1. Introduction

In Malaysia, palm oil production is one of the leading industries for the country’s economy with an annual production of more than 15 Tg (15 million tons). This large amount of palm oil production is accompanied by a large amount of oil waste by-product such as empty fruit bunch (EFB). The annual EFB production is estimated to be as high as 17.1 Tg (17.1 million tons), but most of this is just disposed of. This is a serious problem for the Malaysian palm oil industry, since it often causes damage to the environment.

One of the solutions would be to convert EFB into a useful fuel such as torrefied EFB. Torrefaction technology is recently attracting interest all over the world as a useful technology for obtaining valuable, high energy density fuel from moisture containing biomass. In the torrefaction process, biomass is heated in the temperature range of 150-250 °C, so that drying and partial thermal decomposition take place. The rather low temperature of this thermal treatment prevents excessive decomposition of the feedstock by carbonization and gasification. Since gasification and carbonization results in loss of a large part of the organics in the form of exhaust gas, leaving only a small amount of energy behind, it is not always efficient. The resulting torrefaction product has a high energy density due to the loss of water and partial carbonization.

So far, not much fundamental research on reaction rates and production yields has been carried out for this torrefaction process. Since drying requires energy, the appropriate system configuration is needed for the torrefaction to be effective, but the process analysis of torrefaction has not been sufficiently investigated. This has lead to uncertainties in the effectiveness of torrefaction technology. Thus, an appropriate process analysis is essential for development of torrefaction. The purpose of this study is to conduct a process analysis for EFB torrefaction and to verify its effectiveness.

2. Calculation Model

Table 1 shows the employed assumptions and conditions in the torrefaction process that are common in Malaysia. A rotary kiln reactor is employed for torrefaction in this study. Process evaluation is made for the three cases of palm mill EFB torrefaction in terms of energy and operating cost. In the first case all the heat is supplied by heavy oil. In the second case flue gas from a palm oil mill boiler is employed for drying. In the third case Vapor Re-Compression (VRC) for heat recovery is employed in the drying process. Mass and energy balance calculations reveal that energy saving by VRC largely improves the energy efficiency. In spite of the initial cost increase and electricity cost requirement, the VRC process results in the lowest unit cost of the torrefied product due to the large reduction of heavy oil consumption.
boiler is added, and partial oxidation is employed in the torrefaction process. Case 3 further employs a compressor to recover the heat of evaporation in the drying process. In addition, part of the product gas is used as fuel in the case 3. Nitrogen is delivered to the torrefaction reactor.

Figures 1 and 2 show the reactor set-up and the flow diagram of the torrefaction process for case 1, respectively. Here, the moisture content in the feedstock EFB is denoted water 1, and water produced by the pyrolysis reaction is denoted water 2. Figures 3 and 4 are those for case 2, where flue gas from the boiler is added to the process in place of nitrogen to directly heat the EFB. Carbon dioxide 3 and water 3 are generated by the complete oxidation of EFB. Figures 5 and 6 are those for the case 3, where Vapor Re-Compression (VRC) for heat recovery in the drying process is employed and part of the product gas is used as fuel.

Table 2 shows the conditions specific to each case. Table 3 shows the yields of the torrefied products for the three cases. These assumptions are made based on the literature data\(^{6(9\sim11)}\). It is assumed that the torrefaction results in production of torrefied EFB, a pyrolysis by-product, and for the cases 2 and 3, an oxidation by-

![Fig. 1 Torrefaction Reactor Set-up for Case 1](image1)

![Fig. 2 Torrefaction Process Flow Diagram for Case 1](image2)

![Fig. 3 Torrefaction Reactor Set-up for Case 2](image3)

![Fig. 4 Torrefaction Process Flow Diagram for Case 2](image4)
product. The pyrolysis by-product is assumed to be composed of 90 wt% of liquid and 10 wt% of gas. It is further assumed that this by-product liquid is composed of 87 wt% of pyrolysis oil and 13 wt% of water, and that this by-product gas is composed of 80 wt% of CO₂ and 20 wt% of CO. For the cases 2 and 3, composition of the flue gas supplied to the torrefaction process for direct heating is assumed to be composed of 80 mol% of N₂, 10 mol% of CO₂, and 10 mol% of O₂.

An economic analysis is also conducted for the three cases. Tables 4 and 5 show the parameters and the initial costs employed for this analysis, respectively. The rotary kiln of 19.6 m³ (diameter: 1 m, length: 25 m) and the compressor with a capacity of 76.1 Mg·H₂O/d is employed. These are the values expected in Malaysia. The cost of the dryer was neglected since it is much cheaper compared to rotary kiln reactor and compressor for the simplicity purpose. Please note that for case 3, gas is automatically separated from the oil when cooled down, and thus simple container, which is also much cheaper than rotary kiln and compressor is sufficient for this purpose.
3. Results and Discussions

3.1. Mass Balance

Figure 7 shows the results of the mass balance calculation for case 1. It is to be noted that the ratio of oil and water 2 is 3.2 to 0.5 t/d, which is 87 to 13 %, as assumed in the previous section. For cases 2 and 3, the results of the mass balance calculation are identical, and shown in Fig. 8. The yield of the torrefied EFB for cases 2 and 3 is less than that for the case 1 by 3 %, due to oxidation by the oxygen in the boiler flue gas. Nitrogen and carbon dioxide are assumed to be inert.

