

AIR INTAKE MODIFICATION FOR PYROLYSIS OPTIMIZATION ON RICE HUSK FIXED BED DOWNDRAFT GASIFIER WITH MAXIMUM CAPACITY OF 30 KG/HOUR

Hafif Dafiqurrohman^{1,2*}, Adi Surjosatyo^{1,2}, Felly Rihlat Gibran¹

¹*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*

²*Tropical Renewable Energy Center, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok, Depok 16424, Indonesia*

(Received: November 2016 / Revised: December 2016 / Accepted: December 2016)

ABSTRACT

Rice husk is one of the most abundant biomass wastes in Indonesia. One way to convert it into an alternative source of energy is biomass gasification. This is a thermochemical process which converts biomass feedstock into fuel gas or chemical feedstock gas (producer gas). The gasification type which is developed in this study is fixed bed downdraft type due to its low tar content and compatibility in microscale implementation. One major problem with the implemented biomass gasification reactor was ruggedness of the partial oxidation process due to the absence of air in the reactor's middle section, which consequently affected the pyrolysis zone. Several experiments were conducted previously using coconut shells and rice husks as solid feedstock, where an equivalence ratio (ER) of 0.4 was obtained. Therefore, in order to optimize the pyrolysis zone, the modification conducted involves adding a circular air intake into the gasifier. Experiments were conducted in a pyrolysis temperature range of 300–700°C with ER variation of 0.19, 0.24, 0.27 and 0.31. The results show that a good quality producer gas is produced at an ER value of 0.24. This value shows a promising result because the ER value of biomass gasification standard is 0.25.

Keywords: Biomass gasification; Circular air intake; Fixed bed downdraft; Optimized pyrolysis zone; Rice husk

1. INTRODUCTION

Rice husk is a biomass type which derives from paddy cultivation process waste. It is almost uniform in size and form and is feasibly reprocessed. Nevertheless, it also has a hard structure and is not feasible for fermentation because of its high content of lignin and silica (SiO₂) (Asian Biomass Center, 2012). Several studies have been conducted to harness rice husk by using gasification, pyrolysis and combustion in order to produce various types of energy, such as hydrogen, liquid fuel, heat and electrical energy (Zheng et al., 2006). Biomass gasification is a thermodynamic process which converts biomass raw material into combustible gas (producer gas). Nowadays, methods to increase efficiency and reduce tar content in producer gas have become major issues in biomass gasification researches (Yoon et al., 2012).

A previous experiment on optimizing the pyrolysis zone (improving gas quality and gasifier operation) was conducted for the Updraft Fixed Bed Gasifier in the Thermodynamic Laboratory

*Corresponding author's email: hafif.dafiqurrohman@yahoo.com, Tel. +62-857-1844-1383
Permalink/DOI: <https://doi.org/10.14716/ijtech.v7i8.6889>

Department of Mechanical Engineering, Faculty of Engineering, University of Indonesia. In this experiment, a reactor design with low tar content and high efficiency gas was obtained by adjusting the exit position of producer gas from the gasifier (Surjosatyo et al., 2014). Another experiment was conducted in Plered, Purwakarta using coconut shell, wood and rice husk as fuel. In this experiment, the biomass fuels were mixed with different composition variations. The results showed that the pyrolysis zone temperature was 103.97–141.64°C (Wicaksono, 2013). Then, further improvement was made in another experiment by modifying the grate and adding a mixer and overflow. The experiment used coconut shell and rice husk as fuel. The results showed different pyrolysis zone temperatures for each fuel, i.e., 614.56°C for rice husk and 247.4°C for coconut shell (Achiruddin et al., 2014).

