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ANALYSIS OF POTENTIAL ENERGY AND ENVIRONMENTAL IMPACT FROM COAL GASIFICATION THROUGH SIMULATION OF PLASMA GASIFICATION PROCESS OF INDONESIAN LOW-RANK COAL

ANALISIS POTENSI ENERGI DAN DAMPAK LINGKUNGAN GASIFIKASI BATUBARA MELALUI SIMULASI PROSES GASIFIKASI PLASMA BATUBARA INDONESIA KUALITAS RENDAH

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ABSTRACT

Indonesia's coal reserve is abundant with its lower price and widely distributed than oil and natural gas. However, the coal emits high carbon dioxide gas (CO_2) and sulfur compounds (H_2S, SO_x) to the environment during utilization. Plasma gasification can overcome those lacks using the external electric energy through a plasma torch. The chemical properties of coal have impacts on the energy content and environmental benchmarking. Using steam as a gasifying agent should be adequate to produce H_2 and CO syngas. A research has been carried out to analyze and understand the benefit of using different gasifying agent for maximizing the H_2 production and minimizing the environmental impact. Pure Steam (PS) gasifying agent to coal ratio of 0.4 has shown 43.76% H_2 composition in syngas and cold gasification efficiency (CGE) with 37.71%. The PS to coal ratio of 0.2 has a significant carbon conversion efficiency of 4.75% and the PS to coal ratio of 0.6 has a gross energy potential of 86.5 kW. Using such the PS is significantly better than the mixture of steam oxygen (SO) as the gasifying agent since it needs to have a greater SO flow rate to have the SO to coal ratio of 1.00.

Keywords: plasma gasification, environmental impact; low-rank coal; syngas; energy potential.

ABSTRAK

Cadangan batubara Indonesia sangat melimpah dengan harga yang lebih murah dan tersebar lebih luas dibandingkan dengan minyak dan gas alam, sayangnya batubara mengeluarkan gas karbon dioksida (CO_2) dan gas senyawa belerang (H_2S, SOx) tinggi ke lingkungan saat digunakan. Gasifikasi plasma dapat mengatasi kekurangan tersebut menggunakan energi listrik eksternal melalui obor plasma. Sifat kimiawi batubara berdampak pada kandungan energi dan tolok ukur lingkungan. Penggunaan uap sebagai agen gasifikasi harus cukup untuk menghasilkan syngas *H_2 dan CO. Penelitian untuk menganalisis dan memahami manfaat penggunaan agen gasifikasi yang berbeda untuk memaksimalkan produksi hidrogen sekaligus meminimalkan dampak lingkungan telah dilakukan. Dengan rasio agen gasifikasi uap murni (PS) kepada batubara sebesar 0.4 telah menunjukkan komposisi H_2 sebesar 43.76% pada syngas dan nilai efisiensi gasifikasi dingin (CGE) sebesar 37.71%. Rasio PS terhadap batubara sebesar 0.2 menunjukkan nilai efisiensi konversi carbon sebesar 4.75%. Rasio PS terhadap batubara sebesar 0.6 juga menunjukkan nilai kotor potensi energi sebesar 86.5 kW. Penggunaan PS sebagai agen gasifikasi lebih baik daripada campuran uap dan oksigen (SO), karena dibutuhkan laju aliran SO lebih besar pada rasio SO terhadap batubara sebesar 1.00.*

Kata kunci: gasifikasi plasma, dampak lingkungan, batubara kualitas rendah, syngas, potensi energi.

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INTRODUCTION

Indonesia's coal reserve is abundant with its lower price and widely distributed than oil and natural gas. However, it emits high carbon dioxide gas (CO_2) and sulfur compounds (H_2S, SO_x) to the environment. Because of coal energy conversion pollution, there has been a growing interest in clean coal technology. Gasification means converting the solid into a gas. It is one of the clean energy technologies, which decomposes the coal as a solid by the thermal process, produces a syngas, and comprises hydrogen (H_2) and carbon monoxide (CO). There are 2 (two) available gasification methods, namely: conventional and plasma gasifications. The former relates to the older method that has flaws, such as high-pressure operating conditions, longer start-up periods to heat the environment, and unsuitable for low-rank coal. The later known as thermal plasma, is the newer method that can overcome those lacks. Figure 1 shows the various applications of plasma gasification. It features the plasma, since its high temperature and high reactivity, due to free ions and radicals, benefit plasma as the powerful medium for encouraging chemical reactions (Samal, 2017). Its operating conditions required atmospheric pressure, a shorter start-up period to escalate the required temperature, and external electric energy through a plasma torch. A plasma torch is a device that can reach high gasification reaction temperature using electrical energy with the proper current and voltage values. Plasma is a physical state of matter with high electrical conductivity with gaseous properties (Samal, 2017). Within high temperatures, oxidation occasionally happens, resulting in minimal CO_2 generation. Aside from its advantages, there are some disadvantages: abundant energy consumption and the sophisticated requirement of the process equipment to withstand the high temperature. Besides its advantages and disadvantages, thermal plasma technology has some limitations, such as very short raw material residence time in the high-temperature zone, of 0.1 to 10. Waste heat recovery technology is needed for a syngas because of their moderate heat loss and the decomposition material in the reactor is slower than that of the gasifying agent reaction in the torch (Samal, 2017).

There is a particular type of coal reserve in Indonesia, low-rank and high-rank. Significant volumes of water and ash lead to the low-rank coals has lower calorific value, and high-rank coal has less water content and ash. Indonesian low-rank coal (brown coal) has a calorific value less than 5,700 kcal/kg (24MJ/kg) (moist, ash-free basis) (United Nation, 2018) and a high-rank, having a calorific value greater than 5,700 kcal /kg. The percentage of low-rank coal coverage is 88%, while high-rank coal coverage is only 12%, and their locations are over South Sumatra, South Kalimantan, and East Kalimantan province (Sihite, 2012). The low-rank coal is much more reactive than the high-rank coal because of the high content of reactive sites, such as chemisorbed oxygen in the coal matrix from low-rank coal (Mishra, Gautam and Sharma, 2018). The government has already started a plan to establish a clean coal technology to utilize the low-rank coal with less environmental impact and economically that can be used in the diverse industry by gasification technology since 2005 in the Research and Development Centre for Mineral and Coal Technology, Bandung (BLU *tek*MIRA, 2019). The chemical properties of coal have effects on the energy content and environmental benchmarking, which are often used as the basis of sale contacts. Those are low heating value (LHV) as of energy losses used to vaporize water, volatile matter (VM), inherent moisture (IM), sulfur (S), chlorine (Cl), and an ash content of coal and fuel ratio (FR) (Nursanto and Ilcham, 2018).

