The study of palm kernel shell updraft gasification for supplying heat to an asphalt mixing plant

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Abstract. Air-gasification converts biomass using air into combustible gaseous components which also known as producer gas. The combustion of those gases provides energy for any purposes. In an asphalt mixing plant, this technology is implemented using palm kernel shell as feedstock to generate heat for aggregate heating as a part of hot-mixed asphalt production. Both Cold Gas Efficiency (CGE) and Carbon Conversion Efficiency (CCE) are the common performance indicators of such process. This study examines a performance of an updraft fixed-bed gasifier to convert the shell into producer gas in supplying heat for increasing aggregate temperature from ambient to about 145 – 165°C at capacity of 800 kg/min. The feedstock flowrate was set at 990 kg/hour and equivalence ratios were varied at 0.04, 0.05 and 0.08. Because the gasification reactions were in equilibrium, the producer gas composition for calculating the CGE was predicted using thermodynamic model with minimizing Gibbs free energy. The feedstock and solid residue of the process were analysed to determine the carbon content for calculating the CCE. It is indicated that the performance of the gasification operation for supplying heat in an asphalt mixing plant is limited by operating conditions.

1. Introduction

In the recent years, the world energy demand raised along with the world economy growth. International Energy Agency (IEA) predicts a significant increase on the energy needs by 45% or equivalent to average rate of 1.6% per year in the end of 2030. About 80% of the needs are supplied with fossil fuel. The Ministry of Energy and Mineral Resources of the Republic of Indonesia also reported in National Energy General Plan 2015 that the industrial sectors will consume about 47.7% of energy supply in the country.

As an energy intensive process which all the time depends on fossil fuel to provide aggregate heating energy through direct combustion, an asphalt mixing plant (AMP) needs 315 MJ or equivalent to 7.6 – 11.14 L of diesel fuel for producing one ton of hot-mixed asphalt [1]. Recently, several hot-mixed asphalt (HMA) producers start considering renewable energy as main energy source though The Ministry of Public Works and Housing Settlements of the Republic of Indonesia recommends only diesel fuel, natural gas or synthetic gas from coal gasification as the energy sources. It is a challenge of an energy producer while the limited stock of fossil fuel and various energy resources are available. In addition to that, environmental issues as a consequence of fossil fuel utilization make various types of renewable energy resources attractive solutions.
On the other hand, the country provides huge amount of biomass as potential renewable energy sources for substituting the fossil fuel, such as palm kernel shell (PKS). The Central Bureau of Statistics of Indonesia reported in 2019 that the country produces about 2.0 – 2.4 million tones PKS every year as a biomass waste from palm oil mills which are scattered mainly in Sumatra Island and Kalimantan island. According to Indonesian Palm Oil Association, about 1.12 million ton or equivalent to 54% of the PKS production was exported to Japan in 2017 and only small amount were used as fuel source by direct combustion in the country. It is attractive as the heating value of the PKS is high enough at about 20.2 – 23.9 MJ/kg [2].

Because lower operating cost, direct combustion is very common utilization of raw PKS for thermal energy production system [3]. The shell also could substitute coal combustion as fuel in domestic boiler with consideration on sintering and fouling of the heating surface of the boiler [4]. Some studies proposed co-combustion of PKS with other fuels, such as anthracite coal and empty palm oil fruit bunch [5]. By pyrolyzing, the shell is a promising raw material of biochar or activated carbon for power generation through direct carbon fuel cell technology [6], heavy metal removal [7], carbon dioxide adsorption [8], methylene blue adsorption [9], dye removal [10], bio-fertilizer [11], and bio-adsorbent for the treatment of POME final discharge with the reduction of total suspended solid, color, COD and BOD [12].

