

SIMULATION OF CO-PROCESSING BIO-OIL AND VGO IN FLUID CATALYTIC CRACKING UNITS

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ABSTRACT

Biofuel is a promising substitute for fossil fuels to reduce greenhouse gas emissions and to provide highly sustainable fuels. Several technical challenges are indeed present during upgrading bio-oil to transportation fuel on a large scale. Co-processing bio-oil with some petroleum fractions in existing refineries serves as an alternative method to minimise processing costs. This paper aims to evaluate the co-processing by exploring the effects of temperature, bio-oil ratios and types of bio-oil to the product yields and quality in a Fluid Catalytic Cracking (FCC) unit within a refinery complex. The considered bio-oil are produced from pyrolysis of Palm Kernel Shell (PKS) and Empty Fruit bunch (EFB). The results show that bio-oil from PKS is better suited to produce gasoline due to its aromatic nature and its carbon range similarities compared to that from EFB. A mixture of 20% of hydrodeoxygenated (HDO) PKS in vacuum gas oil (VGO) shows a 5% improvement of naphtha yield while 20% raw bio-oil from PKS produces 4% increase in light cycle oil (LCO) yield.

Keywords: co-processing, fluid catalytic cracking, bio-oil, palm kernel shell, empty fruit bunch, simulation

INTRODUCTION

The Ministry of Energy, Science, Technology, Environment and Climate Change of Malaysia has a new goal to generate 20% of clean fuels from the total production of primary energy by 2030. Currently, the power generated from renewable energy in Malaysia is only 2% [1]. The mismatch between growing energy demand, depleting resources and increasing environmental concerns, the global dependence on fossil resources can be relieved by using renewable feedstock [2],[3]. Liquid fuels obtained from lignocellulosic biomass, also known as second-generation biofuels, are considered as a sustainable energy source and are currently the best substitute to replace fossil fuels [4]. The fuel production from bioethanol or the first-generation biofuel competes with the food supply for food industries [5]. Thus, second-generation biofuels are from non-edible fuel sources, which are from lignocellulosic biomass [5]. The drawback of this type of biomass is it requires

high-investment costs that lead to expensive fuels [6]. As Malaysia is one of the biggest palm oil producers, solid palm oil waste can produce second-generation biofuels via pyrolysis technology [7]. Hence, wastes and natural resources can be utilised optimally.

Bio-oil obtained from lignocellulosic biomass pyrolysis is a liquid of high density and moderate heating values. Its boiling point range and densities are within the range of typical crude oil properties [8]. These properties make bio-oil suitable as a feed to conventional refineries. On the other hand, it has a high content of oxygenated compounds, which makes it thermally and chemically unstable [9], [10]. Bio-oil must be upgraded to reduce its oxygen content and produce hydrocarbons suitable for internal combustion engines [9] as well as to reduce coke formations and catalyst deactivation [11]. Hence, upgrading the bio-oil via hydrodeoxygenation process is necessary.

Co-processing bio-oil into available refineries can reduce the cost of bio-oil upgrading [12]. Co-processing is the ability to put together various types of bio-oil and crude oil feedstock without compromising product quality [12]. Additionally, co-processing ensures full usage of the existing facilities on a long-term basis. Two main technologies for the co-processing of bio-oil with petroleum fractions are catalytic hydrocracking and fluid catalytic cracking (FCC) [13]. Co-processing of bio-oil with petroleum on FCC conditions are less technological challenging as compared with cracking whole bio-oil [13],[14]. FCC is regarded as a notable unit for co-processing due to the catalyst activity in FCC that promotes deoxygenation reaction as bio-oil has a distinct amount of oxygenates [14]. The largest part of literature studies has been conducted with zeolite catalysts that had been verified to be effective for deoxygenation. FCC is utilised to increase gasoline production by crack VGO into smaller hydrocarbons [13].

Experimental research on co-processing bio-oil in FCC unit requires a simulation model to integrate bio-refinery and refinery design further. The simulation of a model is important as it can determine how a system works when variables are manipulated. This paper presents the simulation of co-processing raw bio-oils from solid palm oil waste which is palm kernel shell (PKS) and empty fruit bunch (EFB) with vacuum gas oil (VGO). The ratios of bio-oils and petroleum feed considered in this study ranged from 5 to 20 wt% since the majority of the previous experimental works were performed within this range [9],[11],[13]. The developed model will be analysed to investigate the influence on conversion and product yields.