To maintain higher temperatures in the gasification reactor for the low-rank coal process, the plasma torch supplies additional heat (Yoon and Goo Lee, 2012). For plasma gasification technology, using steam as the gasifying agent, however, as a pure or as a mixture, should generate syngas containing H_2 and CO (Sesotyo, Nur and Suseno, 2019). Partial oxidation happens by gasifying oxygen, and the calorific content of coal feedstock is low. The more oxygen provided, the less electric energy consumed for the thermal plasma generator (Georgiev and Mihailov, 1992). The use of oxygen from the oxygen generator as the mixture with steam for the gasifying agent can raise the gasification efficiency, but the mixing ratio should be kept as low as possible for the steam content since it can cause an increase in the moisture of the syngas (Sesotyo, Nur and Suseno, 2019).

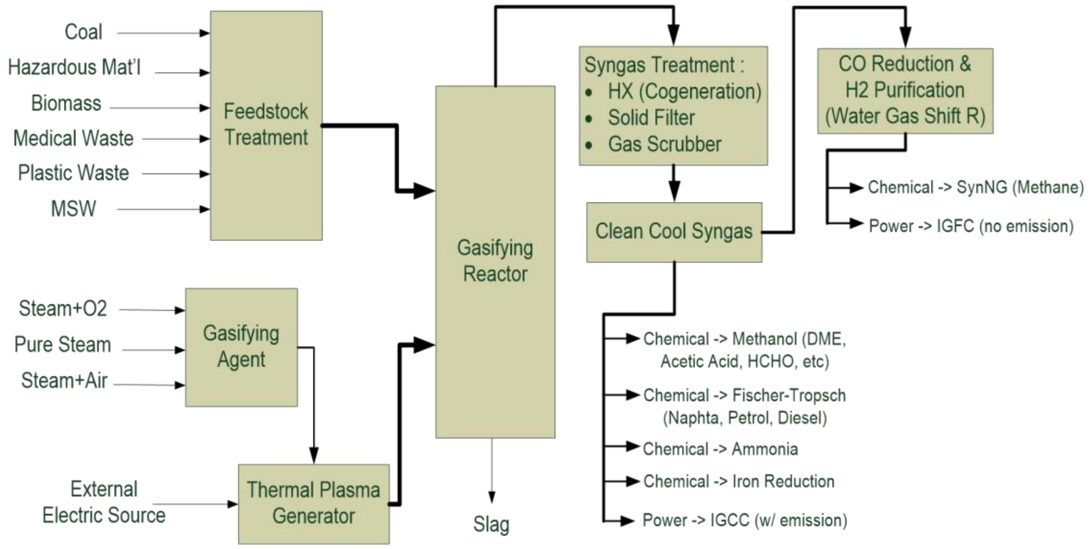

Figure 1. Alternate plant configuration for various applications of plasma gasification (Pourali, 2010; Tobergte and Curtis, 2013; Enersol Technologies, 2019; Sesotyo, Nur and Suseno, 2019)

Coal gasification thermodynamic analysis in the formation of syngas involves the equilibrium reaction. The syngas mainly consists of hydrogen and carbon monoxide. The syngas composition depends on the source of coal, coal flow rate, gasifying agent flow rate, type and composition of the gasifying agent, and energy consumed (Sesotyo, Nur and Muraza, 2020).

In this study, the low-rank coal gasification characteristics subjected to the plasma torch and referring to coals and operating conditions properties, were studied. Therefore, the changes in the composition of the supplied gasifying agent (steam, oxygen, and a mixture of steam and oxygen), characteristics of the syngas composition, energy potential, temperature distribution, overall efficiency, and greenhouse gases (GHG) emission were investigated. This study aims to better understand the benefit of using a certain gasifying agent of plasma gasification, considering the economic coal rate consumption for a better new energy method of coal gasification.

METHOD

This section describes the research method that is used in conducting this study.

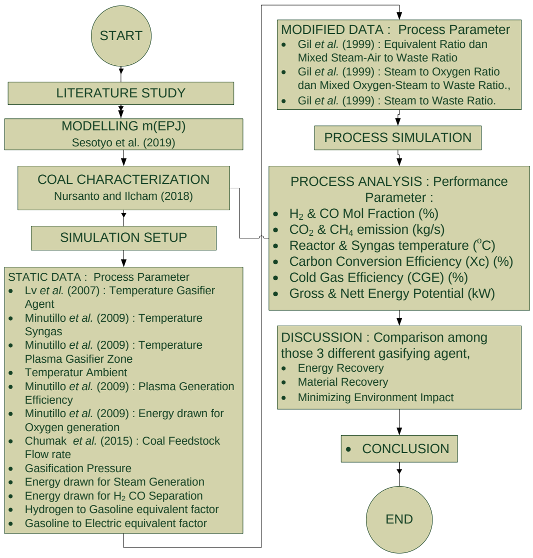

Figure 2. Research method of plasma gasification modeling

Coal Characterization

The sample is taken from Warukin formation, South Kalimantan. The calorific value, proximate analysis, and ultimate analysis data of the lignite coal refers to Wara 120. Table 1 shows the calorific values in high heating value (HHV) and low heating value (LHV), proximate and ultimate values of coal used in this study.

According to the research by Sesotyo, Nur and Muraza (2020), it was found out that the lignite coal possesses more energy potential rather than the sub-bituminous coal.