Optimizing the pyrolysis zone is very important in the biomass gasification process because it greatly affects the producer gas quality, tar content and producer gas heating value. Moreover, the presences of primary and secondary air have a significant role in the pyrolysis zone of a gasifier due to their relation with the char and tar conversion process in biomass (Di Blasi & Branca, 2013). Furthermore, the addition of air stage can affect the air to fuel ratio (AFR) value, which significantly correlates with the temperature distribution inside a gasifier. The drying, pyrolysis, oxidation and gasification zone temperatures are greatly affected by this AFR value. A high temperature in the oxidation zone can increase the reduction reaction and tar breakdown rates so that heating value increases and tar content decreases (Guo et al., 2014). Finally, creating modifications in the air intake flow rate can affect the temperature distribution and equivalence ratio (ER) inside a gasifier (Gai & Dong, 2012).

Previous experiments have shown several problems, i.e., (a) non-uniform pyrolysis and partial oxidation zones rendered rice husk unable to be gasified optimally; (b) the air to fuel ratio (AFR) composition needed to optimize the pyrolysis zone had not been determined so that the continuous producer gas was produced; and (c) the optimal operation temperature had not been set so that the pyrolysis zone and producer gas quality could be optimized. In order to solve these problems, several steps were performed, i.e., (a) determine the feeding rate, Specific Gasification Rate (SGR), Specific Gas Production Rate (SGPR) and gasification efficiency; (b) determine the equivalence ratio (ER) composition needed to optimize the pyrolysis zone; and (c) determine the optimal temperature in the pyrolysis zone.

2. EXPERIMENTAL METHODS

The experiment was conducted in the Research Collaboration Laboratory between the Thermodynamic Laboratory (Biomass Gasification Research Group), Department of Mechanical Engineering, Faculty of Engineering, University of Indonesia and Sarandi Karya Nugraha Co. Inc., Sukabumi Industry Central District, Cibatu, Cisaat, Sukabumi. The ambient temperature and pressure were 30–35°C and 1 atm, respectively. The gasification system used is shown in Figure 1.

This system consisted of several apparatus with specific functions, i.e. (a) feeder: to deliver solid biomass into the reactor; (b) gasification reactor: equipped with overflow, air settings valve and circular air intake, this tool served as the most important part where the biomass gasification process took place; (c) stirrer system: to clean up ash which could disturb the producer gas flow; (d) reactor grate: to hold the biomass from imprecise falling; (e) residue eliminating system: to remove gasification residue (tar, ash) from the reactor; (f) Gas filtering system: consisted of cyclone and gas storage tank; and (g) cyclone gas burner: equipped with an inverter to control producer gas flow, this tool's function was to check the producer gas quality. Moreover, the measuring devices in this gasification system were a K-type thermocouple with a diameter of 0.65 mm (installed in the drying, pyrolysis and fuel surface zone of the reactor and

cyclone gas burner to measure flame temperature), orifice meter to measure air mass flow rate and Adam View DAQ system connected with a Laptop to process measured data.

