



Gasification of Coffee Parchment as Potential Method for Coffee Agro-Industry Waste Utilization

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Abstract

Coffee parchment is a lignocellulosic waste material that has the potential to be transformed into a synthetic gas. This research aimed to examine the feasibility of coffee parchment conversion through downdraft gasification method. The temperature profile in each zone of the reactor was investigated, assessing the effect of different equivalence ratios (ER) as well as analyzing producer gas characteristics such as ignition time, flame duration, color, and temperature, gasification residue, and biomass conversion. Initially, coffee parchment collected from the dehulling process was sun-dried for a duration of three to four days. The gasification process was initiated by igniting approximately 300 grams of wood charcoal inside the reactor before loading the coffee parchment. Subsequently, the reactor was tightly sealed, and the gasification time was measured once the combustible gas was generated. The result showed that the highest operational temperature inside the reactor was 715.66°C within the combustion zone. The biomass conversion tends to increase with higher ER, but this high ER also leads to increased carbon dioxide production, which in turn causes dilution of the producer gas. In addition, the syngas dilution also indicated the presence of nitrogen input from higher ER injection. The syngas dilution was signified by the change of flame duration, color, and temperature. Introducing an ER of 0.3 into the gasification reactor provided an adequate amount of oxygen to convert the coffee parchment into producer gas. This investigation suggests that coffee parchment is feasible to be converted into synthetic gas. However, providing an advanced process integrated with the cleaning system would be required in the future to obtain a fuel-grade synthetic gas.

Keywords: coffee parchment, downdraft reactor, green energy, equivalence ratio, synthetic gas

1. Introduction

Indonesia is one of the world's leading coffee producers in the world. In 2020, the country recorded a coffee bean production of 762.38 tons, with an average production of 756.98 tons over the three preceding years (Direktorat Statistik Tanaman Pangan, Hortikultura, 2020). The substantial coffee bean supply significantly contributes to the large-scale production of coffee parchment production. Coffee processing generates waste ranging from 30-50% of total weight depending on the processing method employed. The primary residues obtained after extracting the beans through dry, wet, or semi-wet processes include coffee pulp, husks, and parchments. The dry processing of coffee beans generates a byproduct known as coffee husk, which is a combination of coffee pulp and parchment (Banti and Abraham, 2021; Chala et al., 2018). This byproduct accounts for approximately 45-50% (w/w) of the fresh

beans (Esquivel and Jiménez, 2012). Besides, wet and semi-wet processing yields coffee pulp and parchment as the separate residues (Banti and Abraham, 2021; Borém and De Andrade, 2019), which are approximately 43% and 6.1% (w/w) of the beans, respectively (Gadhamshetty et al., 2010).

Traditionally, the waste generated from coffee processing was often left unused by local farmers and accumulated within the industry. Indeed, the abundant availability and high calorific value of coffee parchment make it a promising biomass fuel source for supporting the transition from fossil fuels to renewable energy sources. Using coffee parchment directly as a solid fuel is not recommended due to its low density. A more attractive method is converting it into gas fuel through thermochemical process. This approach not only converts the waste into energy but also helps reduce environmental

pollution due to greenhouse gas emissions from decaying biomass in landfill locations.

In general, the transformation of biomass into renewable energy products can be carried out through a thermochemical conversion process: pyrolysis, combustion, and gasification. These methods produce carbon monoxide, hydrogen, carbon dioxide, methane, and various heavier chemical substances (Iannello et al., 2020; Ripoll and Toledo, 2021; Safarian et al., 2021a). Consequently, gasification is considered a green and effective process for converting low-quality biomass into valuable fuel gas, addressing waste management problems (Kumar and Anand, 2019; Segneri et al., 2022).

Gasification is the conversion of solid or liquid raw materials into gaseous fuels or useful and value-added chemicals. The most common materials for synthetic gas production are lignocellulosic compounds from plantation, agricultural, and agroforestry residues. These compounds contain high thermal conversion into hydrogen and carbon monoxide (Safarian et al., 2021a). Meanwhile, a thorough understanding of biomass properties is essential to determine the most suitable gasification method.

