Study of Indonesia low rank coal utilization on modified fixed bed gasification for combined cycle power plant

T Hardianto¹, A R Amalia¹, A Suwono¹, P Riauwindu¹
¹Faculty of Mechanical and Aerospace Engineering, Department of Mechanical Engineering
Institut Teknologi Bandung
Jalan Ganesa 10, 40132, Bandung, Indonesia

Email: toto@termo.pauir.itb.ac.id

Abstract:
Gasification is a conversion process converting carbon-based solid fuel into gaseous products that have considerable amount of calorific value. One of the carbon-based solid fuel that serves as feed for gasification is coal. Gasification gaseous product is termed as syngas (synthetic gas) that is composed of several different gases. Syngas produced from gasification vary from one process to another, this is due to several factors which are: feed characteristics, operation condition, gasified fluid condition, and gasification method or technology. One of the utilization of syngas is for combined cycle power plant fuel. In order to meet the need to convert carbon-based solid fuel into gaseous fuel for combined cycle power plant, engineering adjustment for gasification was done using related software to create the syngas with characteristics of natural gas that serve as fuel for combined cycle power plant in Indonesia. Feed used for the gasification process in this paper was Indonesian Low Rank Coal and the method used to obtain syngas was Modified Fixed Bed Gasifier. From the engineering adjustment process, the yielded syngas possessed lower heating value as much as 31828.32 kJ/kg in gasification condition of 600°C, 3.5 bar, and steam to feed ratio was 1 kg/kg. Syngas characteristics obtained from the process was used as a reference for the adjustment of the fuel system modification in combined cycle power plant that will have the same capacity with the conversion of the system’s fuel from natural gas to syngas.

1. Introduction
1.1. Indonesia Coal Reserves Potential and Properties
Indonesia is one of the largest country in the world in term of coal reserves with approximated total reserves of 5.5 billion metric ton and also world’s top coal producer with 237.4 million metric ton mined in 2012 [1]. Medium and low rank coal constitutes the biggest portion of Indonesia coal reserves. It is accounted for 85% of the total Indonesia coal reserves [1]. Medium and low rank coal possesses high level of moisture content and volatile matter with relatively low calorific heating value, therefore the utilization of this type of coal usually involve direct combustion either on coal-fired power plant or domestic application in Indonesia such as cooking and heating.

1.2. Energy Need in Non-coal-fired Power Plant in Indonesia
Having possessed abundant coal reserve, Indonesia doesn’t solely rely on coal to generate the electricity. Several types of power plant were built to meet the electrification target of the nation, for example: diesel, combined cycle, hydropower, and other renewable sources. There’s a possibility to utilize other type of alternative fuel instead of conventional fuel into these existing power plants, especially for combined cycle power plant (PLTGU). The fuel possibility can be derived indirectly from low rank coal due to the abundance presence of this type of fuel in Indonesia.
1.3. Study of utilization of coal through gasification for non-coal-fired power plant

Utilization of coal to supply fuel for combined cycle power plant can be achieved by converting solid coal into gaseous product through process called gasification. This paper focuses on the study of utilization of Indonesia low rank coal for combined cycle power plant (PLTGU) with capacity of 400 MWe with 267 MWe of gas-fired power plant and 133 coal-fired power plant by utilizing modified fixed bed gasification. Reasoning of modified fixed bed utilization will be further discussed in point 2.3. Gasification produces several gaseous products in form of CO, H2, and CH4 with different composition based on the coal feed characteristics, gasification method, gasifier fluid condition, and operational condition of the gasification process itself. These gaseous products will be utilized into combined cycle power plant through several adjustments to meet the condition of the existing gas used in Indonesia combined cycle power plant.