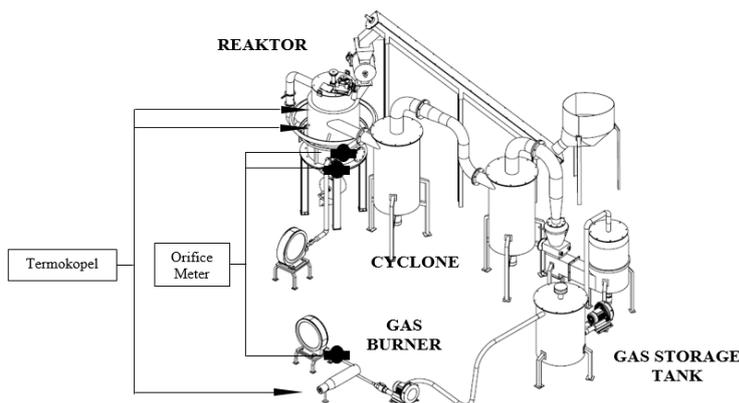


Figure 1 Experimental apparatus setup for gasification system

The experiment procedures consisted of several steps. The first step was initial combustion. Rice husk was poured inside the reactor (1.4 kg) and mixed with kerosene and burned paper so that it ignited. To initiate the combustion, gasification air was flowed through primary and secondary air intake inside the reactor using a blower. The process took 20 minutes to reach a producer gas temperature of 700°C. At this point, rice husk could be poured continuously at 1.4 kg per 10 minutes. The second step was biomass fuel feeding rate. Rice husk was poured into the reactor with a feeding rate of 8.4 kg/hour after the ignition process was finished. The third step was biomass stirring. Rice husk was stirred inside the reactor at pyrolysis temperature (700°C) with a rotational speed of 6 rpm. The fourth step was producer gas suction. After the pyrolysis temperature was achieved, the suction blower was switched on to flow producer gas from the reactor to the cyclone gas burner with an initial pull of 450 rpm (adjusted by inverter). The fifth step was residue elimination. Gasification residue (ash) was eliminated using screw ash removal by adjusting the rotating blade speed to 6 rpm. The sixth step was cyclone gas burner ignition and settings. To ignite the burner, a torch was used as an igniter, and air was blown using a blower with a valve opening of 22.5°. Initially, air valve and producer gas blower rotational speeds were set at 22.5° open and 450 rpm, respectively. The purpose was to obtain a rich mixture (more producer gas) so that the flame would appear faster. However, as the process continued, a turbulent flame developed in the mixing chamber, and it had to be eliminated. Hence, more pressure was needed to discharge this flame. As a result, the valve open and burner rotational speeds were set to 45° and 600 rpm, respectively. The seventh and last step was measuring the reactor and cyclone gas burner temperatures, air into the reactor and air and producer gas into the reactor mass flow rates: (a) measurement of temperature distribution inside the reactor was conducted every one minute with variation to air mass flow and feeding rates; (b) measurement of flame temperature in cyclone gas burner was conducted every one minute with variation to air and producer gas mass flow rates; (c) measurements of air mass flow rate into the reactor and producer gas mass flow rate into the cyclone gas burner were conducted with variation to temperature distribution inside the reactor and flame temperature inside the cyclone gas burner.

3. RESULTS

3.1. Result of Air Intake Modification using Circular Air Intake

As shown in Figure 2a, using only a primary air intake cannot uniform the pyrolysis zone so that flame only exists at the surrounding edge (inner surface) of the reactor. This is because air

flow from the primary air intake cannot uniform the combustion process in the partial oxidation zone, which transfers heat to the pyrolysis zone through convection. The non-uniformity of the pyrolysis zone causes the rice husk decomposition of pyrolysis products (char, tar, oil, CO, CH₄, H₂, etc.) to become incomplete. Therefore, in the previous experiment, the combustible gas production process (indicated by the burner operation) only lasted for 10–15 minutes after the ignition process. As a result, in this experiment, secondary air intake was added into the reactor to uniform the partial oxidation zone so that the pyrolysis zone could be optimized (Guo et al., 2014). This air intake was circular in shape, and its number of holes were adjusted with those of primary air intakes, i.e., six. The configurations of primary and secondary air intake installations are shown in Figure 3. Finally, after the secondary air intake had been installed, as shown in Figure 2b, the combustion distribution became uniform inside the reactor. This phenomenon indicates not only that air distribution was uniform but also that the pyrolysis process had been undergone as well.

