Group in *Universitas Indonesia* is conducting a research on biofuel production derived from palm-based bio oil through FCC. However, the research requires many aspects that need to be studied and developed. For example, the development of the kinetic model of the catalytic cracking reaction and the development of the catalyst. Yet, those studies require an experiment data. Therefore, the pilot-scale FCC can be used to obtain the required the data [1]. The initial step in this research is begun by designing a pilot-scale FCC system.

Modern FCC system comprise of many components. In order to design and simulate the overall FCC system, it takes very complex model and calculation [14]. Hence, to simplify the design and calculation, it will focus on the heat balance analysis in two-main component in FCC, that is riser and regenerator. The Riser section is the place where the catalytic cracking is carried on and the regenerator section is the place where the catalyst receives thermal energy from combustion process [15]. It is noted that the catalytic cracking reaction along the riser required a certain temperature value to obtain the optimum result. Hence, the regenerator should be designed such the required optimum temperature in riser can be achieved. In addition, Liquid Petroleum Gas (LPG) will be used as the fuel for the combustion reaction in the regenerator. Thus, the mass flow rate of LPG ($\dot{m}_{LPG}$) plays an important role to provide the required temperature in the riser section. The objective of this paper is to find out the appropriate value of $\dot{m}_{LPG}$ according to the given value of mass flow rate of the palm oil which is used as feed ($\dot{m}_{feed}$).

2.   Fluid catalytic cracking

Catalytic cracking is a process that crack heavy hydrocarbon into a lighter products [16]. Currently, most of the catalytic cracking reaction process is carried on by using FCC [17]. The Modern FCC consist of some components, such as riser, regenerator, riser, cyclone, heat exchanger, stripper, and feed injector [14,18] as shown in **Figure 1**.

The catalytic cracking reaction process in FCC runs continuously, where the catalyst dispersed by the lifting fluid. Feed enters the riser through the injector placed in the bottom of the riser chamber. Afterward, the feed contact with the lifting fluid and high-temperature catalyst (regenerated catalyst) particles [14]. Then, the catalytic cracking reaction is carried on along the riser. The reaction will form an amount of coke particles, some of which will be deposited in the catalyst particles. The deposited coke will decrease the activity level of the catalyst. After passing through the riser, both coke and catalyst particles will be separated from the others product in cyclone separator and stripper. Both coke and catalyst particle then falling down into regenerator section, while the remaining product will be cooled down in Heat Exchanger. Then, the coke particles will be burned in the regenerator by injecting an amount of ambient air into the regenerator. LPG can be used as an additional fuel in regenerator to create a more stable and continuous combustion reaction. The combustion reaction in the regenerator is intended to remove the coke particles deposited on the catalyst particles, so that it will restore the catalyst activity level [14]. In addition, it also increases the catalyst temperature and thermal energy. Afterward, the high temperature catalyst (regenerated catalyst) will exit the regenerator and return to the riser for the next cracking reaction.
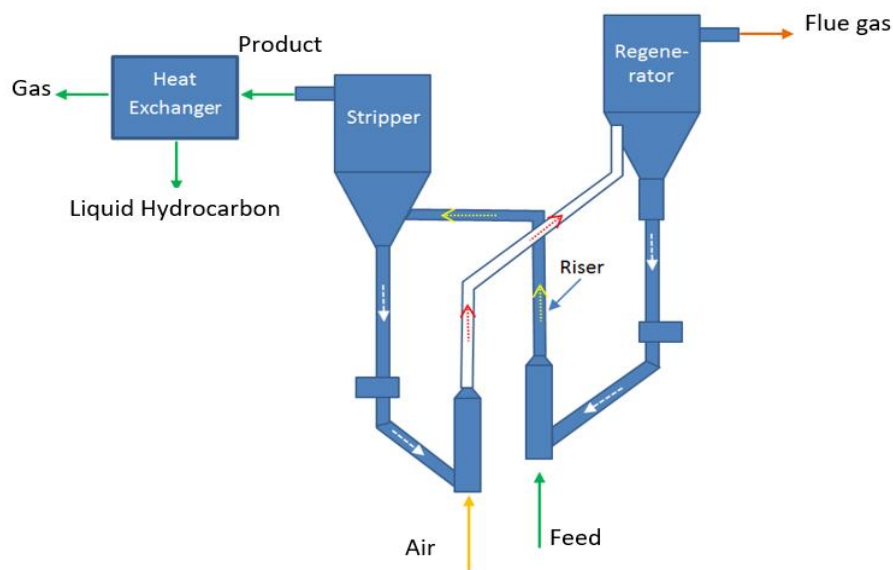
Figure 1. Scheme of modern FCC system