2. GASIFICATION TECHNICAL REVIEW

2.1. Combined Cycle Power Plant Fuel Property

Prior to coal conversion process into gaseous fuel for combined cycle power plant, combined cycle power plant fuel characteristics has to be determined. Fuel characteristics in combined cycle power plant is marked as steady aerodynamics and steady flame kinetics [2]. Indonesia combined cycle power plant (PLTGU) utilizes Compressed Natural Gas (CNG) to fuel its gas turbine with the stated characteristics above. CNG used in Indonesia PLTGU with capacity of 400 MWe is mainly dominated by CH4 gas (70.68%) with molecular weight of 23.21 g/mole and lower heating value of 40630 kJ/kg. Fuel consumption rate in which the fuel is consumed by gas turbine is defined by the following equation [3];

\[
\dot{m} = \frac{\dot{H}}{LHV_{fuel}}
\]  

Where: \(\dot{m}\) = Fuel consumption rate [kg/s]; \(\dot{H}\) = Generated power from the gas turbine inside the PLTGU system [MW]; and \(LHV_{fuel}\) = lower heating value from gas turbine fuel [MJ/kg]

2.2. Existing Coal Gasification Technology

Gasification process consists of several phases and is described in the Figure 1 below. Existing gasification technologies are grouped and developed based on these three categories, which are: fixed bed gasifier, fluidized bed gasifier, and entrained flow gasifier [4]. The Table 1 presents the comparison between various gasification technologies in the world.

| Parameter                        | Fixed Bed       | Fluidized Bed | Entrained Flow |
|----------------------------------|-----------------|---------------|----------------|
| Ash Condition                    | Dry ash         | Dry ash       | Slagging       |
| Feed Size                        | 5 - 80 mm       | 0.5 - 10 mm   | <0.1 mm (homogen) |
| Coal Feed Quality                | All type of coal| Low – Medium rank | All type of coal |
| Oxygen Requirement               | Low             | Medium        | High           |
| Water Steam Requirement          | High            | Medium        | Low            |
| Working Pressure                 | 1 bar-100 bar   | 10 bar-25 bar | 1 bar-40 bar   |
| Reaction Temperature             | 800 – 1000°C (Below AFT) | 950 - 1100°C (Below AFT) | >1400°C |
| Flue Gas Temperature             | Low (400 - 900°C) | Medium (900 - 1100°C) | high (1200 - 1600°C) |
| Coal Residence Time              | Updraft: 1 - 2 hour, downdraft: 20 - 30 minutes | 5 - 50 seconds | 1 - 10 seconds |
| Main Gas Product                 | \(H_2 = 41-43\%\) mole | \(H_2 = 6-37\%\) mole | \(H_2 = 28-34\%\) mole |
|                                 | \(CO = 14-16\%\) mole | \(CO = 30-58\%\) mole | \(CO = 26-57\%\) mole |
|                                 | \(CH_4 = 8-9\%\) mole | \(CH_4 = 1-4\%\) mole | \(CH_4 = 0.04-0.5\%\) mole |
|                                 | \(CO_2 = 30-32\%\) mole | \(CO_2 = 2-13\%\) mole | \(CO_2 = 2-16\%\) mole |
2.3. Modified Fixed Bed Technology Implementation for Indonesia Combined Cycle Power Plant

Considering the Indonesia low rank coal potential and the existing gasification technology characteristics, modified fixed bed gasification technology was chosen as the research concern of this paper to study the possibility of utilizing modified fixed bed gasification technology for low rank coal in the Indonesia PLTGU. Modified fixed bed is a fixed bed with modified batch coal feed into continuous feed therefore in the later simulation, the feed was modeled as continuous feed for fixed bed instead of batch feed. Figure 2 shows the schematic of Lurgi Dry Ash Gasifier as an example for modified fixed bed.

Figure 1. Gasification process phases of coal

Figure 2. Lurgi dry ash gasifier schematic [7].
Modified fixed bed gasifier is applicable for low rank coal with relatively big size, high moisture content, and volatile matter. Modified fixed bed gasifier is also able to employ either air or oxygen as the gasifier fluid with relatively low consumption of oxygen as its gasifier fluid. With the high water steam consumption, modified fixed bed gasifier is also able to maintain low operating temperature.