METHODOLOGY

Feed Composition and Properties

The properties of reference feed VGO was taken from the Chang et al. [15] shown in Table 1. The bio-oil composition from Nayaggy and Putra [16] which is fast pyrolysis oil (FPO) and hydrodeoxygenated oil (HDO) of palm kernel shell (PKS) and empty fruit bunch (EFB).

Table 1 Reference feed VGO properties [15]

Feed	VGO
Specific Gravity	0.9233
Distillation Type	D1160
Initial point (°C)	269.0
5%	358.6
10%	376.4
30%	419.0
50%	452.3
70%	488.0
90%	541.8
95%	567.9
End Point	665.8
Nitrogen (ppm wt)	2409.0
Sulfur (wt.%)	0.5

Process Simulation

Process simulations were done in Aspen HYSYS V10. Base case simulation for FCC unit was done and validated based on literature [15]. The operating conditions for FCC unit are given in Table 2.

Table 2 FCC operating conditions [15]

Volume Flow, m ³ /hr	150
Temperature (°C)	175
Pressure (kPa)	601.3
Total Feed Temperature (°C)	175
Steam Mass (kg/h)	5200
Steam Temperature (°C)	200
Steam Pressure (kPa)	1301
Riser Outlet Temperature (°C)	518
Stripping Steam Rate (kg/h)	5000
Regenerator Pressure (kPa)	296.5

The simulation model was modified by co-processing bio-oil with the petroleum fraction in FCC unit. There were four types of bio-oil used in this study, which were fast pyrolysis oil from PKS and EFB, and hydrodeoxygenated oil from PKS and EFB. The modified simulation result was validated by performing sensitivity analysis and was compared

with the experimental result obtained from existing literature. The selected parameters studied was the effect of reactor temperature ranging towards the feed conversion, and the product yield mainly naphtha and light cycle oil. Furthermore, the effect of the bio-oil blend ratio with the petroleum fraction was also studied that ranging between 5% to 20% bio-oil. The effect of using stabilised bio-oil compared to the fast pyrolysis oil was studied.

RESULTS AND DISCUSSION

Co-processing VGO and PKS in FCC unit

There were two different types of bio-oil feed used in this analysis, which were fast pyrolysis oil (FPO) and hydrodeoxygenated oil (HDO). Both bio-oils were produced from palm kernel shell (PKS). Reaction conversion was defined as the sum of the dry gas, LPG, gasoline, coke, carbon monoxide, carbon dioxide, water, light cycle oil (LCO), and residual bottoms [15]. Figure 1 illustrates the conversion of feed at different riser outlet temperature (ROT) ranging from 505°C to 555°C for pure VGO and PKS bio-oil ratio of 5% and 20%. Typical cracking temperature is in the range of 500-550°C. The higher temperature is not favourable due to high production of unwanted light gases. All the experimental results for the co-processing were also performed within this temperature range. Pure VGO was used as the reference for a comparable analysis of co-processing bio-oil. ROT in the Figure 1 is referred to the Riser Operating Temperature.

Based on Figure 1, it can be observed that the trend between pure VGO and co-processing show that the conversion increases as the reactor temperature (ROT) increase. Co-processing with pyrolysis oil PKS resulted in lower conversions compared to pure VGO. On the other hand, by using the hydrodeoxygenated oil (HDO PKS), the significant increase in conversion of up to 10% was shown as the reaction temperature increased from 505°C to 555°C. Compared to the raw pyrolysis oil of PKS, its hydrodeoxygenated oil was stable and had a higher energy density as compared with the FPO [13], [14]. HDO has a reduced amount of oxygen as a result of hydrotreatment. This could be the reason why the overall feed conversion of HDO PKS was higher than that of the PKS oil only.