Table 1. Calorific, proximate and ultimate values of coals (Nursanto and Ilcham, 2018)

Parameter	Unit	Wara 120
High heating value	MJ/kg, db	31.59
Low heating value	MJ/kg, db	29.31
Inherent Moisture	wt.%, adb	30.90
Fixed Carbon	wt.%. db	28.94
Volatile Matter	wt.%. db	64.95
Ash	wt.%. db	6.11
Carbon	wt.%. db	61.52
Hydrogen	wt.%. db	6.24
Nitrogen	wt.%. db	0.68
Oxygen	wt.%. db	25.45

Note: adb: air-dried basis db: dry basis

Simulation Setup of Plasma Gasification

The plasma gasification process models were built using the process simulator software of ASPEN PLUS. This model results from the customized, modified EquiPlasmaJet (mEPJ) model, with the coal properties as in Table 1 to be key-in in the properties and input of process simulation block. mEPJ model, firstly developed by Minutillo, Perna and Di Bona (2009) EPJ, with a little modification by introducing RStoic for the chemical stoichiometric approach to determine the syngas compound compositions, was second developed by Sesotyo (Sesotyo, Nur and Suseno, 2019). The different stages involved in the ASPEN PLUS simulation show the overall plasma gasification process. The plasma gasification device consists of six main parts: dryer, plasma generator, updraft gasifier high-temperature section, updraft gasifier lower temperature section, water separator, and mixer, as found in Figure 3.

Table 2 shows the process parameter primary assumption. Table 3 shows the boundary conditions, such as the decomposing calculator and chemical stoichiometry. Those conditions work inside the simulator to gain a thermochemical-equilibrium reaction to the plasma gasification process modeling.

Figure 3 shows the Modified EquiPlasmaJet (mEPJ) using PS as the gasifying agent with the variation of coal feedstock: Wara 120 (Lignite). Figure 4 shows the Modified EquiPlasmaJet (mEPJ) using a SO as the gasifying agent with the type of coal feedstock: Wara 120 (Lignite).

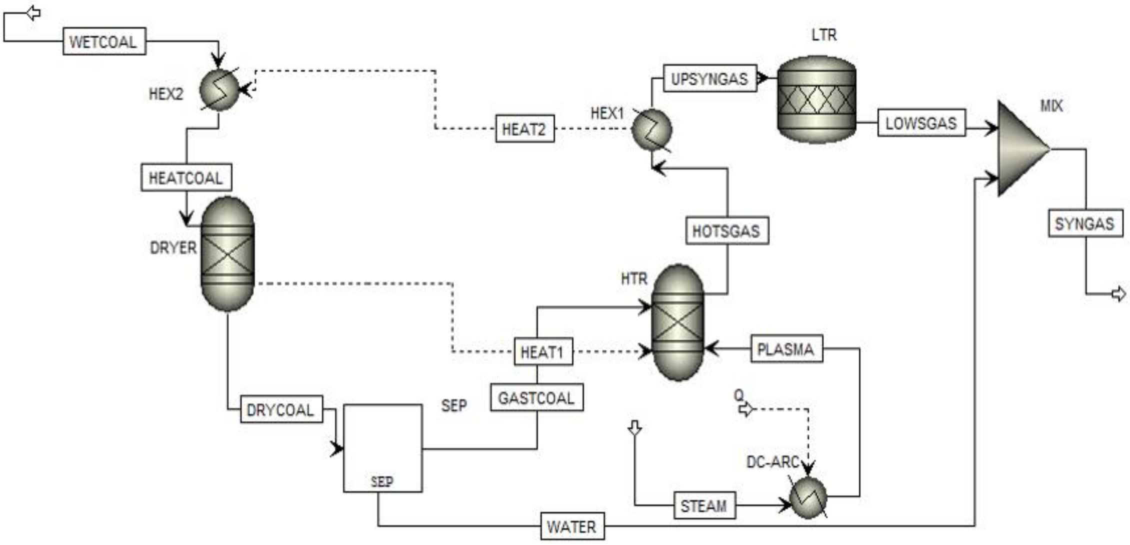

Figure 3. Gasification process model mEPJ with gasifying agent PS

Table 2. Assumptions for the simulation

Variable	Unit	Value
Gasification process pressure	atm	1
Thermal plasma temperature	°C	4000 (Minutillo, Perna and Di Bona, 2009)
Steam gasifying agent temperature	°C	200 (Nayak and Mewada, 2011)
Ambient temperature	°C	25
Coal mass flow rate	Kg/s	1.39 *10^{-3} (Nayak and Mewada, 2011)
Steam to coal ratio		0.2 ~ 1.0 (Yoon and Goo Lee, 2012)
Equivalent ratio		0.24 ~ 0.51 (Gil *et al.*, 1999)
Oxygen to coal ratio		0.2 ~ 1.0 (Yoon and Goo Lee, 2012)
Mixed steam & oxygen to coal ratio		0.2 ~ 1.0 (Yoon and Goo Lee, 2012)
Energy for steam generation	MWs	4.27 per 1 kg/s (Sesotyo, Nur and Suseno, 2019)
Energy for H_2-CO separation process	kWh/ton	600 (Air Liquide, 2017)
Plasma generation efficiency	%	90 (Minutillo, Perna and Di Bona, 2009)

Table 3. Boundary conditions for the simulation

- Steady-State Process Simulation
- The isobaric and adiabatic process state occurs inside the gasification reactor. Aspen Plus' HCoalgen and DCoalligt property models were used to project non-conventional enthalpy formation and specific heat in stable process pressure and density based on the proximate and ultimate analysis.
- The coal devolatilization duration time is instantaneous.
- The chemistry element and compounds used are: H_2, O_2, CO, CO_2, CH_4, and H_2O.
- Char is considered a non-volatile solid and contains carbon and ash.