For PLTGU application, gasifier with high working pressure is required. Modified fixed bed gasifier is able to operate within wide operational pressure, ranging from 1 – 100 bar. Low operational temperature in this type of gasifier compared to other type of gasifier is capable to produce gaseous product with low temperature thus resulting in high efficiency of the gasification process. Efficiency is defined as;

\[
\eta_{cg} = \frac{HV_{syngas}}{HV_{feed}} \times 100\%
\]

Where: \( \eta_{cg} \) = gasification cold gas efficiency [%]; \( HV_{feed} \) = heating value (LHV or HHV) from gasification process feed [kJ/kg]; \( HV_{syngas} \) = heating value (LHV or HHV) from gasification product [kJ/kmol]; \( \dot{m}_{in} \) = mass flow rate from feed [kg/s]

3. FIXED BED GASIFICATION MODELLING FOR INDONESIA PLTGU

3.1. Gasification Process Model and Operational Parameter

In order to meet the defined objectives above, process diagram of gasification was then modeled using thermodynamic numerical software in Figure 3. The diagram is divided into three parts which are left side part, middle part, and right side part. Left side part describe the drying, pyrolysis, reduction, and oxidation process in the gasification. Middle part describe the heat transfer process as a representative from the presence of water jacketing in gasifier. For simplification, in this paper water jacketing was removed because the function of water jacketing is to maintain the operational temperature to prevent over temperature. Due to the fact that the simulation was done in numerical software, the final temperature was still under reasonable value, therefore in this paper the process in the water jacketing part was modeled as adiabatic. On the other hand, the right side part of the model was the result of the process simulation.

![Figure 3. Process diagram of coal gasification](image)

In the initial condition, specific operational condition was determined based on the modified fixed bed gasifier characteristics which were: coal feed rate 8 ton/hour, oxygen to coal ratio 1.25, water steam to coal ratio 1, working pressure 3.5 bar, and operational temperature 800°C. Several variables were also determined. Fixed variables in the simulation were gasifier type (modified fixed bed), coal type (low rank coal), coal feed rate 2 kg/s, gasifier fluid (oxygen), and water steam. The dependent
variables were defined as $\text{H}_2$, $\text{CH}_4$, $\text{CO}_2$, and $\text{H}_2\text{O}$ composition in the gasification gaseous product, heating value of the product, gasification simulation result, gasification efficiency, and final temperature of gasification product.

### 3.2. Operational Temperature Effect on Low Rank Coal Gasification

There were 6 different simulated operating temperatures in this simulation which were 600°C, 700°C, 800°C, 900°C, 1000°C, and 1100°C. Result shown in Figure 4 shows that CO gas was increasing with the increasing operating temperature. On the other hand, the $\text{CH}_4$ and $\text{CO}_2$ gas composition was decreasing with increasing operating temperature. $\text{H}_2$ was also increased with the increasing temperature but only until maximum peak at certain temperature and was decreasing with the increase in temperature beyond peak temperature. The effect of operating temperature to the main gas LHV, cold gas efficiency, and final temperature of the product is shown in the Figure 5. Increasing temperature increased the gasification process efficiency but was decreasing the LHV of the main gas as well as the product temperature of gasification.

From 6 operating temperatures simulated, the temperature that yielded the highest yield of $\text{CH}_4$ was at 600°C which is 3.29% of the total composition with LHV at 92.92 kJ/mole and main gas LHV at 92.19 or equal to 31828.32 kJ/kg with gasification cold gas efficiency at 71.20%. At the prescribed condition the highest heating value was also obtained.

### 3.3. Water Steam to Feed Ratio Effect on Low Rank Coal Gasification

Figure 6 shows that with the increasing water steam to feed ratio, the $\text{H}_2$ and $\text{CO}_2$ composition tend to increase until certain optimum point in which beyond that optimum point the product gas composition was decreasing. On the other hand CO and $\text{CH}_4$ gas decreased with the increase in water steam to feed ratio. The product temperature of the gasifier also decreased with the increase in the water steam to feed ratio. This phenomenon happens due to the ability of water steam to control the reaction process through decreasing the gasification process temperature. The addition of water steam in the water steam to feed ratio also created water shift reaction in the reduction process of gasification that resulted in the increasing composition of $\text{H}_2$ and $\text{CO}_2$. Simulation result shown in Figure 7 predicts that the highest value of gasification process efficiency attained at water steam to feed ratio equal to 0, but the increase of the ratio did not result in a significant decrease in the gasification efficiency. The increase of the ratio instead resulted in the increasing value of gas LHV per kilogram increase of the water steam.