The gasification process primarily takes place in four stages, drying (endothermic stage), pyrolysis (endothermic stage), oxidation (exothermic stage), and reduction (endothermic stage) (Iannello et al., 2020; Segneri et al., 2022). The primary chemical reactions responsible for generating product gases during gasification include partial oxidation, water gas shift, Boudouard, and steam reforming (Seo et al., 2018). These gases consist of a mixture of carbon monoxide (CO), hydrogen (H₂), methane (CH₄), and carbon dioxide (CO₂), and impurities such as tar, particles, nitrogen, and sulfur compounds. The precise composition of the producer gas depends on factors such as the raw material, moisture content, gasification mediums, equivalence ratio, and operational temperature (Havilah et al., 2022). In addition, the choice of reactor type plays an important role in determining the effectiveness of gasification, reaction, and products (Zhang et al., 2019). The selection of the appropriate reactor particularly depends on the type of biomass and the desired gas product (Narnaware and Panwar, 2022). The downdraft reactor has a higher conversion efficiency, with lower tar and particulate content in synthetic gas compared to other types of reactors (Havilah et al., 2022; Kumar and Anand, 2019; Neubauer and Liu, 2013), therefore, it is used in this experiment.

The utilization of high-temperature operations has been explored as a means to achieve low

tar content in producer gas, primarily due to its effectiveness in carbon conversion. This approach has a direct impact on the heating value and producer gas composition. Carbon conversion can effectively occur within the temperature range of 700°C to 800°C, resulting in a higher composition of H₂ and CO (Zhang et al., 2019). Wilson et al. performed a kinetic investigation of coffee husk gasification at a temperature of 700, 800, and 900°C, demonstrating that elevated temperature led to enhanced CO production (Wilson et al., 2010). This research used high operational temperature, which means, an additional heating apparatus was applied. In addition, the pyrolysis of coffee parchment at temperatures of 350 and 500°C showed the ability of the materials to deliver synthetic gas (Zaichenko et al., 2021). Therefore, further process by gasification was predicted to be able to produce more synthetic gas.

It is important to note that maintaining the desired temperature inside the gasification reactor requires energy input from an external source, resulting in additional operational costs. Meanwhile, the combustion process generates energy that can be utilized for the three other processes in gasification. The application of the 'auto-thermal supply' method in this research is relatively less discussed in existing literature but serves as an initial step to assess the feasibility of converting solid fuel into gas fuel. The previous literature did not investigate the temperature profile within each level of gasification in the reactor, as well as gasification properties such as initial ignition time, gasification duration, and flame properties. Furthermore, the maximum operational temperature, and other physical parameters during gasification can be the preliminary research of the gasification properties.

This research aimed to develop a simple technology for coffee parchment waste utilization through the auto-thermal gasification method. To achieve this objective, a comprehensive research plan was formulated including the design and fabrication of a pilot scale downdraft gasifier, testing and evaluation were conducted through several parameters. The operational heat for drying, pyrolysis, and reduction is generated from the combustion zone. The effect of equivalence ratio (ER) on the temperature profile within the gasifier was deeply investigated. In addition, the physical characteristics of the producer gas including ignition time, flame duration, flame temperature, and flame color were determined in order to

examine the correlation to ER as the basic parameters for further investigation. This result is important before the next step to build an advanced gasification process for coffee parchment and other biomass fuels.

2. Methodology

2.1. Materials

In this research, the materials used were coffee parchment and wood charcoal (Figure 1). Coffee parchment was collected from the coffee bean dehulling industry in Aceh Tengah, Indonesia. It was sun-dried several days prior to being used as solid fuel. Charcoal was obtained from the local market in Lhokseumawe, Aceh, Indonesia.



Figure 1. Coffee parchment (a) and wood charcoal (b)

2.2. Gasification

A purposely built downdraft reactor of cylindrical shape made of carbon steel alloy with 15 cm of inside diameter, and 68 cm of height was used for the gasification. The initial gasifier design is shown in Table 1. The gasification setup is shown in Figure 2.

Table 1. Gasifier initial design

Type of gasifier	Downdraft (Throatless)
Type of fuel	Coffee parchment
The calorific value of fuel	16.868 J. g ⁻¹
Coffee husk bulk density	147 kg.m ⁻³
Gasification efficiency	±60%
Specific gasification rate	100 kg.m ⁻² .h ⁻¹
Equivalence ratio (ER)	0.3, 0.4, 0.5
α stoichiometric	1.0364 mol air. (mol C in fuel) ⁻¹

The gasification was initiated by igniting 300 grams of wood charcoal, used as an ignition agent, and introducing it into the reactor. Furthermore, one kg of the coffee parchment was gradually added into the reactor through the biomass inlet (Figure 2). Furthermore, the cap was tightened, and the start-up time was recorded. Air, acting as the gasifying agent, was injected into the reactor through the combustion zone with an equivalence ratio (ER) set at 0.3, 0.4, and 0.5. The burning of coffee parchment provides heat for a further

gasification process; hence, it is called the auto-thermal process.