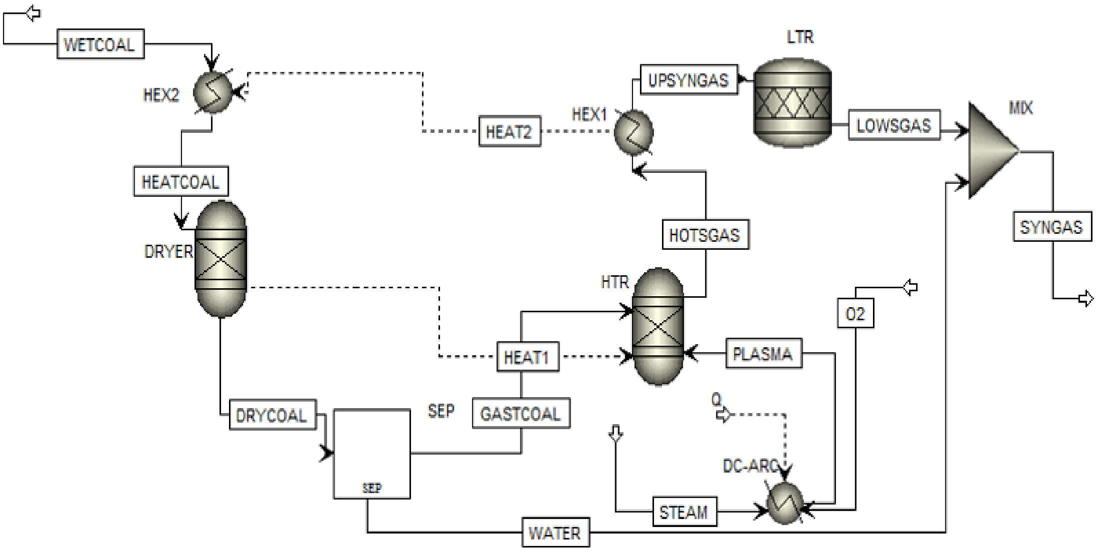

Figure 4. Gasification process model mEPJ with gasifying agent SO

As the temperature inside the reactor varies from top to bottom, the temperature was separated into two reaction zones to simplify the model. Two reaction zones represent the high-temperature reactor (HTR) and low-temperature (LTR). The balanced composition is accomplished within the HTR by directly reducing Gibbs free energy for a given range of gas products without the predicted thermochemical reaction. Within the LTR, in a non-stoichiometric reaction, the equilibrium composition is obtained by a low-temperature setting. Table 4 shows a short description of the block used. Since only the coal's organic element is decomposed, the mEPJ model abandons the inorganic element.

Coal Decomposition

The ASPEN PLUS yield reactor, RYield, was used to simulate the decomposition of the feed. In this step, coal was altered into its essential components, including C, H, O, S, N, and ash, by determining the yield distribution according to the ultimate analysis (Nikoo and Mahinpey, 2008).

Table 4. Process block diagram of Modified EquiPlasmaJet (Sesotyo, Nur and Suseno, 2019)

Block name	Block Type	Description
Dryer	RYield	Non-Stoichiometric reactor on accepted yield element distribution
HTR	RGibbs	Accurate hydrate reactor and multiphase equilibrium on Gibbs free energy minimization
LTR	RStoic	Stoichiometric reactor with accepted chemical reaction
HEX1 & HEX2	Heater	Conventional heat exchanger
SEP	Separator	Water separator from feedstock
DC-ARC	Heater	Thermal plasma generator
MIX	Mixer	Gas Stream Mixer

Volatile Reactions

The ASPEN PLUS Gibbs reactor, RGibbs, was used for elusive combustion in obedience to the assumption that volatile reactions follow the Gibbs equilibrium. Coal consists of C, H, N, O, S, Cl, ash, and water content. Some carbon reacts with other atoms, becoming during the devolatilization process a gas compound form. The remaining forms of carbon take place in char gasification (Nikoo and Mahinpey, 2008).

Char Gasification

The ASPEN PLUS stoichiometric reactor, RStoic, is responsible for the char gasification process by determining the gasification reactions (Sudiro and Bertucco, 2009).

Plasma Gasification Operation

Several reaction processes occurred to convert the solid fuel into syngas. The fix-bed updraft gasifier reaction cycle consists of four stages, i.e., drying, pyrolysis, combustion, and char gasification. The combustion reaction was an exothermic mechanism that provides other exothermic energy (drying, pyrolysis, and char gasification section).

Moisture-containing coal (wet coal) was dried and evaporated to create dry coal at the drying point. The drying step is a quick process, considered complete when the temperature reaches 300 °C.

The next step is pyrolysis. Dry coal components were treated with the devolatilization reaction and yielded a solid products (char), condensable (H_2O), and non-condensable gases (CO, CO_2, H_2, and CH_4). Most of the coal weight was lost during pyrolysis and occurred rapidly during the initial stages as coal heats up. During this process, the labile chemical bonds between the aromatic coal branches were sundered, creating molecular weight fragments. Low molecular weight fragments were vaporized and disappeared from the particle of coal to constitute light, non-condensable, and char. Under standard devolatilization conditions, the fragments of high molecular weight and low vapour compound, condensable gas, remained in the coal until they were bound to the char lattice. The side product from the plasma gasification process was char, or in general, called slag. The chemical compositions of the slag, as the process residues, are different, as the various number of ash chemical compounds of the feed coals. Also, the different methods and operating conditions of the process are other factors of the slag's various chemical components. During the gasification process, non-volatile trace elements (including rare earth elements and yttrium (REY)) remain in the slag (Guo *et al.*, 2021). REY is critical to modern society due to its excellent physicochemical industrial properties (Pagano *et al.*, 2019).

The pyrolysis product then was reacted with air or O_2-deficient, and in the combustion step, a partial oxidation reaction occurred. The amount of air was stoichiometric, and a partial oxidation reaction occurred with char, H_2, and CH_4. Partial combustion occurs in an oxygen-deficient atmosphere in a plasma-gasification reactor. A gasification reactor requires roughly 30% to 50% of the theoretical oxygen content needed for full combustion to produce carbon dioxide and water. Carbon monoxide and hydrogen are the ideal materials, and only a portion of the carbon is fully oxidized to carbon dioxide. Partial combustion heat (exothermic) supplies the energy required to drive gasification reactions.