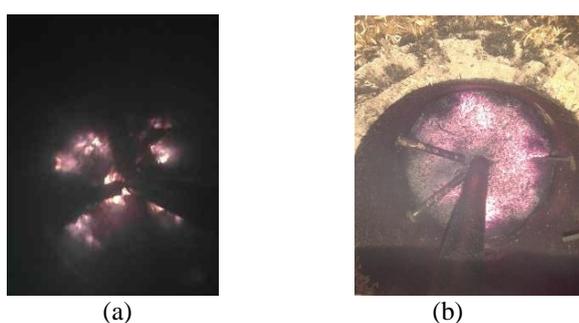


Figure 2 Combustion distribution inside reactor: (a) before modification; (b) after modification

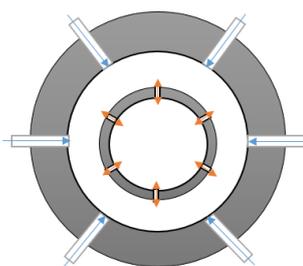


Figure 3 Circular air intake position inside reactor (blue: primary; orange: secondary)

3.2. Result of Fixed Bed Downdraft Type Rice Husk Gasification after Modification

As a result, the optimum condition achieved at 45° opening had an average flame temperature of 536.77°C. Compared with other conditions, flame in this condition is the most stable and has the highest value. Therefore, it can be concluded that the best quality gas was produced.

3.2.1. AFR_{st}

Based on rice husk ultimate analysis (Houston, 1972), the oxygen and carbon content inside a rice husk are 36% and 38.7%, respectively. Considering that the rice husk mass entering the gasifier was 8.4 kg, the O₂ (Mr = 32) and C (Mr = 14) mole can be obtained, i.e., 0.09 and 0.27 moles. Moreover, by using the equation $C + O_2 \rightarrow CO_2$ and $C + CO_2 \rightarrow 2 CO$, the amount of O₂ required can be calculated using the stoichiometric mole and coefficient comparison:

$$O_2 \text{ required} = 0.27 \times 1/1 + 0.27 \times 1/2 = 0.41 \text{ moles}$$

Thus, the theoretical O₂ can be obtained:

$$O_2 \text{ theoretical} = O_2 \text{ required} - O_2 \text{ in fuel} = 0.41 - 0.09 = 0.32 \text{ moles}$$

The amount of air can be calculated by O_2 percentage inside air (i.e., 21%):

$$\text{Air theoretical} = 0.32 \times 100/21 = 1.48 \text{ moles}$$

Finally, the AFR_{st} value can be obtained:

$$AFR_{st} = 1.48 \times 77.4/100 = 1.14$$

3.2.2. \dot{m}_{air}

The value can be calculated using the equation $SGPR \text{ (hearth load)} = \frac{Q_{producer\ gas}}{A}$ with $d = 12.5$ mm, $\rho = 1.2 \text{ kg/m}^3$, $\beta = 0.1$ and $Cd = 0.6$ (ISO 5167-1). The value of $P_1 - P_2$ varies with the monometer measurement.

3.2.3. Feed rate

Ignition

The ignition process lasted for 20 minutes with a total rice husk mass of 1.4 kg. By using the equation $\dot{m}_{ignition} = \frac{m_{ignition}}{t}$, the ignition feed rate can be calculated. The result is 0.0001 kg/s.

Combustion

During the combustion process, 1.4 kg of rice husks were poured every 10 minutes. Thus, the combustion feed rate can be calculated using the following equation: $\dot{m}_{combustion} = \frac{m_{combustion}}{t}$.

The result is 0.0002 kg/s.

3.2.4. SGR

With a throat diameter of 0.35 m, the SGR can be calculated by using the equation $SGR \text{ (hearth load)} = \frac{\dot{m}_{fuel}}{A}$. The result is 0.024 kg/m²s.

3.2.5. SGPR

The SGPR value can be calculated by using the measurement result of the suction blower inverter, which showed the most stable initial suction, i.e., at the rotational speed of 450 rpm (ω_1). Furthermore, by using the blower specification, the values of ω_{max} and Q_{max} can be obtained, i.e., 2820 rpm and 2.75 m³/minute, respectively. By applying the equation $\dot{m}_{fuel} = \frac{m_{fuel}}{t}$, $Q_{producer\ gas}$ can be calculated, i.e., 0.0016 m³/s. Finally, by using the equation $SGPR \text{ (hearth load)} = \frac{Q_{producer\ gas}}{A}$, the SGPR value can be calculated. The result is 0.016 m³/m²s.