Bio-oil blend conversion is higher than the conversion of pure VGO is due to a synergistic effect of the joint cracking between VGO and bio-oil [8],[13]. Furthermore, the co-processing of HPO with light cycle oil (LCO) increases overall conversion with increased temperature [17]. This increase of conversion for the co-processing of VGO with HDO bio-oil was also observed in the experiments done by Bezergianni et al. [13]. The experimental result of co-processing bio-oil in FCC unit resulted in a substantial increase in conversion up to 15% when the reaction temperature increased from 500°C to 550°C. Thus, based on this experimental result, the simulation result was validated. Typical cracking temperature is in the range of 500-550°C [15]. The higher temperature is not favourable due to the high production of

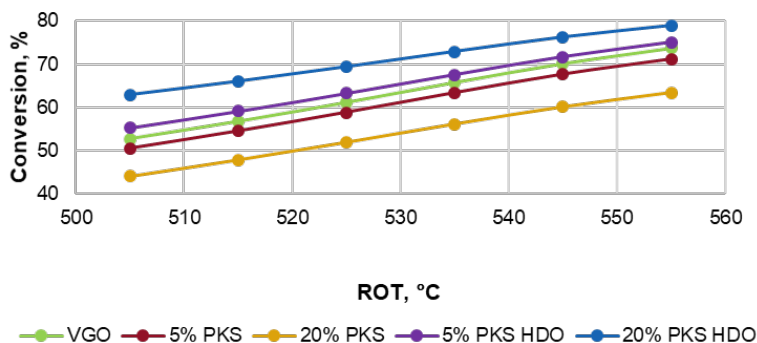


Figure 1 Feed conversion against ROT for pyrolysis oil of PKS and hydrodeoxygenated pyrolysis oil of PKS (HDO PKS)

unwanted light gases [15]. Hence, this explained that all experimental results for the co-processing were also performed within this temperature range.

and thermal cracking pathway which is an undesired result as we want to maximise naphtha yield that has significant value as compared with dry gases [15]. By

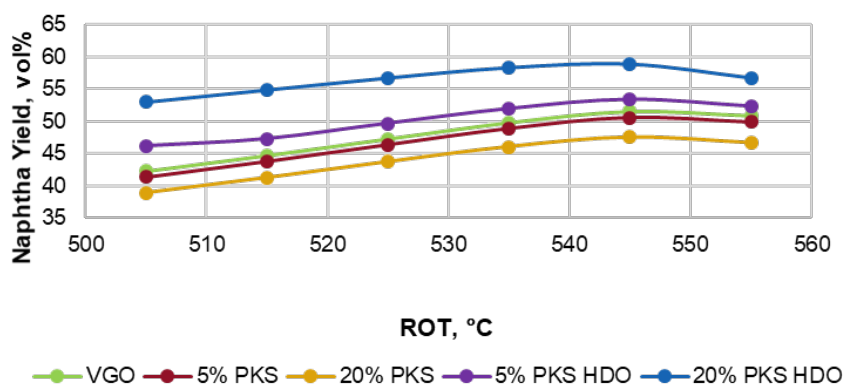


Figure 2 Naphtha yield against ROT for pyrolysis oil of PKS and hydrodeoxygenated pyrolysis oil of PKS (HDO PKS)

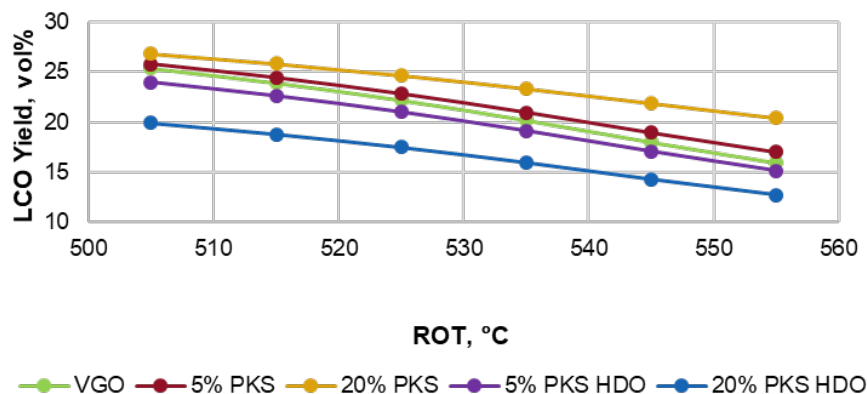


Figure 3 LCO yield against ROT for pyrolysis oil of PKS and hydrodeoxygenated pyrolysis oil of PKS (HDO PKS)