The last reaction was a gas-reduction reaction. A solid-gas reaction called the gasification phase was a crucial reaction to determine the flammable gas composition (CO, H_2, and CH_4) and low heating value (LHV). Reduced carbon, carbon dioxide, nitrogen, and water vapour, creating carbon monoxide, hydrogen, and methane. Oxygen was absorbed immediately in the combustion region, which required a small portion of the reactor section. Moreover, char conversion happened by much slower, reversible reactions with CO_2, H_2O, and H_2. The chemical reaction that occurs in the gasification is shown in Table 5.

Simulation Procedure

Once the simulation model is established, then prepare the simulation scenario according to each type of gasifying agent. In this study, there are 2 (two) gasifying agents: pure steam (PS) and mixture steam with oxygen (SO). There are 5 (five) different situations for each type of gasifier depending on the increment ratio of the gasifier's mass flow rate to coal flow rate, sort of 0.2, 0.4, 0.6, 0.8, and 1.00. Because of variations in the mass flow rate, there was a particular value of external electrical source energy consumption for each thermal plasma generator scenario. Both assumptions and measured energy usage were essential in ASPEN PLUS' mEPJ model input. Model findings were a molar fraction of syngas composition, syngas mass flow rate, syngas density, CO_2 emission, reactor, and syngas' thermal distribution.

The equations below were used to estimate the performance parameter, which was calculated syngas yield (Nm^3/kg), CH_4 rate (kg/s), LHV syngas (MJ/Nm^3), carbon conversion efficiency (Xc,-%), cold gas efficiency (CGE, -%), energy potential (EP,-MW) were as follows:

$$\text{Rate } CH_4 = \upsilon * \frac{\varkappa CH_4}{100} * \frac{m\,C}{m\,CH_4} * \delta CH_4 \text{.............} (1)$$

$$\text{Gas yield } \left(\frac{Nm^3}{kg}\right) = \frac{\text{syngas production rate } \left(N\frac{m^3}{h}\right)}{\text{coal consumption rate } \left(\frac{kg}{h}\right)} \text{.......} (2)$$

$$LHV_{Syngas} = HHV - 10.79\gamma_{H_2} + 12.62\gamma_{CO} + 35.81\gamma_{CH_4} \text{..} (3)$$

$$Xc = \left[\frac{LHV_{syngas} * (CO\% + CO2\% + CH4\% + COS\%)}{LHV_{feedstock} * C\%}\right] * 100\% \text{..} (4)$$

Where ɣCO_2, CO, CH_4, and C are product percentages of CO_2, CH_4, and CO on the syngas and carbon content from MSW. LHV_{syngas} and $LHV_{feedstock}$ were LHV for syngas and coal.

$$CGE = \frac{LHV_{syngas} F_{syngas}}{LHV_{coal} \dot{m}_{coal} + P_{plasma}} * 100\% \text{.................} (5)$$

Where F_{syngas} was the volumetric flow rate of syngas, m_{coal} was the mass flow rate of coal, P_{plasma} is energy consumption for thermal plasma generator to generate heat to reach the desired plasma temperature.

$$\text{Electric Energy Potential (EEP)} = \gamma_{syngas} * \frac{\varkappa H_2}{100} / N * \delta H_2 * GGE/CF \text{.....................} (6)$$

$$\text{Nett Energy Potensial} = EEP - (P_{Sep} + P_{Plasma} + P_{Steam} + P_{Oxygen}) \text{..........................} (7)$$

Table 5. Coal Gasification reactions

Reaction	Reaction type	Reaction	ΔH (kJ/mol)
Oxidation Reaction			
R1	Carbon Combustion	$C + O_2 \rightarrow CO_2$	-394
Carbon Reaction			
R2	Baoudouard	$C + CO_2 \leftrightarrow 2CO$	+172
R3	Water-gas or steam	$C + H_2O \leftrightarrow CO + H_2$	+131
Methanation Reaction			
R4	Methanation of Carbon	$C + 2H_2 \rightarrow CH_4$	-74
Shift Reaction			
R5	Water Gas Shift	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41.2

Where γ_{syngas} is the syngas yield, $\varkappa H_2$ is the molar fraction of H_2, N is the normalized factor, δ H_2 is the density of H_2. GGE/CF is the conversion factor for energy potential. P_{Sep} is the energy consumption for H_2 Purification Plant, P_{steam} is the energy consumption for Steam Generator, P_{oxygen} is the energy consumption for Oxygen Generator.

Once the performance parameter is summarized, those data are analyzed by comparing each scenario's parameters on each gasifying agent—data analyzing for energy recovery, material recovery, and minimizing environmental impact.

RESULT AND DISCUSSION

The effect of gasifying agent ratios on the feedstock of the syngas structure, temperature distribution, energy potential, overall quality, and polluting gas emission was recorded in this analysis.

Effect of Gasifying Agent on the Syngas Composition

There are 2 (two) main products: Hydrogen and Carbon Monoxide since only those two can be utilized as raw materials of energy and chemical industry. The other significant syngas fraction of water was considered as the byproduct of gasification and can be utilized for the steam generator water input, which was not the focus of this research.

The variation of the gasifying agent mass flow ratio to the hydrogen molar fraction's coal mass flow indicates a decreasing PS trend. Still, an increasing trend occurred for the SO. The R-squared value on the chart shows that the R2 = 0.2589 and on SO trend line on the PS trend line have the R^2 = 0.9879. Among 5 (five) ratios on PS, the first ratio of 0.2 was unfitted to the regression line, as seen in Figure 5. The Hydrogen molar fraction shows that PS has a better value than SO, which the highest molar fraction of PS was approximately 3 (three) times higher than SO, as can be seen in Figure 5.