3. Mathematical modelling

This section will discuss the mathematical modelling and the heat balance calculations in two-main components of FCC, that is riser and regenerator. The heat balance analysis in the regenerator and riser rely on the kinetic model of the catalytic cracking reaction. It is because the amount of the coke formed in the riser will affect the combustion process in the regenerator. However, as the best author's knowledge, no kinetic model of catalytic cracking of palm oil in FCC have been developed yet. Most of the existing kinetic model of catalytic cracking reaction of palm oil have been developed for the fixed-bed reactor [19,20]. Hence, to simplify the calculations, some assumption are used in this study as follows:

- No coke is formed, neither in the riser nor in the regenerator.
- Thermal energy required for the catalytic cracking along the riser is neglected.
- The feed's inlet temperature ($T_{in.feed}$) in the riser is considered as equal to its boiling point.
- Outlet temperature of the resulting vapour product and the catalyst at the riser is equal to the riser temperature
- Riser and regenerator are isothermal and adiabatic.
- Thermal losses in the riser and regenerator are neglected.
- Air enters regenerator at ambient temperature ($T_{in.air} = T_{amb.} = 25°C$).
- There is no energy consumed during the catalytic cracking reaction in the riser.

3.1 Format heat balance analysis at the riser section

The Heat balance analysis at riser section is shown in **Figure 2a**. The regenerated catalyst, feed, and lifting fluid will be contacted at the bottom of the riser. Then, it will flow upward along the riser. In this study, nitrogen will be selected as a lifting fluid. The heat balance analysis can be calculated through the change of the enthalpy of the feed, the catalyst, and the lifting fluid. Because of the assumption that no energy is consumed during the catalytic cracking, the energy balance can be re-written in equation 1.

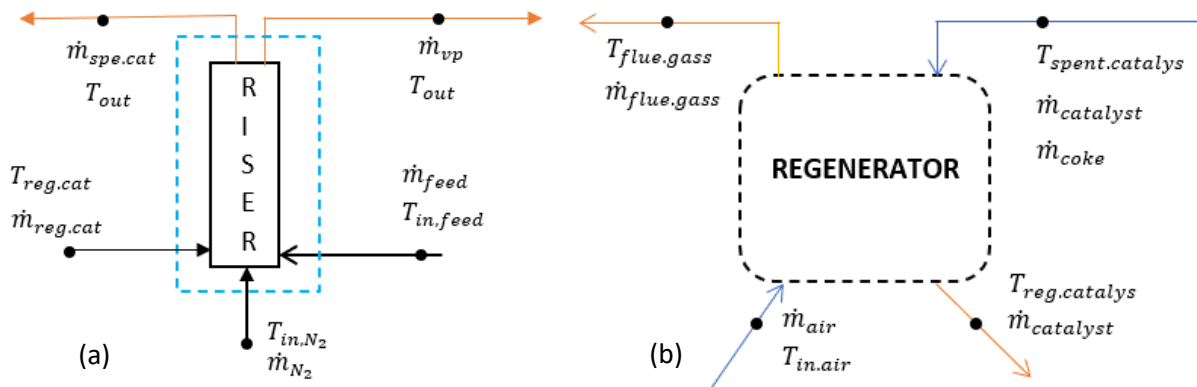$$\Delta H_{feed} + \Delta H_{N_2} = \Delta H_{reg.cat} \qquad (1)$$

Figure 2. Control volume at: a) riser section and, b) regenerator section

The change of the feed's enthalpy represents an amount of energy which increases the feed temperature. Since the regenerated catalyst has the highest temperature, it will be the source of thermal energy in the riser which is transferred to the feed and the nitrogen. Therefore, the required temperature of regenerated catalyst in the riser can be obtained from equation 2.