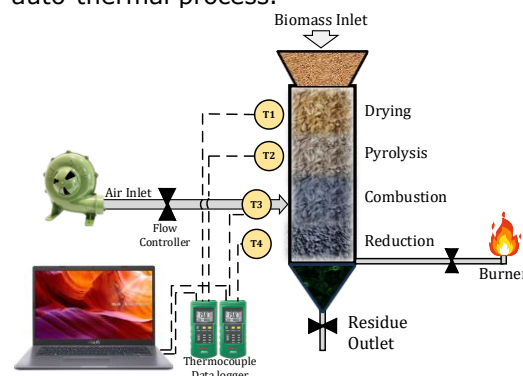


Figure 2. Experimental setup for coffee parchment gasification

ER was determined using the method established by (Anyaocha et al., 2020; Neathery, 2010) which includes the mol ratio of oxygen required for the combustion divided by the mol ratio of oxygen required for stoichiometric complete combustion of biomass. The calculation of the ER relied on the data obtained from the proximate analysis of coffee parchment, as shown in Table 2. Specifically, each oxidative component identified in the proximate analysis was paired with the corresponding amount of oxygen required to establish the stoichiometric oxygen demand for burning. This precise calculation ensured a comprehensive understanding of the combustion process in relation to the coffee parchment's composition. The ER was then calculated according to Eq. (1).

$$ER = \alpha / \alpha_{\text{stoich}} \quad (1)$$

Where α is an actual ratio of air to fuel, which is equal to the amount of air injected into the gasifier divided by the amount of solid fuel. The α_{stoich} is the stoichiometric ratio of air to solid fuel, which refers to the amount of air required to completely burn solid biomass divided by the amount of solid biomass.

2.3. Measurement and Analysis

The data of proximate, ultimate, calorific value and bulk density analysis of coffee parchment was investigated in previous research (Setiawan et al., 2022). During the gasification experiment, the reactor temperature was monitored every five minutes within the drying, pyrolysis, oxidation, and reduction zones.

The gas released through the right down-side to the gas burner was ignited and the initial time required to obtain spontaneous

combustion was recorded. Furthermore, the time required from the initial ignition to the end of flaming in the gas burner was recorded as flame duration. The temperature of the flame was measured using an infrared thermometer.

The flame color was analyzed using the guidelines proposed by Ilminnafik et al. by recording the flame using a 1280 x 720 resolution camera (Ilminnafik et al., 2019). Finally, after the complete process, the solid residue was carefully collected from the residue outlet (Figure 1) and weighed. The residue content was calculated using Eq. (2).

$$R = \frac{W_r}{W_b} \times 100\% \quad (2)$$

W_r = weight of residue (g)

W_b = initial weight of biomass (g)

The biomass conversion (B_c) was calculated by Eq. (3).

$$B_c = (100 - R) \% \quad (3)$$

3. Results and Discussion

3.1. Feedstock Analysis

The characteristics of biomass waste, including its proximate and ultimate analysis, play a significant role in determining the composition of producer gas during gasification. Key factors such as the type of feedstock, moisture content, and air equivalence ratio (ER) have a notable influence on the resulting gas composition (Salem et al., 2022). Selecting the appropriate biomass is one of the most important factors in obtaining a valuable synthetic gas. In general, biomass with a high ratio of hemicellulose and cellulose to lignin will produce a higher content of synthetic gas (Ren et al., 2019). The cellulose, hemicellulose, and lignin content of coffee parchment was 45%, 20%, and 32%, respectively.

Table 2 shows the composition of coffee parchment according to proximate and ultimate analysis from previous research (Setiawan et al., 2022). It contains high carbon and oxygen, which were in accordance 44 and 45%. Additionally, the hydrogen content was in average of 6.19%. These high carbon and hydrogen are important for generating better producer gas composition. Coffee parchment exhibits low levels of nitrogen, sulfur, and chloride, which were found to be 1.04%, 0.28%, and 0.031%, correspondingly.