The variation of the gasifying agent mass flow ratio to the coal mass flow for the carbon monoxide molar fraction shows that a decreasing trend occurred on PS and SO. The R-Squared value on the PS trendline = 0.9213 and the SO trendline = 0.4165. On SO, the ratio of 0.4 and 0.6 did not fit into the regression line. Both PS and SO trendlines had the highest carbon monoxide value on the ratio of 0.4. The carbon monoxide molar fraction shows that PS had a better value than SO, which the highest molar fraction of PS was approximately 2 (two) times higher than SO, as can be seen in Figure 6.

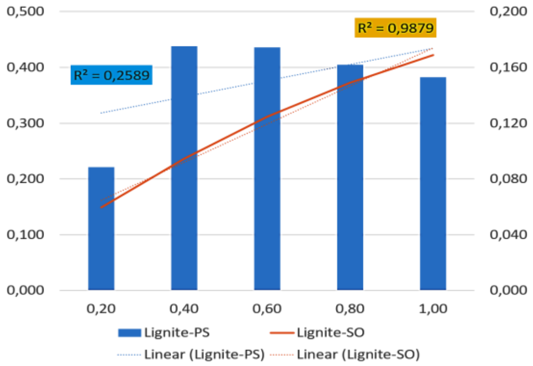

Figure 5. H_2 molar fraction versus gasifying agent ratio

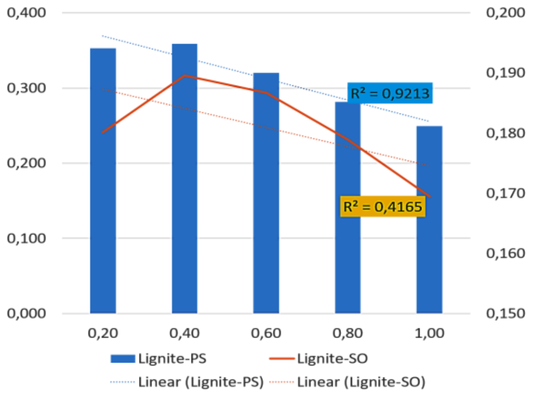

Figure 6. CO molar fraction versus gasifying agent ratio

Using the PS as the gasifying agent has the advantage of enriching the molar fraction of hydrogen in the syngas since it can introduce more H elements from the steam into the syngas composition (Favas, Monteiro and Rouboa, 2017). Oxygen's introduction to the reactor reduces the H element since it drives combustion and consumes more energy (Mapamba, Conradie and Fick, 2016).

Effect of Gasifying Agent on the Temperature Distribution

There are 2 (two) concerning areas to monitor temperature variation: the hottest parts of the reactor, which was called PGZ-HTR Temp, where the gasifying agent contact with the coal, and the exit of syngas, which was the nozzle parts of the syngas exit's gasifying reactor.

The variation of the gasifying agent mass flow ratio to the coal mass flow for the PGZ-HTR temperature indicated that an increasing trend occurred for the PS and SO. The PS trendline steepens from 1722 °C to 3114 °C, and the SO trendline slops from 3226 °C into 3336 °C. The R-squared the PS trendline = 0.9852, and the SO trendline = 0.796. The temperature distribution on PGZ-HTR of PS as the gasifying agent had better values compared to the SO. The temperature distribution on the PGZ-HTR area showed that PS had a better value than SO. The lowest temperature of PS was approximately half of SO's temperature on the first ratio, as shown in Figure 7. The lower the temperature distribution, the easier to fabricate the gasification reactor.

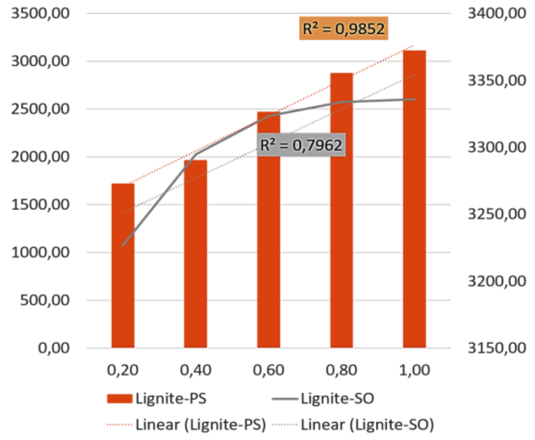

Figure 7. PGZ-HTR temp (°C) versus gasifying agent ratio

The gasifying-agent mass flow ratio variation to the coal mass flow for the nozzle of syngas exit temperature indicates an increasing PS and SO trend. The PS was steepened from 978 °C to 1092 °C, while the SO was sloping from 1097 °C to 1127 °C. The R-squared on the PS trendline = 0.9798 and the SO trendline = 0.9901. The temperature distribution on SO's syngas exit as the gasifying agent had better values than the PS, as shown in Figure 8. The lesser the temperature distribution, the easier to fabricate the syngas treatment.

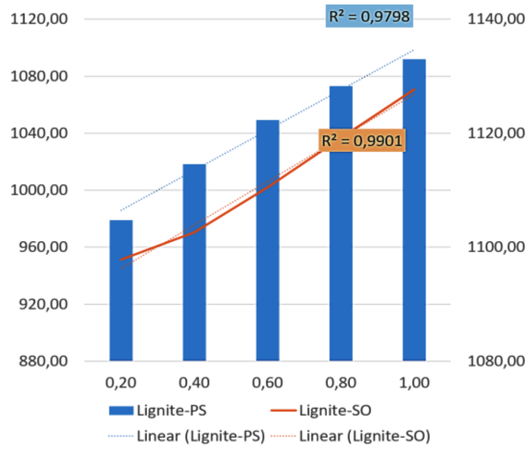

Figure 8. Syngas temp (°C) versus gasifying agent ratio

Effect of Gasifying Agent on Energy Potential

There are 2 (two) kinds of energy that need to be analyzed and prioritized since the research's primary concern was to develop new energy potential from low-rank coal. The first was gross energy potential, where the hydrogen fraction of syngas was converted into gasoline gallon equivalent (GGE) and converted into electricity equivalent. Those equivalent constants were considered since the NIST (national institute of standard and technology) defines its value as equal to 5,660 pounds of natural gas. It is difficult to compare gasoline costs with other fuels if they are purchased in different units. One GGE of electricity has the same energy content as one gallon of gasoline (UCI Physics, 2014). Using GGE as the comparison of fuels for an internal combustion engine (ICE) is an integral part of this research to estimate the energy potential.