Naphtha yield at different reactor temperatures ranging from 505°C to 555°C is shown in Figure 2 for 5% and 20% bio-oil ratio. From the figure, it can be observed that as riser outlet temperature increases, the yield of naphtha reaches the maximum at ROT of 545°C. Beyond this point, the naphtha yield drops. These trends indicate that the feed is “over cracking” [15]. The high temperature accelerates the production of light components ($C_1 - C_4$) through the catalytic

comparing bio-oil types, 5% fast pyrolysis bio-oil has the same naphtha yield as pure VGO while increasing the concentration of bio-oil further reduces the naphtha yields. On the other hand, HDO bio-oil of PKS always has higher naphtha yields compared to that of pure VGO. Nayaggy and Putra [16] stated that upgraded oil from palm kernel shell best suits gasoline due to its aromatic nature and more similar boiling point ranges.

Figure 3 shows the result of LCO yield with a different bio-oil ratio ranging from 0% to 20% at ROT of 545°C. From the figure, that LCO yield decreases as reactor temperature increases due to a higher temperature will further crack light cycle oil into lighter products [15]. In addition, fast pyrolysis bio-oil of PKS produces higher LCO yield up to 4% when compared with pure VGO. Based on these results, it is seen that the raw bio-oil of fast pyrolysis PKS is more suitable than the HDO PKS in producing more LCO than naphtha. As explained by Naik et al. [18], highly oxygenated fast pyrolysis oil containing the lignin-derived monomers that could not be successfully cracked with the FCC catalysts thus resulting in a higher yield of LCO [19], [20].

Co-processing VGO and EFB in FCC unit

Based on Figure 4, the trend between pure VGO and co-processing shows that the conversion increases as the reactor temperature increases. As such, this trend is similar to the co-processing of bio-oil PKS. The simulation result of co-processing EFB in FCC unit shows a significant increase in conversion up to 10% as the reaction temperature increased from 505°C to 555°C. It is observed that 5% of EFB blend for both raw and HDO bio-oil of EFB yield almost similar feed conversions. While higher bio-oil blend yields higher feed conversion than the conversion of pure VGO. Previous experimental results mentioned that it could be due to the synergistic effect of the joint

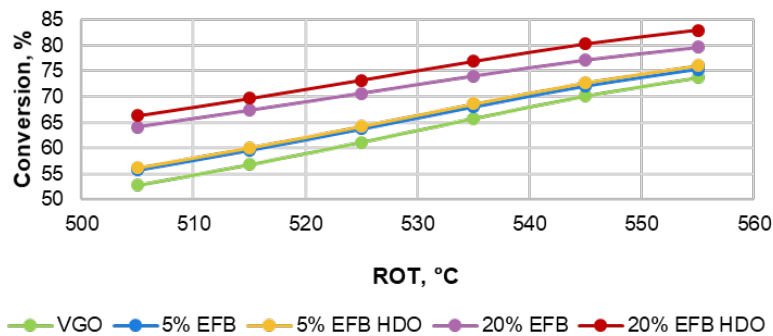


Figure 4 Feed conversion against ROT for pyrolysis oil of EFB and hydrodeoxygenated pyrolysis oil of EFB (EFB HDO)