$$T_{reg.cat} = \frac{\dot{m}_{feed} . Cp_{feed}\left(T_{riser} - T_{in.feed}\right) + \dot{m}_{N_2} . Cp_{N_2} \left(T_{riser} - T_{in\ N2}\right)}{\dot{m}_{cat.} . Cp_{cat.}} + T_{riser} \qquad (2)$$
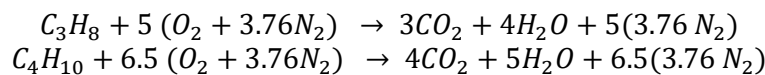
3.2 Heat balance analysis at the regenerator section

In the regenerator sections, combustion process is carried out continuously using LPG. Basically, the combustion process is intended to remove the deposited coke from the catalyst particles. In addition, the combustion process will also increase the catalyst temperature. However, to estimate the coke formation, it requires the kinetic model of catalytic cracking reaction. Therefore, to simplify the calculation, it is assumed that there is no coke formation, neither in the riser nor in the regenerator.

Scheme of the heat balance analysis at the regenerator is shown in **Figure 2b**. The heat balance equation at the regenerator can be defined as follows:

$$-Q_{combustion} = \Delta H_{catalyst} \qquad (3)$$

The total energy produced from the combustion of LPG can be calculated from the reaction's stoichiometry. As LPG is composed 50% of propane and 50% of butane, the stoichiometric reaction of the combustion can be written as follows:

$$C_3H_8 + 5\ (O_2 + 3.76N_2) \ \rightarrow 3CO_2 + 4H_2O + 5(3.76\ N_2)$$
$$C_4H_{10} + 6.5\ (O_2 + 3.76N_2) \ \rightarrow 4CO_2 + 5H_2O + 6.5(3.76\ N_2)$$

The heat released from the combustion reaction of each substance can be calculated from the following equation 4 and 5.

$$\frac{\dot{Q}_{Comb.C_3H_8}}{n_{C_3H_8}} = \left\{3 \left[\overline{hf°} + \Delta\bar{h}\right]_{CO_2} + 4 \left[\overline{hf°} + \Delta\bar{h}\right]_{H_2O} + \left(\frac{\%EA}{100} + 1\right) 18.8\left[\overline{hf°} + \Delta\bar{h}\right]_{N_2} \right. \qquad (4)$$
$$+ \left(\frac{\%EA}{100}\right) 5 \left[\overline{hf°} + \Delta\bar{h}\right]_{O_2}\Big\}$$
$$- \left\{\left[\overline{hf°} + \Delta\bar{h}\right]_{C_3H_8} + \left(\frac{\%EA}{100} + 1\right) 5 \left[\overline{hf°} + \Delta\bar{h}\right]_{O_2} + \left(\frac{\%EA}{100} + 1\right) 18.8 \left[\overline{hf°} + \Delta\bar{h}\right]_{N_2}\right\}$$

$$\frac{\dot{Q}_{Comb.4H_{10}}}{n_{C_4H_{10}}} = \left\{ 4\left[\overline{hf°}+\Delta\bar{h}\right]_{CO_2} + 5\left[\overline{hf°}+\Delta\bar{h}\right]_{H_2O} + \left(\frac{\%EA}{100}+1\right)24.4\left[\overline{hf°}+\Delta\bar{h}\right]_{N_2} \right. \tag{5}$$
$$\left. + \left(\frac{\%EA}{100}\right)6.5\left[\overline{hf°}+\Delta\bar{h}\right]_{O_2} \right\}$$
$$- \left\{ \left[\overline{hf°}+\Delta\bar{h}\right]_{C_3H_8} + \left(\frac{\%EA}{100}+1\right)6.5\left[\overline{hf°}+\Delta\bar{h}\right]_{O_2} + \left(\frac{\%EA}{100}+1\right)24.4\left[\overline{hf°}+\Delta\bar{h}\right]_{N_2} \right\}$$