From several simulated ratios, ratio that resulted in the highest yield of $\text{CH}_4$ was on 0.01 that was 0.16% with the gas LHV at 165.42 kJ/mole and the main gas LHV at 164.21 kJ/mole or equal to 13383.15 kJ/kg at calculated gasification efficiency (cold gas) of 81.65%. On the other hand the ratio that resulted in the highest value of LHV, 26315.14 kJ/kg, was at 2 kg/kg of water steam to feed as a result of the increasing production of $\text{H}_2$ gas due to the increasing value of water steam.
3.4. Working Pressure Effect on Low Rank Coal Gasification

Working pressure effect on gasification of low rank coal is shown in the Figure 8 and Figure 9. Figure 8 shows that the higher the working pressure the higher the CH₄ and CO₂ composition but resulted in the decreasing composition of CO and H₂. CO and H₂ experienced more drastic decrease with the increasing working pressure and decreasing operating temperature while CO and CH₄ increased.

On the low operating temperature, the change in working pressure significantly affected the gaseous product of gasification. The increase in CO₂ and CH₄ gas composition with the increase in working pressure can be explained based on equilibrium shift of the chemical reaction. The higher the system pressure, the chemical reaction will shift to the reaction with the lowest coefficient number. Another phenomenon that could be observed was that the lower the operating temperature in the process, the increase and decrease in product gas composition resulted in a drastic decrease with the increasing working pressure, while high operating temperature did not significantly affect the composition of the gaseous product of gasification. This is due to the chemical reaction of the process has started to attain the equilibrium state with the increase in operating temperature. It can be concluded that the change in gasification working pressure only had significant impact to the product with the low operating temperature.

The working pressure effect to the gas product LHV, gas product temperature, and gasification efficiency on 3 different operating temperatures is shown on Figure 9. The gasification efficiency decreased with the increase in the operating temperature and product gas temperature and LHV increased with the increase in the working pressure. The relationship between working pressure and gas product temperature can be explained with assuming that the gas product as ideal gas in which the temperature is the function of the pressure, pressure increase will result in the increase of the temperature.

![Figure 6 H₂O feed ratio effect at 5.3 bar and temperature 800°C on the gas composition of gasification product](image6)

![Figure 7 H₂O feed ratio effect at 5.3 bar and operating temperature 800°C to LHV, cold gas efficiency, and product temperature of gasification.](image7)

From several simulated relation between operating temperature and working pressure, the condition that resulted in the highest yield of CH₄ is at 700°C and 30 bar with gas LHV at 93.41 kJ/mole and main gas LHV at 92.65 kJ/mole with cold gas efficiency at 70.03%. Due to the different composition of CH₄ between gasification products and natural gas that is used in PLTGU, therefore the gasification...
condition that resulted in highest value of main gas LHV was chosen. Main gas LHV was obtained at the same operating condition that results in the highest composition of CH₄.

4. SYNGAS ADAPTATION FOR UTILIZATION IN EXISTING PLANT

4.1. Lower Heating Value Comparison

From the chosen gasification main gas product LHV, the comparison of the gasification main gas product LHV with the existing LHV of natural gas in PLTGU was conducted. The LHV of natural gas is at 40630 kJ/kg, therefore to generate electricity from PLTGU with capacity of 400 MW will require 267 MW electric power from gas-fired power plant (PLTG) and 133 MW electric power from coal-fired power plant (PLTU). Thermal efficiency of gas turbine in the PLTGU system was assumed to be at 32% then to generate net electric power of 267 MW requires heat as much as:

$$\text{heat} = \frac{\text{power}}{\text{efficiency}} = \frac{267 \text{ MW}}{0.32} = 834.37 \text{ MW}$$