3.2. Energy Balance

Figures 9, 10, and 11 show the result of energy balance calculations for cases 1, 2, and 3, respectively. All the data needed for this calculation are shown in Tables 1-4. The energy balance is calculated based on the results of mass balance. In case 1, heat needed for the torrefaction process is 253 GJ/d. In case 2, the heat needed for the torrefaction process is less, at 226 GJ/d due to the partial oxidation by the oxygen in the flue gas, and heat carried in by the flue gas (QF = 68 GJ/d) in case 2. In case 3, the heat needed for the torrefaction process is 75 GJ/d. This value is the lowest of the three cases. This is due to the heat recovery of VRC in the drying process. As much as 151 GJ/d is recovered to produce steam by heat of condensation, which otherwise would be discarded\(^{11}\). It is to be noted that the net heat release by water 2 is 41 GJ/d for this case.

3.3. Torrefaction Cost

The heat for the torrefaction process for all the cases is supplied by heavy oil. Thus, the torrefaction cost is determined using the heavy oil cost, together with labor cost, and EFB cost. The EFB cost is the amount to be paid for obtaining the EFB feedstock for torrefaction. A negative EFB cost means that the palm oil producers have to pay for its disposal. On the other hand, a positive EFB cost means that palm oil producers can sell EFB to make their income. Labor cost is 100 RM/d (50 RM/d/person, 2 persons). Figure 12 shows the results of costs to produce 1 GJ of torrefied EFB, which is composed of feedstock, oil, and labor costs, for cases...
1 through 3. The costs of coal and heavy oil B are also shown in Fig. 12. For the case 1, when EFB cost is higher than \( \$70 \) RM/t, the torrefaction cost becomes higher than the coal cost. At least, the EFB cost has to be lower than \( \$70 \) RM/t to compete with coal. For case 2, when EFB cost is higher than \( \$80 \) RM/t, the torrefaction cost becomes higher than the coal cost. Considering that initial cost and electricity cost for VRC for the case 3 are additionally needed, at least, the EFB cost has to be lower than \( \$80 \) RM/t to compete with coal. For the case 3, if EFB cost can be as high as \( \$450 \) RM/t for the torrefaction cost to compete with coal. Case 3 is the best of these three cases. In all cases, the torrefaction cost decreases with decreasing EFB cost.

It is desirable that the EFB cost is negative to improve its economic efficiency. However, the palm oil producers cannot always afford the cost of disposing of EFB. Table 6 shows the distribution of EFB costs in Malaysia. Only 10% of the EFB is available at a negative cost. On the other hand, 50% of EFB is available at zero cost. A zero EFB cost is the practical situation to realize the torrefaction process. It is notable that for all cases, the torrefaction cost can be less than coal cost for zero EFB cost.

3.4. Total Cost

Figure 13 shows the cost of torrefied product including the initial cost, which was calculated by

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\text{(torrefied product cost)} = \frac{\text{(initial cost)/(recovery years)} \times \text{(total weight of product)}}{\text{(torrefaction cost)} + \text{(electricity cost)}}.
\]

This value depends on the recovery years, and electricity needed for VRC for the case 3. Electricity cost was included in this stage, since it is not needed for the torrefaction itself. The cost is calculated at zero EFB cost. Case 3 shows the highest economic efficiency even with the initial cost and electricity needed for VRC. The cost of torrefied product decreases with increasing recovery years. However, the cost of the torrefied product stays almost constant after 3 years in each case. Thus, for the implementation plan, recovery years can be as short as three years. The cost of the torrefied EFB is lower than the cost of coal (12 RM/GJ) for all the cases. Thus, it is concluded that commercialization of the EFB torrefaction plant is feasible.

4. Conclusion

Process evaluation for the three cases of palm EFB torrefaction has been conducted in terms of energy and operation cost. Most of the energy requirement for the torrefaction is heat needed for EFB drying and heat of reaction from the torrefaction. Utilization of palm oil mill boiler flue gas and employment of VRC for heat recovery for the drying process largely improves the process energy requirement from 253 GJ/d of heat to 58 GJ/d of heat and 17 GJ/d for compression. This improvement results in the highest operating cost due to electricity needed for the compressor, but its unit cost of the product is the cheapest. For all cases, the torrefaction cost decreases with decreasing EFB cost, but a zero EFB cost is the most appropriate assumption. The cost of the torrefied EFB for this case is lower than the cost of coal (12 RM/GJ), even when initial cost is included. Thus, commercialization of EFB torrefaction plants is a feasible proposal.
References


要 旨

マレーシアにおける空果房の半炭化プロセスの評価

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マレーシアのパーム油製油所から発生する空果房（EFB）の半炭化は廃棄物からのエネルギー回収を実現するものとして期待されているが、プロセスの検討は十分に行われていない。本研究では、パーム油製油所からの EFB の半炭化のプロセス評価をエネルギーならびに経済性の観点から行った。半炭化のために必要となるエネルギー需要の大部分は EFB の乾燥と半炭化反応のために用いられるものである。この熱を軽油で供給するケース1、製油所ボイラー排ガスを乾燥のために利用するケース2、熱回収のためにさらに圧縮蒸気凝縮を行うケース3について検討を行った。物質収支ならびにエネルギー収支計算の結果、圧縮蒸気凝縮により大きな省エネルギーが実現できることが確認された。ケース3は初期コストも高くなり、蒸気圧縮動力が必要となるが、大量の軽油を必要としないため、半炭化製品単価は最低にすることが可能だった。