3.2.6. $\eta_{gasification}$

First, the HHV_{fuel} value should be calculated using the equation $HHV = [34,1C + 132,2H + 6,8S - 1,53A + 12,0(O + N)] \text{ MJ/kg}$. The HHV_{fuel} obtained is 24.5 kJ/kg. Then, the LHV_{fuel} can be calculated using the equation $LHV = HHV - h_g \left(\frac{9H}{100} + \frac{M}{100} \right)$ with $h_g = 2260 \text{ kJ/kg}$, $H = 5\%$, $M = 10\%$, and the LHV_{fuel} obtained is 10.09 MJ/kg. By using the reference (Ma, 2015), with an ER value of 0.2 – 0.3, the $LHV_{producer\ gas}$ can be obtained, which is 4.44 MJ/Nm³.

Finally, the gasification efficiency can be calculated using the equation $\eta_{gasification} = \frac{Q_{producer\ gas} \times LHV_{producer\ gas}}{\dot{m}_{fuel} \times LHV_{fuel}}$, and the result is 30.2%.

Table 1 Equivalence ratio as experiment result

Air intake opening	Mass of fuel (kg/s)	Mass of air (kg/s)	AFR	ER
0.25	0.0023	0.0005	0.22	0.19
0.50	0.0023	0.0006	0.27	0.24
0.75	0.0023	0.0007	0.31	0.27
1.00	0.0023	0.0008	0.34	0.31

As shown in Table 3, the ER value at the 45° valve opening is 0.24. Based on an experiment conducted by Prabir Basu in 2010, with an ER range of 0.2 to 0.3, the optimum ER value obtained for rice husk gasification was 0.25. Thus, this is a promising value considering that it is quite similar to the international standard (0.25).

4. DISCUSSION

4.1. Analysis of Equivalence Ratio (ER) Effect on Pyrolysis Zone Operational Temperature and Producer Gas Quality

In this research, several experiments were conducted using varying equivalence ratios (ER) as the independent variable. The purpose was to analyze the effects of each ER on the temperature distributions inside the reactor and burner and the producer gas quality. In order to facilitate the analysis, an experiment conducted by Guo et al. (2014) was set as a reference. One of this experiment's results was a graph which shows the effects of ER on producer gas composition and LHV (Figure 4).

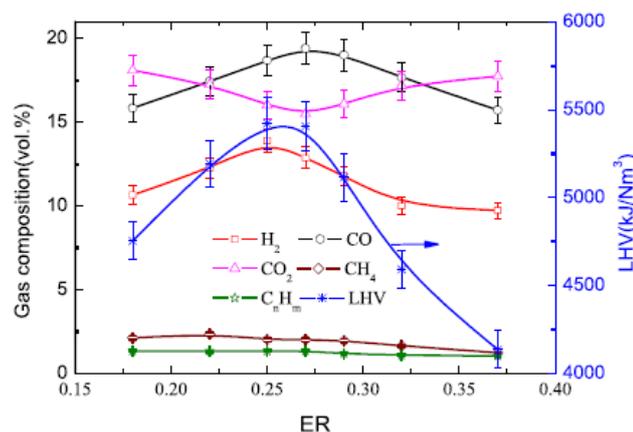


Figure 4 Graph of producer gas composition vs. equivalence ratio (Guo et al., 2014)

Based on Figure 4, it can be seen that, for ER values between 0.25–0.27, the LHV (energy) of producer gas reached its maximum value. This high value of LHV indicates that more H₂ and CO (the biggest energy contributor in producer gas) were generated and more tar was decomposed by biomass pyrolysis inside the reactor. Meanwhile, as ER increased (> 0.27), the LHV, CO and H₂ contents decreased. This is because, as ER increases, more O₂ is supplied into the reactor, which yields higher temperatures (more complete combustion). As the combustion becomes more complete, more CO₂ (incombustible) is formed, resulting in a decreased LHV value.