Where %EA is the percentage of the excess air. In addition, $\overline{hf°}$ is the enthalpy of formation, and $\Delta\bar{h}$ is the different between the specific enthalpy in a certain temperature condition and the specific enthalpy in standard condition ($T_{standart} = 25°C$). Hence, the total energy release from the combustion of LPG will be following equation 6.

$$\dot{Q}_{Comb.\ Total} = \dot{Q}_{Comb.C_3H_8} + \dot{Q}_{Comb.C_4H_{10}} \tag{6}$$

Afterward, the resulting temperature of the regenerated catalyst, which can be represented by the temperature of the regenerator, can be calculated from Equation 7.

$$T_{regenerator} = \frac{-Q_{Comb.Total}}{(\dot{m}_{cat}.Cp_{cat})} + T_{riser} \tag{7}$$

4. Design methodology

The design scheme is divided into two parts as shown in **Figure 3**. The first part is the design consideration at the riser side. The main goal of this part is obtaining the required temperature of the regenerated catalyst in the riser. Firstly, the input parameters, such as feed mas flow rate ($\dot{m}_{feed}$), riser temperature (T_{riser}), and catalyst to oil ratio (RCO), should be determined. Then, the amount of catalyst can be calculated from the value of RCO and mass feed flow rate. In addition, the nitrogen mass flow rate ($\dot{m}_{N_2}$) should be determined properly to ensure that the nitrogen can bring the feed and the catalyst particles upward.

Table 1. Input Parameters of calculation

Variable	Value
T_{riser} (K)	773
$T_{in.feed}$ (K)	653
$T_{in.N_2}$ (K)	623
RCO	11

The most important of the input parameters is the riser temperature, because its value will greatly affect the catalytic cracking reaction process in the riser. The input parameters in this study are provided in **Table 1**. After determining the input parameters, the required temperature of catalyst can be obtained from equation 2. The value of catalyst represents the required thermal energy to run the catalytic cracking reaction in the riser. The second part is the design consideration at the regenerator sections. The main goal in this part is obtaining appropriate amount of the fuel flow rate and the air flowrate that can achieve the required temperature of the regenerated catalyst which is represented by the regenerator temperature. The initial mass flow rate of LPG ($\dot{m}_{LPG}$) is determined. Afterward, the heat released from the combustion process is calculated from Equation 6. Then, the resulting temperature of regenerator can be calculated by using Equation 7. If the resulting $T_{regenerator}$ does not meet the required $T_{reg.\ cat.}$ in the riser, it will return to determine the new value $\dot{m}_{LPG}$. Hence, the process will be iterated untill the appropriate value of $\dot{m}_{LPG}$ is obtained.
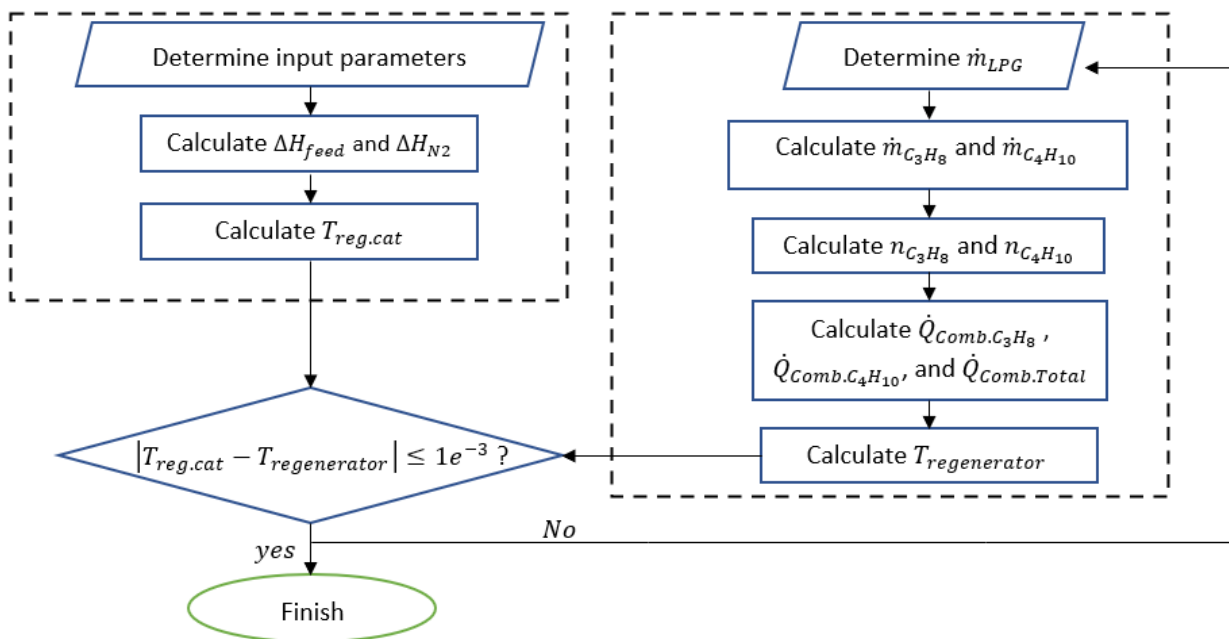
Figure 3. Calculation flow chart