But, implementation of PKS direct combustion in an AMP is possible to deteriorate the hot-mixed asphalt quality, because the ash content on the aggregate may reduce the asphalt-aggregate cohesion. Gasification technology offers the solution through converting the solid shell into combustible gases such as carbon monoxide, hydrogen, and methane, and leaving ash as solid residue of the process. Then, combustion of the clean gases generates energy for heating the aggregate to temperature of about 145 – 165°C without ash particle impurity. This temperature range should be attained before mixing the aggregate with asphalt without thermal decomposition of the asphalt to produce high quality hot-mixed asphalt as supporting material for infrastructure sectors especially highway construction.

Several air-gasiﬁcation experiments using different biomass feedstock, equivalence ratio, and gasifier type were previously studied to convert biomass into energy at almost similar temperature range (Table 1). Air is the most practical and economical for gasifying agent, but the gaseous products which is also known as producer gas contains lower CO and H₂, and consequently lower heating value which is expressed as cold gas efficiency (CGE). It is reasonable because nitrogen in the air as inert potentially reduces heating value. However, it is likely to be improved at proper equivalence ratio (ER). The flow characteristics of gasifying agent and the producer gas in the updraft (counter-current) gasifier result higher CGE than any other types. While the gasifying agent flows upwards, the biomass feedstock is fed from the top of the reactor and moves down through a drying zone at 100°C, followed by a pyrolysis zone at about 300°C where char and gaseous products are generated [13]. The char goes down to reduction and oxidation zone to react with incoming air to produce ash, remaining carbon, CO and CO₂. The hot upcoming gaseous component reacts with incoming feedstock in the upper bed zone to produce more H₂ and CO. It also cools the gas temperature and heats the incoming biomass at the same time which then gas leaves the reactor at certain temperature.

Palm kernel shell gasification in an updraft gasifier offers an attractive and flexible technology to supply power and heat using air, enriched air, steam, carbon dioxide or their mixture as gasifying agent. Hydrogen content in the producer gas is possible to be increased using steam as gasifying agent [14–16]. Various gasification reactor types were introduced for PKS gasification process [13], such as fixed-bed [17,18] and fluidized bed type [19,20]. Low rank coal [21,22] and plastic wastes [19,23] are popular to be co-gasified with the shell as feedstocks to produce higher heating value producer gas.

Not only as renewable energy source, palm kernel shell is also possible to be a coarse aggregate partial substitution for building construction material. The raw shell is mixed together with aggregate to form lightweight concrete [24–26]. Related to its utilization for construction, this research studies of the palm kernel shell as feedstock of an updraft gasification reactor to produce combustible gaseous component for substituting fossil fuel of an aggregate heater in an asphalt mixing plant. This evaluates
the air-gasification operation performance from the points of view cold gas efficiency (CGE) and carbon conversion efficiency (CCE).

Table 1. Previous studies of biomass air-gasification.

| No. | Feedstock                  | ER  | Gasifier Type        | T (°C) | CGE      | CCE      | Ref.   |
|-----|---------------------------|-----|----------------------|--------|----------|----------|--------|
| 1.  | Rice husk                 | 0.275 | Fluidized bed      | 725    | 64.11%   |          | [27]   |
| 2.  | Wood waste                | 0.205 | Downdraft           | 900 – 1050 | 56.87%   |          | [28]   |
| 3.  | Coffee husk               | 0.6  | Semi-industrial fluidized bed | 815 | 60%      |          | [29]   |
| 4.  | Pinus thunbergiana pellet | 0.285 | Updraft (packed bed) | 943    | 91.03%   | 84.26%   | [30]   |
| 5.  | Rice husk                 | 0.6  | Downdraft fixed-bed | 600 – 850 | > 60%    |          | [31]   |
| 6.  | Rice husk pellet          | 0.3  | Downdraft fixed-bed | 500 – 850 | > 70%    |          | [31]   |
| 7.  | Rubber wood               | 0.31 | Updraft             | 700 – 1100 | 75%      |          | [32]   |
| 8.  | Sewage sludge             | 0.25 | Updraft             | 700 – 1100 | 21%      |          | [33]   |
| 9.  | Poultry litter            | 0.15 | Updraft (fixed-bed) | 580 – 680 | 26%      | 44%      | [34]   |