Table 2. Proximate and ultimate analysis (Setiawan et al., 2022)

Parameter	Composition (%)
Proximate	
C	44.00
H	6.19
O	45.15
N	1.04
S	0.28
Cl	0.031
Ultimate	
Moisture	10.44
Ash	3.34
Volatile	68.58
Fixed carbon	10.44
Calorific value	4,031.55 cal.g ⁻¹
Bulk density	147.01 kg.m ⁻³

Regarding moisture content, solid fuels need to have moisture levels below 20% to ensure beneficial gasification parameters (Salem et al., 2022). High moisture content contributes to lower gasifier temperature, increases tar production, promotes unstable processes, and higher energy requirements for drying. However, the coffee parchment used in this research had a moisture content of 10.44% galling within the normal range of typical biomass for gasification.

Ash content refers to the final solid residue after oxidation, which generally contains minerals, carbon, and unburned materials. Higher ash content would result in higher tar production in the gasification (Salem et al., 2022). Coffee parchment exhibited an ash content of 3.34%, categorized as a low-ash composition biomass.

The presence of carbon in biomass is required in the char oxidation reaction. Higher carbon content transforms to more concentration of CO, CH₄, and heating values of producer gas (Salem et al., 2022). Higher C and H content in raw materials contributes to the increased CO and H₂ in the producer gas, which leads to a higher LHV (Safarian et al., 2021). Furthermore, the calorific or heating value of feedstock is another important parameter to consider during the production of bioenergy. Subsequently, the arabica coffee parchment had 4,031.55 cal.g⁻¹ of the heating value.

3.2. Effect of Equivalence Ratio

To perform the gasification reaction, a gasification medium with a specific ER or composition was introduced into the process. Several common gasification mediums include air, carbon dioxide, oxygen, and steam (Ren et al., 2019). In this research, air was used as the gasification agent due to the cost-effectiveness and ease of preparation compared to the others. The air supply in the

gasification process was below the theoretical amount of air required for complete combustion. It was set at the ER of 0.3; 0.4, and 0.5.

Gasification is an endothermic process that converts biomass into fuel gas through four distinct zones, each operating at different temperatures. Gasification temperature is an important parameter in the overall biomass gasification process controlling the chemical reactions for the biomass conversion into producer gas. In the gasification process, synthetic gas was produced in the pyrolysis, combustion, and reduction zones, at temperatures ranging from 600-1,500°C. The highest efficiency in the gasification process was observed at an oxidation temperature ranging between 800°C (Sadaka and Johnson, 2010) - 850°C reaching an efficiency of 82%. There were no significant changes in values of CH₄ and CO₂ when the temperature was more than 850°C (Neubauer and Liu, 2013).

Generally, the heat required for drying can be provided by radiation flames or heat available in the unit process (Sadaka and Johnson, 2010). In the gasification reactor, the heat required for the biomass drying is coming from the pyrolysis zone below (James K. Neathery, 2010). In the auto-thermal supply method, the combustion of biomass provides the heat for the whole process, as conducted in this research. Figure 3 shows the temperature profile of the process in each gasification zone. In general, the higher the ER input into the reactor, the higher the temperature obtained after 25-30 minutes of the gasification in the oxidation zone. The oxidation reaction is an exothermic process where the more oxidation occurs, the more heat is released. This heat is then utilized in the pyrolysis and drying zones. However, the oxidation process must be controlled to allow for syngas production.

The highest temperature in the drying zone (T1) was obtained at the ER of 0.3 (Figure 3a); 0.4 (Figure 3b); and 0.5 (Figure 3c) corresponding to 71.23°C, 84.23°C, and 107.3°C after 25 to 30 minutes of the process. The moisture in the biomass evaporated due to heat and convective force, flowing into the pyrolysis zone. The temperature in this zone was relatively stable due to physical process only with no chemical decomposition occurring. In addition, the pressure was relatively equal to the ambient, which was not the focus of this research.

The highest temperatures observed in the pyrolysis zones were 347.53°C, 330.93°C, and 459.66°C, corresponding with the ER. It is

assumed that the free water was completely evaporated from the biomass in the drying zone. As the process continued, the goal was to eliminate the volatile content from the solid fuel. Higher temperatures led to the formation of charcoal (C), tar, gases, and other pyrolysis products through chemical reactions. In general, pyrolysis products consist of three components, gases (H₂, CO, CO₂, H₂O, and CH₄), tar, and charcoal.