5.   Result and discussion

5.1   Result analysis at riser section

The variation of RCO will affect the required $T_{reg.cat}$ in the riser. It is because the RCO represents the proportion of the catalyst to the feed. At constant value of $\dot{m}_{feed}$, it is obtained that tha required $T_{reg.cat}$ is decreases as RCO increased as shown in **Figure 4a**. As $\dot{m}_{feed}$ remains constant, the required thermal energy in the riser is also remaining the same. The increasing value of RCO will increase the amount of $\dot{m}_{catalyst}$. Therefore, to meet the required thermal energy in the riser, a higher RCO value needs a lower $T_{reg.cat}$, and vice versa.
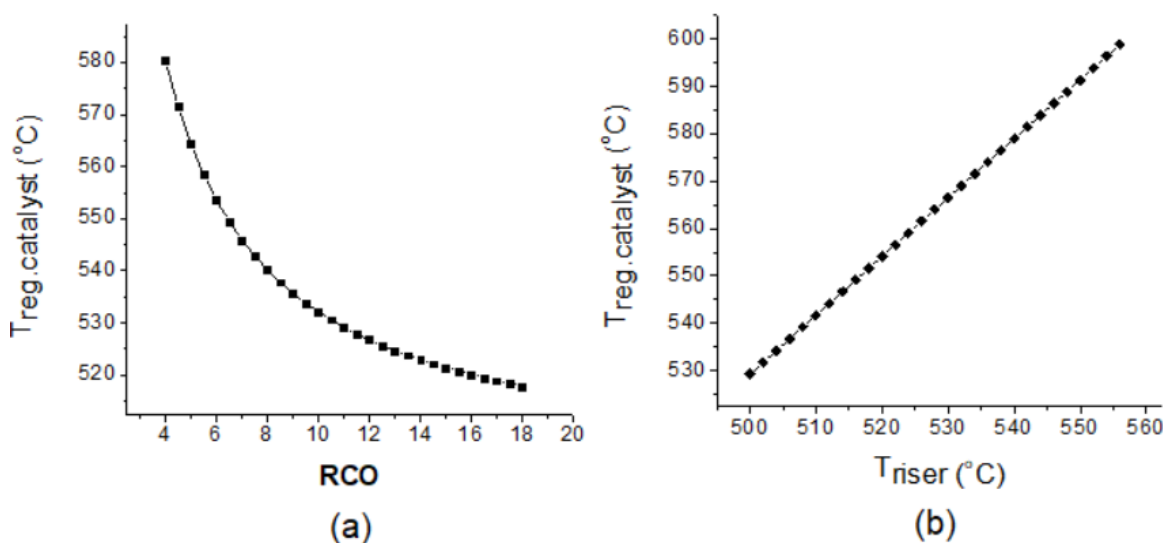

Figure 4. Resulting estimations of the required regenerated catalyst temperature on the variation of (a) feed mass flow rate, (b) RCO value, and (c) desired temperature at riser section

Catalytic cracking reactions has a specific range of optimum operation temperature. The reaction temperature can be represented by the riser temperature. To reach a particular value of riser temperature, it needs an appropriate amount of thermal energy. Hence, in the condition where RCO and $\dot{m}_{feed}$ are constant, the relation between the desired T_{riser} and the required $T_{reg.cat}$ is shown in **Figure 4b**. It is shown that the required $T_{reg.cat}$ is increased as the desired T_{riser} increased. The required thermal energy is increased as the desired T_{riser} increased. Thus, a higher thermal energy will need a higher $T_{reg.cat}$.