2. Materials and methods

2.1. Materials

Several palm kernel shell from three plantation areas in Indonesia were characterized in the point of view proximate, ultimate, and calorific value as shown on Table 2. It is observed that those have similar characteristics especially in calorific value which is about 17.95 – 18.28 MJ/kg. However, a significant different in ash content was identified in palm kernel shell from Lampung Province. This study used palm kernel shell as a waste of a palm oil plant in West Kalimantan Province because the study location is about 50 – 60 km from the plant. The samples of each PKS were analyzed for proximate, ultimate and calorific value in an accredited laboratory of The Center for Mineral and Coal Technology Research and Development, Bandung.

Table 2. Chemical characteristics various palm kernel shell in Indonesia.

| PKS                  | Ultimate Analysis (db) | Proximate Analysis | GCV<sup>d</sup> (MJ kg<sup>-1</sup>) |
|----------------------|------------------------|--------------------|-------------------------------------|
|                      | C          | H          | O          | N          | S          | Ash       | VM<sup>a</sup> | FC<sup>b</sup> | M<sup>c</sup> |                |
| Riau                 | 46.83%    | 6.88%     | 44.03%    | 0.37%     | 0.14%     | 1.75%     | 65.39%     | 20.06%     | 12.80%     | 17.99        |
| Lampung              | 45.96%    | 6.93%     | 43.47%    | 0.43%     | 0.14%     | 3.07%     | 65.58%     | 18.29%     | 13.06%     | 17.95        |
| West Kalimantan      | 48.35%    | 6.10%     | 42.88%    | 0.48%     | 0.03%     | 2.16%     | 71.24%     | 19.57%     | 7.03%      | 19.07        |
| Central Kalimantan   | 47.72%    | 6.81%     | 43.63%    | 0.34%     | 0.15%     | 1.35%     | 67.21%     | 19.85%     | 11.59%     | 18.28        |

<sup>a</sup>Volatile matter; <sup>b</sup>Fixed carbon; <sup>c</sup>Moisture content; <sup>d</sup>Gross calorific value

2.2. Gasification reactions

Although biomass gasification reactions are very complicated, the reactions are possible to be classified into drying, pyrolysis, oxidation and reduction steps. Gasification reactions mostly take place in reduction process. This study focuses on some major chemical reactions which refers to previous studies, such as reduction, oxidation, methanation, Bouduard reaction, and Water-Gas reaction (see Table 3). Endothermic and exothermic reactions are occurred during reduction process. Bouduard and Water-Gas reaction are endothermic, while methanation is exothermic reaction. Those reactions are in equilibrium at certain temperature.
### Table 3. Typical gasification reactions at 25°C [35].