The experiment results can be analyzed in Figure 5. Based on the temperature distribution, these ER variations can be categorized into three types, i.e.;

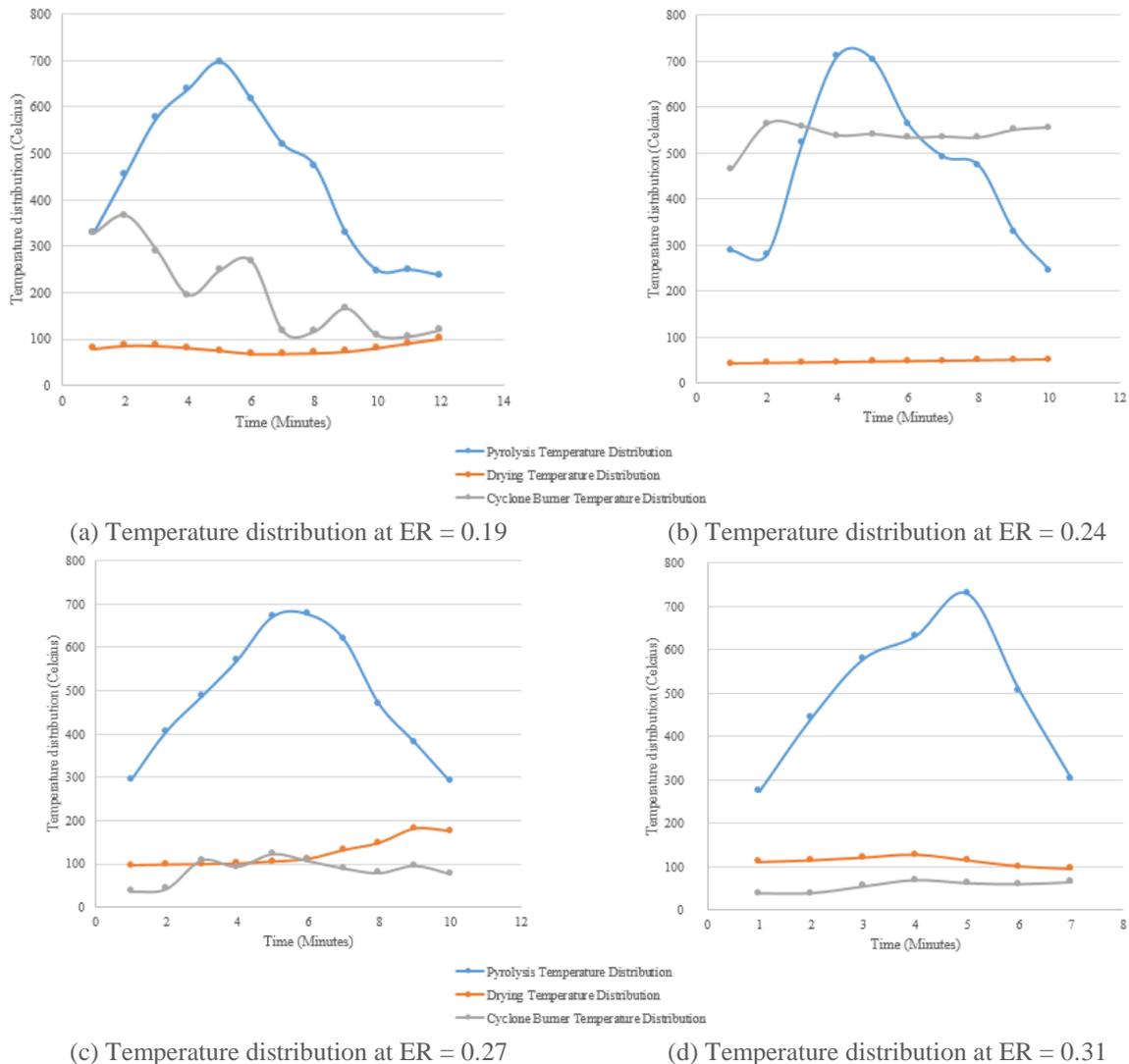


Figure 5 Reactor and burner temperature distributions with ER variations of (a) 0.19, (b) 0.24, (c) 0.27 and (d) 0.31