The second was the net energy potential, the gross energy potential minus the energy intake of hydrogen purification, the plasma torch, the oxygen generator, and the steam generator. Hydrogen energy potential was estimated from its chemical energy source.

The variation of the gasifying agent mass flow ratio to the gross energy potential coal mass flow indicates an increasing PS and SO trend. The R-squared value on the chart shows that on the PS trendline, it had the $R^2 = 0.3275$. On the SO trendline, it had the $R^2 = 0.9978$. Among 5 (five) ratios on PS, the first ratio of 0.2 was unfitted to the regression line, as seen in Figure 9.

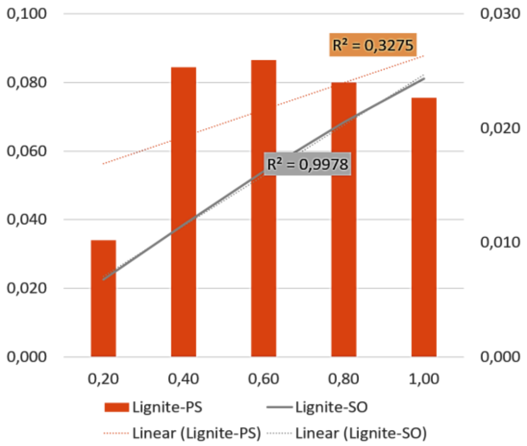

Figure 9. The gross energy potential versus gasifying agent ratio

The gross energy potential shows that PS had a better value than SO, which the highest molar fraction of PS was approximately 7 (seven) times higher than SO, on the ratio of 0.4, as can be seen in Figure 9.

The variation of the gasifying agent mass flow ratio to the Net Energy Potential coal mass flow indicates an increasing trend for the PS and SO. The R-square value of 0.0445 on the PS trendline and 0.9468 on the SO trendline. Among 5 (five) ratios on PS, on the first ratio: 0.2 was the unfitted to the regression line, as seen in Figure 10. The net energy potential shows that the PS had a better value than the SO, which the highest value of the PS was approximately 17 times higher than the SO, on the ratio of 0.4, as can be seen in Figure 10.

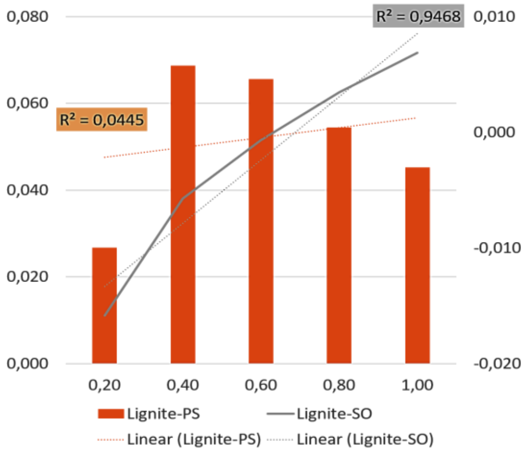

Figure 10. Net Energy Potential versus gasifying agent ratio

Effect of Gasifying Agent on the Overall Efficiency

There are 2 (two) forms of efficiency that need to be evaluated and prioritized. The research's primary concern was to estimate the new energy potential from low-rank coal and ensure that it was commercially viable to ensure that the technology achieved the anticipated efficiency. The first was cold gas efficiency, defined as the ratio of syngas LHV to coal/feedstock LHV and plasma generator energy consumption (Pagano *et al.*, 2019). The second was carbon conversion efficiency, defined as the percentage of total carbon in the syngas to the percentage of total carbon in feedstock (coal) (Favas, Monteiro and Rouboa, 2017). These two indices are critical to measuring plasma gasification performance (Mapamba, Conradie and Fick, 2016).

The variation of the gasifying agent mass flow ratio to the coal mass flow for the cold gas efficiency showed that a decreasing trend occurs on PS, and an increasing trend occurs on SO. The R-Squared value on the PS trendline = 0.325, and the SO trendline = 0.9903. With the highest CGE value on the ratio of 0.4, 37.71%, and SO trendline, PS trendline had the highest CGE value on the ratio of 1.00, which was 23.17%. The CGE value showed that PS had a better value than SO, which the highest molar fraction of PS was approximately 2 (two) times higher than SO, as can be seen in Figure 11.

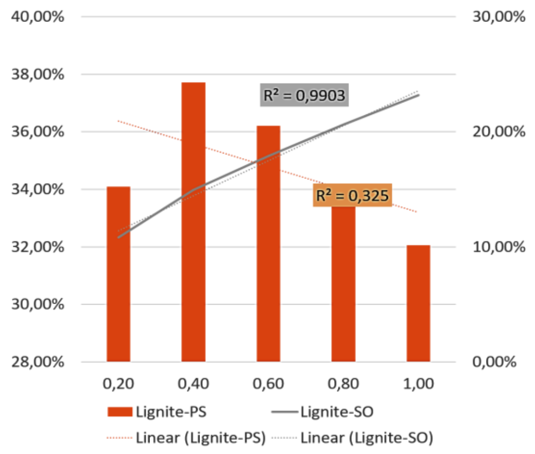

Figure 11. Cold gas efficiency versus gasifying agent ratio

The gasifying agent mass flow ratio variation to the coal mass flow for the carbon conversion efficiency showed that a decreasing trend occurred on PS. An increasing trend occurred on SO. The R-Squared value on the PS trendline = 0.8482, and the SO trendline = 0.308. The carbon conversion was limited by the methane (CH_4) reforming (Mapamba, Conradie and Fick, 2016). PS trendline, with the highest Xc value on the ratio of 0.1, which was 4.75 %, and SO trendline had the highest Xc value on the ratio of 0.6, which was 0.61%, as shown in Figure 12.