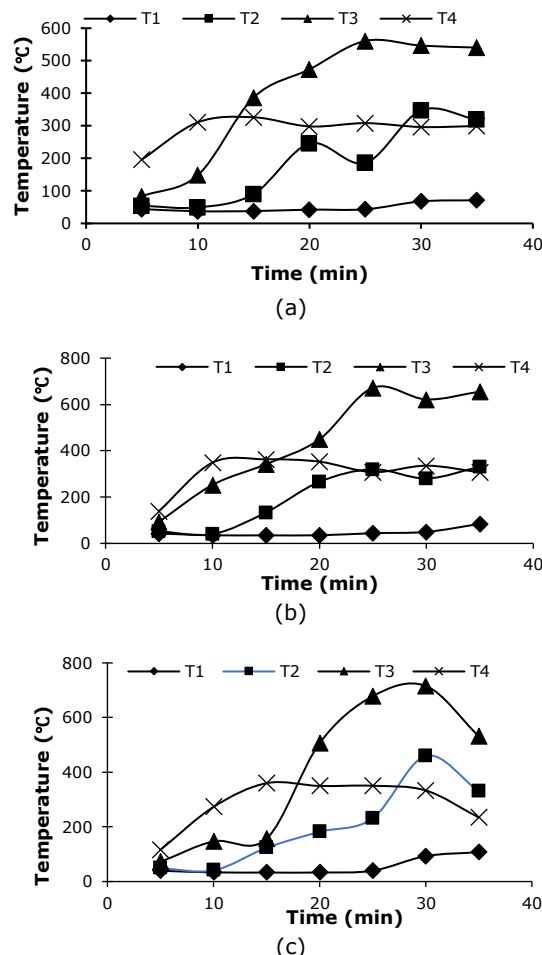


Figure 3. The temperature profile of the gasification reactor under ER of (a) 0.3, (b) 0.4, (c) 0.5

The subsequent zone is oxidation/combustion which is the most important process in gasification. The heat required for all the reactions that occurred within the gasifier was produced in this zone. Subsequently, a limited amount of oxygen was injected using a blower to oxidize the charcoal, tar, and gaseous products from the pyrolysis zone.

Figure 3 shows the maximum oxidation zone temperatures corresponding to ER values of 0.3, 0.4, and 0.5, which were measured at 561.03°C, 671.90°C, and 715.66°C, respectively. Increasing the air injection into the zone resulted in higher temperatures. This

oxygen injection gasifier temperature gradually promotes the oxidation of pyrolysis products into a more flammable gas concentration in the producer gas. Subsequently, the exothermic process led to the highest temperature in the gasifier.

The last zone was the reduction part, where the highest temperatures for each ER were 326.23°C, 363.10°C, and 359.9°C, respectively. In this zone, pyrolysis products such as charcoal, tar, and methane were decomposed into CO and H₂ as fuel gases. The hot glowing char below the reduction zone provided more heat to convert tar and oil in the producer gas to the more flammable components before leaving the gasifier. This is one of the advantages of downdraft gasifier compared to other types (James K. Neathery, 2010).

The quantity of oxygen input into the reactor significantly controls the gasification process. Increasing oxygen injection into the combustion zone could expand the combustion area into the reduction zone below, thereby increasing CO₂ formation (James K. Neathery, 2010). Therefore, it is very important to find out the adequate oxygen input to deliver high H₂ and CO content in producer gas. As shown in Figure 3, the ER of 0.5 input into the combustion zone resulted in enhanced gasifier temperature due to the oxidation reaction of pyrolysis products. However, this result should be compared with other parameters before deciding the optimum ER for coffee parchment gasification.

3.3. Gasification Ignition Time, Operational Time, and Flame Duration

Ignition time refers to the duration required from the beginning of gasification and the moment when the gas product ignites. It signifies when the gasification process yields flammable gas. Additionally, the time taken for biomass gasification, recorded from the beginning until the fire is extinguished, is referred to as gasification operational time. Flame duration is the period during which gas is produced, calculated from the first ignition to when the flame extinguishes. This is recorded when the gas in the burner ignites fire, and slowly off when no more producer gas is released. These parameters indicated the duration of the flammable gas produced. Therefore, the operational time is the sum of the ignition time and the flame duration. Longer gasification operational time signified more producer gas yield and vice versa.