1) Less Air Supply

As seen in Figure 5a (ER = 0.19), the maximum pyrolysis temperature was achieved after 5 minutes. Then, pyrolysis began, and the temperature tended to decrease thereafter. This phenomenon indicates a slow pyrolysis time, which results in an incomplete decomposition process in the pyrolysis zone. This, in turn, results in a low quality of producer gas because when the amount of O_2 supplied in the partial oxidation process is small, the amount of producer gas (CO , H_2 and CH_4) produced will be small (shown in Figure 4). When the ER was small, the combustion process in the partial oxidation zone was undergone slowly so that pyrolysis product decomposition was incomplete. Moreover, the flame produced inside the cyclone gas burner was the same with that of the optimum condition but was unstable and tended to decrease. Therefore, it can be concluded that the producer gas has low quality and, if burned, will become unstable.

2) Sufficient Air Supply

As shown in Figure 5b (ER = 0.24), the cyclone gas burner temperature was relatively stable. This result indicates that the producer gas quality is good. According to Figure 4, because the amounts of producer gas CO , H_2 and CH_4 increased, the amount of O_2

supplied in the partial oxidation process was sufficient. Moreover, pyrolysis product decompositions were complete and fast with an indication of relatively fast (4 minutes) pyrolysis time (faster than the previous experiment). When ER (0.24) is sufficient, based on the optimum ER of biomass gasification (0.25), the combustion process in the partial oxidation zone occurs rapidly, which subsequently affects pyrolysis product decomposition in the pyrolysis zone. As a result, producer gas has a good quality and is capable of producing a stable flame in the cyclone gas burner.

3) Rich Air Supply

Figures 5c (ER = 0.27) and 5d (ER = 0.31) show that temperature distribution formed when rich air was supplied to the gasification process. Based on both graphs, the cyclone gas burner temperature was relatively low, which indicates that there no flame was produced in the burner. From this 'no flame' condition, it can be concluded that the producer gas quality is poor. This is because when more air (ER increase) is supplied to the reactor, the combustion process in the partial oxidation zone produces over high temperature. Consequently, pyrolysis products cannot be well gasified and are converted into CO₂ rather than combustible gas. This analysis corresponds with Figure 4. It can be seen that when ER increased, the amounts of producer gas CO, H₂ and CH₄ decreased, while CO₂ increased.

4.2. Analysis of Pyrolysis Zone Operational Temperature and Producer Gas Quality on ER 0.24 (Optimum Equivalence Ratio in Gasification Reactor)

After conducting four different experiments, the optimum ER was obtained by adding a circular air intake into the fixed bed downdraft biomass gasification. Then, a further experiment was conducted to obtain the continuous operational running time for non-stop operation of 60 minutes. The purpose of obtaining this running time was to acquire the optimum pyrolysis zone temperature as the operational temperature to be used in reactor types for rice husk biomass gasification in Indonesia. For 60 minutes of non-stop operation, the operational pyrolysis zone temperatures obtained were between 300–700°C, while the optimum condition was obtained at a temperature of 500–600°C. This condition was indicated by flame in the cyclone gas burner (with optimum ER), with an average temperature of 500–600°C (Figure 6). In this temperature range, pyrolysis product decomposition occurred completely. Combustible gas produced from partial oxidation and reduction zones contained sufficient amounts of producer gas CO, H₂ and CH₄ and a little amount of CO₂ based on the reference graph (Figure 4). As a result, producer gas can be burned continuously in the cyclone gas burner with a stable produced flame. The optimum ER value obtained (0.24) corresponds with that of the reference (0.25). The experiment conducted by Guo et al. (2014) concluded that when ER was 0.25, the producer gas achieved its highest efficiency, which is 65%. This high value of efficiency indicates that more biomass was converted to producer gas, which means that more energy can be harvested from biomass utilization.