If natural gas was used, the fuel consumption rate equal to:

$$\text{fuel consumption rate (natural gas)} = \frac{\text{heat}}{\text{LHV of natural gas}} = \frac{834.37 \text{ MW}}{40630 \text{ kJ/kg}} = 20.53 \text{ kg of natural gas per hour}$$

4.2. Syngas Fuel Consumption Rate

Gasification syngas consumption rate can be obtained by using LHV_{syngas} at 31828.32 kJ/kg, therefore to generate the same power from gas turbine process in PLTGU requires syngas consumption rate at:

$$\text{fuel consumption rate (syngas)} = \frac{\text{power}}{\text{LHV of syngas}} = \frac{267 \text{ MW}}{31828.32 \text{ kJ/kg}} = 8.43 \text{ kg of syngas per hour}$$

In order to generate the same electric power with syngas instead of natural gas, adjustment on fuel consumption rate was conducted. Adjustment was to increase the consumption rate by 1 to 2 times of the natural gas consumption. Based on mass conservation law, it was obtained that:

$$1_{\text{fuel}} + 1_{\text{fuel}} + 1_{\text{fuel}} + 1_{\text{fuel}} = 6.25 \text{ kg of syngas per hour}$$

Syngas mass flow rate produced from low rank coal gasification was:

$$1_{\text{fuel}} = 0.8 \text{ kg of syngas per hour}$$

From the gasification simulation of low rank coal, 8 ton/hour or 2 kg/s coal was needed to produce 0.8 kg/s syngas. Therefore to produce syngas as much as 26.2 kg/s to generate 267 MW with 32% efficiency gas turbine, gasification coal feed required was:

$$1_{\text{fuel}} \times 26.2 = 66.8 \text{ kg of coal per hour}$$

In conclusion to generate electric power as much as 267 MW in gas turbine in PLTGU, 26.2 kg/s syngas was needed that was equal to 66.8 kg/s or 240 ton/day gasification coal feed. There was an increase in coal consumption as much as 33 times bigger compared to the simulation conducted, therefore in order to produce required amount of syngas, additional modified fix bed gasifier was needed or by modifying the current system to be able to accommodate required gasification coal feed to produce required amount of syngas for PLTGU.

5. CONCLUSION

Indonesia low rank coal has the potential and characteristics to be used as alternative fuel in form of syngas for combined cycle power plant through gasification process Syngas characteristics produced from gasification that resembles the natural gas characteristics used in PLTGU occurs at gasification...
operating condition at 600°C, 3.5 bar, and water steam to feed ratio 1 kg/kg. LHV characteristics of the syngas at specified condition is at 31828.32 kJ/kg.

CNG required to generate 400 MWe of Indonesia combined cycle power plant (PLTGU) was at 20.53 kg/s. Syngas needed to replace CNG in PLTGU system was 26.2 kg/s or equal to 66.8 kg/s gasification coal feed.

REFERENCES

[1] Handbook of Energy and Economics Statistic of Indonesia, Ministry of Energy and Mineral Resources, Indonesia, 2012
[2] M. Moliere, Expanding Fuel Flexibility of Gas Turbines, Journal of Power and Energy, 219(A2):109-119, 2005 (http://pia.sagepub.com/content/219/2/109.full.pdf)
[3] Tulus Ruseno, Gas Turbine Performance and Efficiency Analysis for Power Generation, Indonesia Power, Jakarta, 2013.
[4] David A. Bell, Brian F. Towler, and Maohong Fan, Coal Gasification and Its Application, Elsevier, United Kingdom, 2011.
[5] A. Williams, M. Pourkashanian, J. M. Jones, dan N. Skorupska, Combustion and Gasification of Coal, Taylor & Francis, New York, 2000.
[6] Zachary Hoffman, Simulation and Economic Evaluation of Coal Gasification with SETS Reforming Process for Power Production, Thesis, Department of Chemical Engineering Louisiana State University, Baton Rouge, 2005
[7] Chang He, Process Modeling and Thermodynamic Analysis of Lurgi Fixed-Bed Coal Gasifier in a SNG Plant, Applied Energy