Figure 4 illustrates the effect of ER to the operational time. It shows that more flammable gas was produced when using an ER of 0.3. Increasing the ER from 0.3 to 0.5 shortened the operational time. It required 33 and 32 minutes for the producer gas to keep producing when using ER of 0.3 and 0.4, respectively. Besides, using a higher ER of about 0.5 in the gasification of coffee parchment, delivered a shorter duration of producing gas (29 minutes). This indicated the alleviation of flammable gas production. This is in line with the research on gasification of Scottish agriculture, where an ER of 0.30-0.35 produced more synthetic gas (Salem et al., 2022).

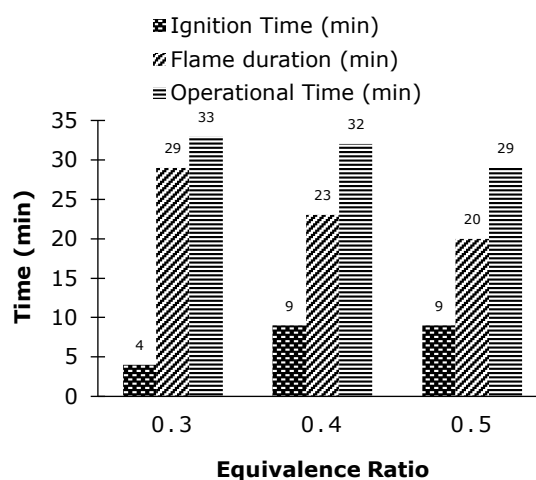


Figure 4. Gasification operational time, initial ignition time, and flame duration

Gasification with an ER of 0.3 produced flammable gas more rapidly than the other ER values. It took 4 minutes from the start of the process until flammable gas was produced and ignited through the burner. Furthermore, the flame remained for 29 minutes. However, the other two needed 9 minutes after the process to generate flammable gas, and each kept flaming for 23 and 20 minutes for the ER of 0.4 and 0.5.

Injecting more oxygen into the gasifier resulted in a shorter time required to release producer gas. A higher amount of oxygen injected can extend the oxidation zone to the reduction zone, leading to the occurrence of a combustion reaction, hence more CO₂ will be produced in producer gas (Fajimi et al., 2021; James K. Neathery, 2010; Park et al., 2021), and reduced the H₂ and CO production (Park et al., 2021). In addition, the flammable gas was also diluted by the high concentration of N₂ from the air input. Since CO₂ and N₂ are non-combustible, a higher content in producer gas could reduce the flame duration during the

gasification. These findings specified that the injection of ER of 0.3 into the reactor tends to give a shorter time required to deliver producer gas and a higher amount of producer gas yield.

3.4. Flame Color and Temperature

The characteristics of gas fuel diffusion flame have been extensively studied as an important parameter related to fuel gas composition (Piemsinlapakunchon and Paul, 2021). Flame color and temperature serve as the initial indicators of combustion fuel quality, reflecting the presence of non-combustible gases such as carbon dioxide and nitrogen in the fuel (Ilminnafik et al., 2019).

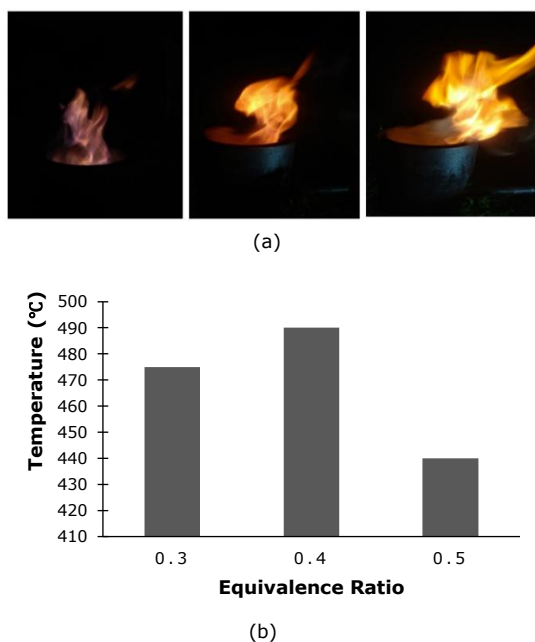


Figure 5. Flame color (a); and temperature (b)