| R  | Reaction                                | $\Delta H^\circ$ (kJ/kmol) | $\Delta G^\circ$ (kJ/kmol) |
|----|----------------------------------------|----------------------------|----------------------------|
| 1  | Carbon reactions                        | C + CO$_2$ ↔ 2CO            | +172.0                     | +120.00                     |
| 2  |                                      | C + H$_2$O ↔ CO + H$_2$     | +131.0                     | +91.41                      |
| 3  |                                      | C + 2H$_2$ ↔ CH$_4$         | -74.8                      | -50.50                      |
| 4  |                                      | C + $\frac{1}{2}$O$_2$ ↔ CO | -111.0                     | -137.20                     |
| 5  | Oxidation reactions                     | C + O$_2$ ↔ CO$_2$          | -394.0                     | -394.40                     |
| 6  |                                      | CO + $\frac{1}{2}$O$_2$ ↔ CO$_2$ | -284.0                     | -257.20                     |
| 7  |                                      | CH$_4$ + 2O$_2$ ↔ CO$_2$ + 2H$_2$O | -803.0                     | -801.12                     |
| 8  |                                      | H$_2$ + $\frac{1}{2}$O$_2$ ↔ H$_2$O | -242.0                     | -228.61                     |
| 9  | Water-gas shift reaction               | CO + H$_2$O ↔ CO$_2$ + H$_2$ | -41.2                      | -28.59                      |
| 10 | Methanation reactions                  | 2CO + 2H$_2$ ↔ CH$_4$ + CO$_2$ | -247.0                     | -170.50                     |
| 11 |                                      | CO + 3H$_2$ ↔ CH$_4$ + H$_2$O | -206.0                     | -141.91                     |
| 12 |                                      | CO$_2$ + 4H$_2$ ↔ CH$_4$ + 2H$_2$O | -165.0                     | -113.32                     |
| 13 | Steam-reforming reactions              | CH$_4$ + H$_2$O ↔ CO + 3H$_2$ | +206.0                     | +141.91                     |
| 14 |                                      | CH$_4$ + $\frac{1}{2}$O$_2$ ↔ CO + 2H$_2$O | -36.0                      | -86.70                      |

2.3. Experimental setup

Figure 1 shows the palm kernel shell gasification for generating producer gas to heat aggregate in an asphalt mixing plant at capacity of 800 kg of aggregate per minute. The feedstock size of 2 – 3 cm (A) was fed into the hopper (B) by a wheel-loader and transported with a belt conveyor (C) to the top of an updraft fixed-bed gasifier (D). This input rates were adjusted with a variable speed gear-box motor of a feeder. By controlling flowrate at 210, 253, and 385 Nm$^3$/hour, air was supplied upward into the gasifier with air blower (E) and the flowrate of outlet solid residue from gasifier (F) was set with adjusting the rotation of a rotating plate system (G). The residue was analyzed for ash and fixed carbon components according to ASTM D-2015 or ASTM 5865-03.

![Experimental configuration of palm kernel shell gasification for aggregate heating.](image)

The reaction temperature was monitored using thermocouples which were installed in the reduction zone of gasifier reactor. As the reactor operates at temperature of about 900°C, a water cooling should be provided to keep the reactor wall and air distributor at acceptable temperature. This cooling water was pumped using a water pump (H). The gaseous products flowed upward into the water scrubber (I) for cleaning from small solid particle, including ash, and flowing to the series of gas pipeline (J) for cooling.
the temperature down before combustion process in a burner (K) using combustion air from air blower (L). The burner was coupled with a rotary dryer where aggregate drying occurred.

2.4. Calculation method
A thermodynamic model was set using simultaneous stoichiometric equilibrium reactions (Table 3) based on minimizing of Gibbs energy approach for predicting the producer gas composition \( y_i \) resulted from those reactions (Equation 1) with \( n_{i0} \) is initial mol of component \( i \), \( n_0 \) is initial total mol of the gas, \( \vartheta_{i,j} \) is the stoichiometric coefficient of component \( i \) in the reaction \( j \), \( \vartheta_j \) is the sum of the component \( i \)'s stoichiometric coefficient in the reaction \( j \), and \( \varepsilon_j \) represents reaction coordinate of reaction \( j \) which characterizes the extent of degree to which a reaction has taken place. The producer gas was assumed as a mixture of hydrogen, water, carbon monoxide, methane, nitrogen and carbon dioxide at certain composition which was affected by air flowrate. An equilibrium constant \( K_j \) of a reaction \( j \) in Table 3 at temperature \( T \) was calculated with Equation 2 where \( \Delta G^o \) represents free energy Gibbs of the reaction at 25°C and \( R \) is universal gas constant.