5.2 Result analysis at the regenerator sections

Combustion reaction in the regenerator, using LPG, is analysed through the reaction's stoichiometric as provided in section 5.2. Ideally, the combustion reaction occurs in stoichiometric conditions where the air is completely reacted with the fuel. The total heat energy produced from the combustion is obtained by using equation 6. The temperature of the reaction's product can be represented by the temperature of the flue gas $(T_{flue.gas})$. Effect of the produced flue gas temperature on resulting catalyst's temperature, which is represented by the regenerator temperature$(T_{regenerator})$, is shown in **Figure 5a**.
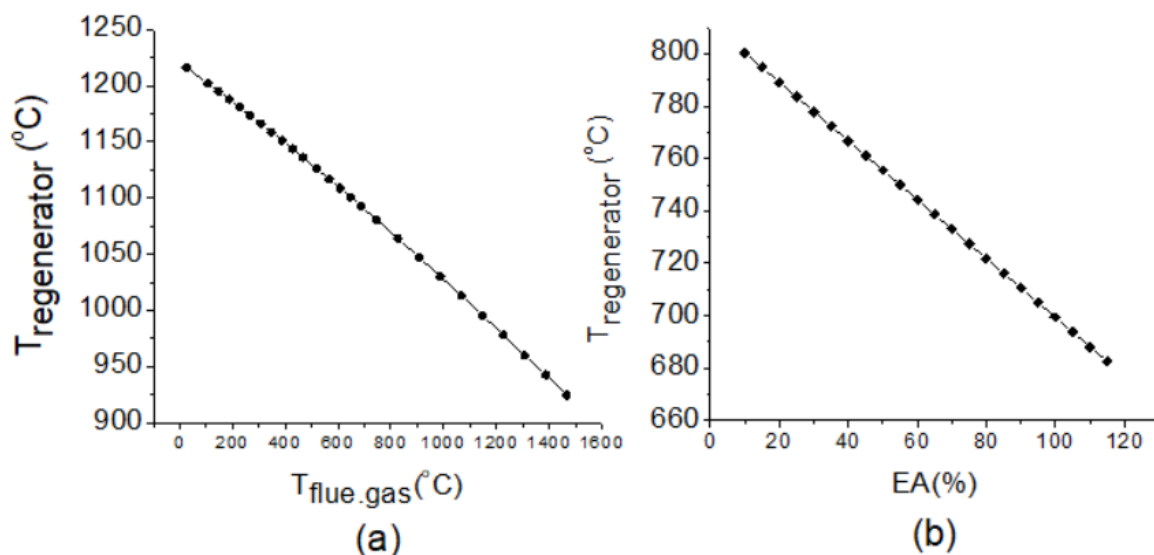

Figure 5. Estimation result of the resulting temperature of the regenerator section on the variation of: a) flue gas temperature, b) percentage of excess air

According to the **Figure 5a**, it implies that the resulting catalyst's temperature is reduced as the temperature of the flue gas increased. Theoretically, the heat energy produced from the combustion reaction will be transferred into two ways, that is heat energy released to the environment and the heat energy contains in the flue gas. Assuming that the system is completely isolated, it is considered that the released heat energy to the environment will directly transferred to the catalyst. The high flue gas temperature indicates that more heat is transferred into thermal energy in the flue gas than the energy transferred to the catalyst. Thus, it implies that the combustion needs to be designed in such a way that can minimize the flue gas temperature.

Presence of excess air also gives a significant effect to the resulting $T_{regenerator}$. **Figure 5b** shows that the resulting $T_{regenerator}$ is declined as the percentage of excess air (%EA) increased. The more excess air in the regenerator will cause more energy absorbed by the excess air. Therefore, the heat transferred to the catalyst will be reduced.