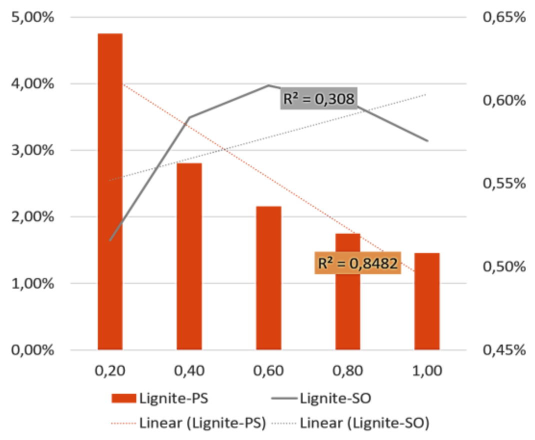

Figure 12. Carbon conversion efficiency versus gasifying agent ratio

Effect of Gasifying Agent on GHG Emission

Gasification-based plasma for power generation results in significantly lower pollutant emissions than traditional gasification, which can be attributed to the fundamental distinction between thermal and conventional plasma. Oxygen is usually supplied to the gasifier and sufficiently combusts in conventional gasification, providing heat to gasify the feedstock. Still, in plasma thermal, the heat is provided through the thermal plasma, delivered by the gasifying agent to react with the feedstock. Although plasma gasification is not negative emission technology (NETs), its contribution by emitting very low carbon dioxide to the atmosphere is considered a friendly technology to the environment.

The variation of the gasifying agent mass flow ratio to the coal mass flow for the CO_2 emission showed that a decreasing trend occurs on PS, and an increasing trend occurs on SO. The R-Squared value on the PS trendline = 0.5929, and the SO trendline = 0.9903. With the lowest CO_2 emission value on the ratio of 0.6, which was 5.98E-05 kg/s and SO trendline, PS trendline has the lowest CO_2 emission value on the ratio of 0.20 7.9.E-04 kg/s. The CO_2 emission value showed that PS had a better value than SO, which the lowest CO_2 emission value of PS was approximately 10 (ten) times lower than SO, as can be seen in Figure 13.

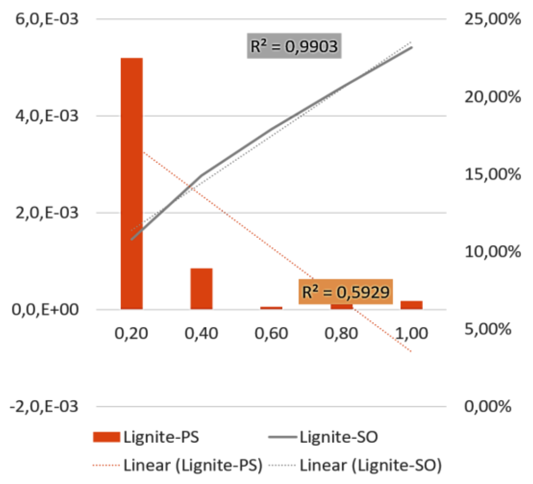

Figure 13. CO_2 emission versus gasifying agent ratio

The variation of the gasifying agent mass flow ratio to the coal mass flow for the CH_4 emission showed that a decreasing trend occurred on PS, and a flat trend occurred on SO approximately to 0. The R-Squared value on the PS trendline = 0.624, and the PS trendline had the lowest CH_4 emission value on the ratio of 1.0, which was 2.48E-15 kg/s. The CH_4 emission value showed that PS has a worse value than SO but can be neglected since the difference was very few, as shown in Figure 14.

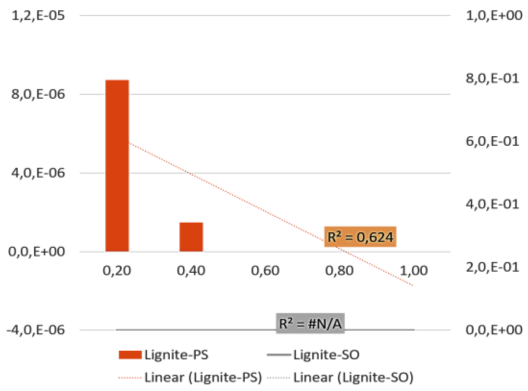

Figure 14. CH_4 emission versus gasifying agent ratio

In overall trends, the use of PS was considered better than SO. It can be found that the PGZ-HTR temperature rosed in line with the power consumption for Plasma Torch boosts the gasification reactions, resulting in the rosed of H_2 and CO concentration in 0.4 ratios of GA to feedstock. Its percentage then falls, which was a little contrary to the literature (Mapamba, Conradie and Fick, 2016). The gasification temperature rosed with the power load rosed and boosted the gasification reactions, resulting in the CO concentration rosed in the syngas product. It was also found that H_2 concentration felled with the rosed in power loads. It can be explained by the reactor's side reaction since, during the high temperature, the reverse water-gas shift (R5) occurred.

Moreover, the concentration of CH_4 fell with the power loads rosed, which was probably due to a side reaction's presence: the reverse methane reforming (R4) occurred. The decrease in H_2 and CH_4 concentration resulted in a decrease in LHV, which was in line with the literature (Maneerung *et al.*, 2018).

CONCLUSIONS

This research has been carried out to understand the impact of the different gasifying agents within Plasma Gasification for Low-Rank Coal better utilization.

PS as the gasifying agent was significantly better than SO in terms of such as having a higher H_2 to coal ratio of 0.4 has shown 43.76%, higher CGE to coal ratio of 0.4 has shown 37.71%, and carbon conversion to coal ratio of 0.2 has shown 4.75%. PS to coal ratio of 0.6 has a gross energy potential of 86.5 kW. Using PS is significantly better than a mixture of SO as the gasifying agent since it needs to have a greater SO flow rate to have SO to coal ratio of 1.00. But the drawback of the PS is having higher CO_2 and CH_4 emissions compared to SO.

Further studies can be carried out by including the hydrogen purification process and the use of syngas CO converted to H_2 with water-gas shift technology.

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