\[
\begin{align*}
    y_i &= \frac{n_{i0} + \sum_j \vartheta_{i,j} \varepsilon_j}{n_0 + \sum_j \vartheta_j \varepsilon_j} \\
    K_j &= \exp \left( \frac{-\Delta G^o}{RT} \right)
\end{align*}
\]

Equilibrium constant also implies the product of all the composition in a reaction \( j \) powered with each stoichiometric coefficient at certain pressure \( P \) with \( P^0 \) is the standard pressure of 1 bar as shown in Equation 3. Substituting Equation 1 and 2 to Equation 3 of every reaction in Table 3 construct 13 simultaneous algebraic equations in \( \varepsilon \) and allow calculation of each reaction coordinate. Then, each considered gas composition could be determined using Equation 1.

\[
\Pi_i(y_i)^{\vartheta_{i,j}} = \left( \frac{P}{P^0} \right)^{\vartheta_j} K
\]

Equivalence ratio (ER) influences temperature and gas composition; CGE and CCE as consequences. It describes the mol flowrate ratio of air as gasifying agent \( (n_{air}) \) to biomass \( (n_B) \) at operating conditions compared to stoichiometric reaction (Equation 4). Higher ER shifts the reaction into exothermic which causes increasing in temperature, while lower ER generates more tar and lower heating value of producer gas. Complete combustion is occurred with ER value of 1.00. This study performed ER value range at 0.04 – 0.10.

\[
ER = \frac{n_{air}/n_B}{(n_{air}/n_{stoich})}
\]

The heating value of producer gas was expressed as lower heating value \( LHV_g \) in MJ/Nm^3 and calculated with Equation 5. The result together with the LHV of biomass \( LHV_B \) in MJ/kg were used for CGE calculation (Equation 6) where \( V_g \) is volumetric flowrate of producer gas (Nm^3/h). This flowrate was monitored using a vortex flowmeter instrumentation. Carbon conversion efficiency (CCE) of this gasification operation was determined with mass balance analysis and calculated with Equation 7.

\[
LHV_g = 12.621y_{CO} + 10.779y_{H2} + 35.874y_{CH4}
\]

\[
CGE = \frac{V_g \times LHV_g}{m_B \times LHV_B}
\]

\[
CCE = 1 - \frac{c_{residue}}{c_B}
\]
3. Results and discussion

3.1. Gas composition
The producer gas composition as a result of thermodynamic model approach were determined at various air flowrates. At constant biomass feedstock flowrate of 990 kg palm kernel shell per hour, the air flowrates were adjusted at 210, 250 and 385 Nm\(^3\)/hour which are equivalent to ER of 0.04, 0.05 and 0.08 and at operating temperature of 772, 748 and 830\(^\circ\)C respectively. This system was operated at ambient pressure of 1 bar. The resulted compositions are shown graphically in Figure 2. It is obvious that the higher ER the more nitrogen and carbon dioxide, while the less combustible gas components (CO, H\(_2\), and CH\(_4\)) because the oxygen from the air tends to react with those gases. These results are in agreement with previous studies [28,36]. While, the air gasification usually operates at ER range of 0.30 – 0.40 [35]. Figure 2 indicates that the higher the ER the lower content of combustible gas component because higher ER implies higher oxygen supplied for the reaction and converts CO and H\(_2\) into CO\(_2\) and H\(_2\)O respectively. As a result, a lower energy density of the gas is produced at more volumetric rate.

During experiments, methane tended to increase as a result of methanation reactions (see Table 3). At higher ER, this component decreases caused by steam-reforming reactions. Thermodynamic calculation results the methane composition of 8.9% and 9.6% at ER of 0.30 and 0.40 or air flowrate of 1450 and 1900 Nm\(^3\)/hour respectively.