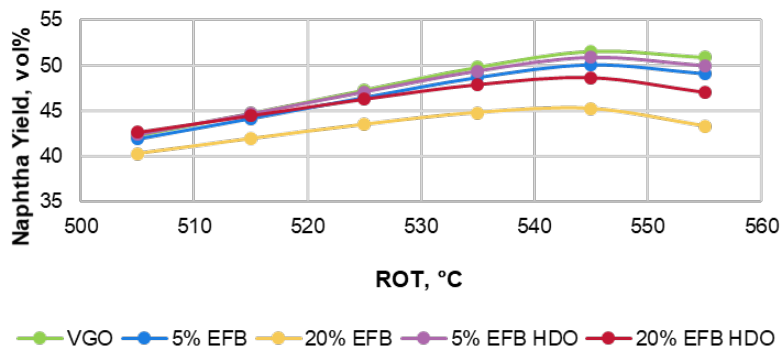


Figure 5 Naphtha yield against ROT for pyrolysis oil of EFB and hydrodeoxygenated pyrolysis oil of EFB (EFB HDO)

cracking between VGO and bio-oil [8],[13]. As such, the presence of oxygenates in the blend causes an increase in dry gas yield (C_1 and C_2), decrease in C_3 and C_4 hydrocarbons [19].

Figure 5 and Figure 6 illustrate the product naphtha yield and light cycle oil, respectively, at different reactor temperatures of VGO and EFB. Similar to co-processing PKS bio-oil, as the riser outlet temperature increases, the yield of naphtha reaches the maximum at ROT of 545°C. Higher reactor temperature will lead to feeding over cracking, which reduces the yield of naphtha [21]. Meanwhile, the high bio-oil blend ratio of EFB produces declined by 5% of naphtha yield compared with pure VGO.

CONCLUSION

Co-processing of bio-oil with petroleum oil is a very promising technique to integrate renewable resources into petroleum refinery for the second generation of biofuels. Greenhouse gas emissions will simultaneously be reduced while allowing steady independence from fossil sources. Therefore, this co-processing of bio-oil will result in low carbon emissions with highly sustainable fuels. In this paper, process simulation of co-processing bio-oil from palm kernel shell and empty fruit bunch in with Vacuum Gas Oil via FCC has been studied. Specifically, the simulation explored the effects of temperature and bio-oil blend ratio to the product yields and quality.

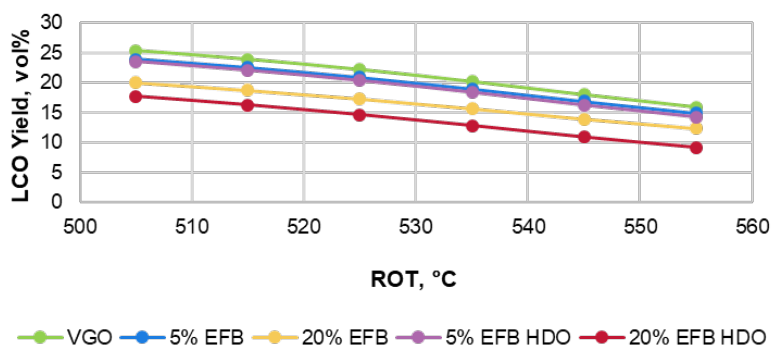


Figure 6 LCO yield against ROT for pyrolysis oil of EFB and hydrodeoxygenated pyrolysis oil of EFB (EFB HDO)

From Figure 6, substantial decrement yields of the LCO trend can be observed as the reactor temperature increases. A higher bio-oil blend ratio also produces lower LCO yield than pure VGO. Although co-processing EFB has higher conversion pure VGO, co-processing EFB has a lower product yield of naphtha and LCO. This obviously means that the co-processing of bio-oil from EFB produces more unwanted light gases compared to that of pure VGO. EFB composition has no similarities with both gasoline and diesel ASTM distillate curves based on literature, as evaluated by Nayaggy and Putra [16]. Thus, EFB is suitable to produce liquid fuels such as kerosene and heating oil as the nature of its structure is a long carbon chain [16].

The results showed that higher riser temperatures of the FCC unit led to higher feed conversions. Co-processing of bio-oil from Palm Kernel Shell was more preferred than EFB. Bio-oil from Palm Kernel Shell was best suited to produce gasoline due to its aromatic nature and its similarity in carbon ranges. Hence, it produced higher naphtha yields compared to feeding pure Vacuum Gas Oil. Co-processing of 20% of hydrodeoxygenated bio-oil of Palm Kernel Shell with Vacuum Gas Oil showed a 5% improvement of naphtha yield could be obtained. Co-processing of 20% of raw bio-oil of Palm Kernel Shell produced a 4% increase in LCO yield.

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