Figure 5a displays the flame color of burning producer gas, which varies depending on the ER used in the coffee parchment gasification. When an ER of 0.3 is applied, it produces a soft-colored flame. The addition of a higher amount of oxygen of about 0.4 and 0.5 in the gasification process, created the yellow orange to red flame of the burning producer gas. This indicates that injecting more air during gasification leads to a lower yield of flammable gas. This might be due to the dilution of the flammable gas in the gas product with the existing N_2 content from the air and the production of more CO_2 during the oxidation reaction in the gasifier. This trend is further confirmed by the producer gas temperature shown in Figure 5b. The highest flame temperature was obtained from the gasification using the ER of 0.3 and 0.4. More

oxygen input tends to decrease the flame temperature of the burning producer gas.

Flame temperature is directly related to the heating value of the fuel. A higher heating value indicates more energy in the form of heat released when the fuel is oxidized, which can be detected by measuring the flame temperature. The presence of high concentration of CO_2 and N_2 , reduce the heat generation from synthetic gas. However, it could be visually seen by the low-stability flame (Piemsinlapakunchon and Paul, 2021). This is in line with the other findings in literature where using a higher or lower ER tended to alleviate the production of gas energy (M.Siedlecki and Jong, 2011; Park et al., 2021).

3.5. Gasification Residue and Biomass Conversion

Gasification does not only produce gas but also other constituent, including liquid and solid residue. The liquid contains water, and heavy hydrocarbon, while the solid includes ash and slag. The solid waste is divided into three points: bottom ash, fireside deposits, and the residue of flue gas cleaning. Ash typically consists of silica, aluminum, iron, calcium, and a small amount of magnesium, titanium, sodium, and potassium. These elements remain together in ash residue (Basu, 2018). Slag, on the other hand, is a thicker accumulation of ash that can be found as fireside deposits and residues from flue gas cleaning. The presence of ash and slag in the gasifier can cause blockages in the gasifier and at a certain point reduce the reaction. The efficiency of gasification can also be inferred from the characteristics of solid residues. However, in this research, only the gasification was performed, without any producer gas cleaning process. The residue referred to the remaining materials collected at the bottom of the gasifier.

The residual percentage was calculated based on the ash, pyrolysis charcoal and unburned material of coffee parchment remained which was collected in the ash collector after complete gasification. It was weighed after cooling down and calculated according to Eq.2. The results, as shown in Figure 6, indicate that less residue is obtained with a higher ER value. Biomass conversion refers to the percentage of biomass fuel converted to gas product, which was simply calculated by measuring the residual content after gasification took place (Eq.3). According to the analysis, the biomass conversion was higher with a higher ER injection, primarily because more oxidation

reaction occurred during gasification. Subsequently, biomass conversion only indicated the amount of biomass converted to gas, without any determination of the gas composition. This parameter provides a rough calculation to predict the amount of gas produced during gasification. However, measuring the gas volume will be required in the future.

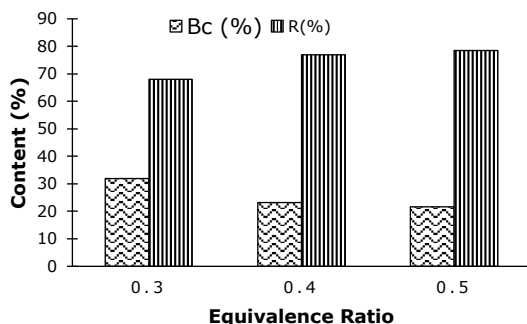


Figure 6. Residue content (R) and biomass conversion (Bc) after complete gasification

4. Conclusion

In conclusion, the gasification of coffee parchment using a lab-scale downdraft reactor through an auto-thermal supply method was successfully developed. Using ER of 0.3 produced the comparable producer gas from coffee parchment according to the gasification temperature, and the producer gas characteristics including ignition time, flame duration, flame color, and flame temperature. Additionally, the gasification residue obtained up to 32%. This research served as a preliminary investigation of coffee parchment gasification. Further research will be required for better biomass conversion through additional heating apparatus, catalyst, and integration into a cleaning system to obtain fuel-grade synthetic gas for commercial applications.

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