![Figure 2. Effect of Equivalence Ratio on producer gas composition.](image)

3.2. Gasification operation performance
As performance indicators, the CGE and CCE of this system at the operating conditions are tabulated in Table 4. Both increased when the flowrates which are expressed as ER was higher. Basically, using more air and consequently more oxygen produces more CO until certain flowrate when complete combustion start occurring at ER of about 1.0. Theoretically, no combustible gaseous component exists at this condition.

| ER  | T (°C) | Proximate Analysis of Solid Residue | GCV (MJ kg\(^{-1}\)) | LHV gas (MJ/Nm\(^3\)) | CGE   | CCE   |
|-----|--------|------------------------------------|----------------------|------------------------|-------|-------|
|     |        | Ash      | VM    | MC     | FC    |       |       |
| 0.04| 772    | 7.10%    | 4.20% | 11.28% | 77.42%| 26.26 | 9.49  | 35.93%| 47.28%|
| 0.05| 748    | 8.22%    | 5.19% | 11.20% | 75.39%| 25.76 | 9.36  | 37.64%| 48.65%|
| 0.08| 830    | 14.36%   | 11.72%| 10.26% | 63.60%| 21.57 | 9.26  | 46.33%| 51.71%|

![Table 4. Cold gas efficiency and carbon conversion efficiency at various equivalence ratios.](image)
This study was performed in a real gasification unit installed in an asphalt mixing plant which operated at lower ER compared with several previous researchers (Table 1) because limitations on operating condition. Based on thermodynamic approach, mass balance and energy balance, it was found that actually the ER was possible to be increased but this requires more power for operating the air blower and larger size of pipeline as more producer gas would be produced. This increasing is insignificant compared to the increasing of ER from 0.08 (Table 4) while more ER will decrease the CGE as more oxygen supply to the reactions.

A previous experiment using rubber wood with slightly lower characteristics than palm kernel shell in term of calorific value as feedstock of an updraft gasifier system at much higher ER of 0.31 resulted CGE of 75% [32]. This research is in good agreement with Adisurjosatyo et al., in the term of CGE which was influenced by ER [32]. At higher ER, the temperature inside the gasifier increased and then increased steam reforming reaction dry reforming to produce CO (see Table 3).

Although operated at higher ER, gasification of sewage sludge at ER of 0.25 and poultry litter at ER of 0.15 in the same type of gasifier showed much lower CGE compared with this study [32,34]. It is obvious that both feedstock moisture contents varied at the range of 20% – 30% which lowering heating value of the gas as consequence compared to 7.03% in this study. With pelletized biomass feedstock, it was also possible to increase the CGE up to 91.03% when using an updraft gasifier type [30] and up to about 70% when using a downdraft gasifier type [31]. Instead of pellet, this experiment used loosed type of palm kernel shell for practical purpose and caused lower CGE as consequence. Again, pelletizing requires more energy which may also reduce net harvested energy as reflected with CGE.

This study applied an updraft gasifier type to generate producer gas from palm kernel shell using limited oxygen in the air. Several previous studies showed that the performance of this type varied greatly in the term of CGE from 21.0% – 91.03% depends on the feedstock and ER compared with other type of gasifier (Table 3). It implies that higher CGE could be attained with adjusting air flowrate up to certain ER in this experiment.

Not many researchers examined CCE when evaluated gasification process performance. This study indicated that ER also influences the CCE. The maximum CCE in this study is 51.71% at ER of 0.08. The higher the ER, the higher the CCE but this is limited with CGE otherwise the overall performance goes down.

4. Conclusion
This study has successfully demonstrated that using palm kernel shell as feedstock of an updraft gasifier for generating producer gas in an AMP performed promising results in the point of view cold gas efficiency and carbon conversion efficiency. A proper ER should be determined in order to have best performance which shows a balance between harvested energy from gasification process and limitations of operating conditions. Instead of the existing air blower for supplying air as gasifying agent, the study recommends a higher capacity air blower of about 1500 to 2000 Nm$^3$/hour to increase the ER at the range of 0.30 – 0.40 which may result CGE of about 70% and CCE of about 55% should be installed in the related AMP.

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