5.3 Analysis of the riser-regenerator system
The heat balance analysis shows that both riser and regenerator section have a close correlation. In the riser sections, $T_{reg.cat}$ represents the energy of the catalyst which is the source of thermal energy for the catalytic cracking reactions. In order to obtain the required $T_{reg.cat}$ in the riser, the catalyst should be heated in the regenerator through the combustion reaction.
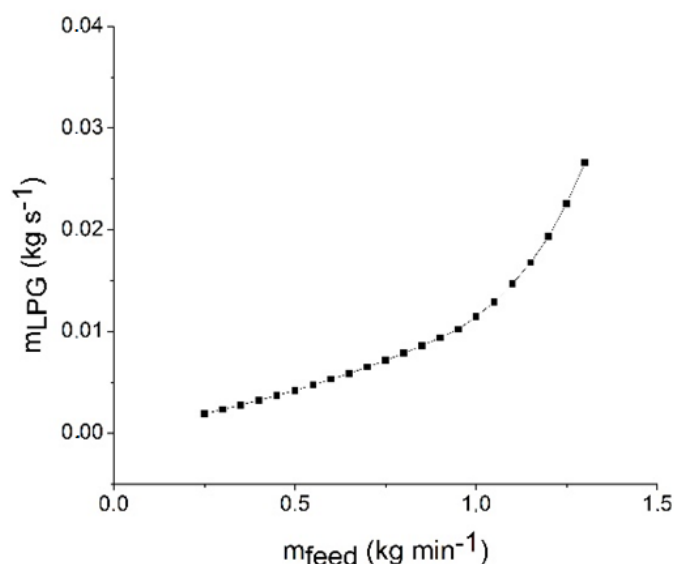

Figure 6. The requirement of LPG's mass flow rate for a given amount of feed mass flow rate

The catalytic cracking reactions that carried on along the riser need a particular optimum temperature. The catalyst entering the riser should contain enough amount of energy to reach the desired riser's temperature. In the other hand, the increasing amount of $\dot{m}_{feed}$ will increase the energy demand in the riser sections. Hence, the increasing $\dot{m}_{feed}$ will increase the required $\dot{m}_{LPG}$ in the regenerator as shown in **Figure 6**.

This study has discussed a simple method from the thermodynamic aspect for designing the two main sub-system of FCC. However, the assumption made in this study should be evaluated, especially for the further development of this study. It is assumed that there is no coke formed in either, riser or regenerator. In fact, this assumption will affect the combustion process in the regenerator. Basically, the catalytic cracking reaction is resulting coke particles which is decomposed on the surface of catalyst particles. The coke decomposition will reduce the activity level of the catalyst. Therefore, to restore the catalyst activity, those cokes particles need to clean up by burning it in the regenerator sections. Moreover, the combustion of the coke will produce additional thermal energy. Hence, the presence of the cokes particle could increase the resulting $T_{regenerator}$ in the regenerator. It implies that the assumption is acceptable because it still gives the required $T_{reg.cat}$. However, it is important to realize that this assumption cannot be implemented to the conventional FCC which only uses the coke particles as the fuel in the regenerator. In addition, it is also more difficult to set up a stable combustion process of the cokes. Therefore, the use of LPG as the fuel in the regenerator can give a more stable combustion.

6. Conclusions
This study gives an initial step for designing an FCC system that used for producing palm-based biofuel. The design process consists of two parts. The first part is the design considerations in the riser sections and the second part is the design consideration in the regenerator sections. It is

obtained that the amount of $\dot{m}_{LPG}$ in the regenerator should be determined appropriately in accordance to the given $\dot{m}_{feed}$ in the riser. This is so that the required $T_{reg.cat}$ can be obtained and the system can run properly. In addition, the amount of air flow rate in the regenerator ideally follows the amount its stoichiometric reaction, because the excess air will drop the temperature and reduce the effectiveness of the combustion. For the further study, the resulting result in this study need to be developed, especially the kinetic model reaction of the catalytic cracking reactions in the riser which used to estimate the reaction's product. Nevertheless, this study could be used as a baseline for designing the FCC system.

7. Aknowledgement

8. References

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