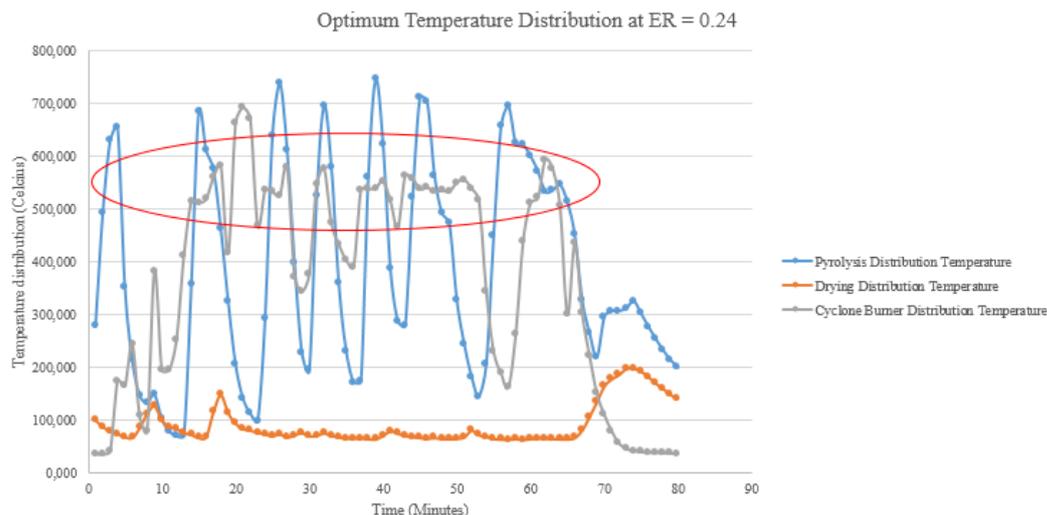


Figure 6 Graph of Biomass Gasification Optimum Temperature at ER 0.24

5. CONCLUSION

The conclusions obtained from this experiment are: (1) after the circular air intake was modified, the feeding rate for the optimum gasification process was 8.4 kg/h or 2.33 g/s; (2) after the circular air intake was modified, the Specific Gasification Rate (SGR) for the optimum gasification process was 0.024 kg/m²s; (3) after the circular air intake was modified, the Specific Gas Production Rate (SGPR) for the optimum gasification process was 0.016 m³/m²s; (4) after the circular air intake was modified, the gasification efficiency (cold efficiency) for the optimum gasification process was 30.2%; (5) the optimum equivalence ratio (ER) was 0.24 with a circular air intake valve opening of 45°. This condition was indicated by the producer gas burner in the cyclone burner generating a stable flame; (6) the optimum pyrolysis zone operational temperature ranged between 500–600°C. In this range, producer gas formed in gasification process can be stably burned in the cyclone gas burner.

6. REFERENCES

- Achiruddin, S., Patih, G., Qasthari, H., 2014. Study of Coconut Shell and Rice Husk Gasification. *Bachelor Thesis*, Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia
- Asian Biomass Center, 2012. *Asian Biomass Handbook*
- Basu, P., 2010. Biomass Gasification and Pyrolysis Practical Design. *Academic Press Publication: Elsevier*.
- Cao, Y., Wang, Y., Riley, J.T., Pan W-P., 2006. A Novel Biomass Air Gasification Process for Producing Tar-free Higher Heating Value Fuel Gas. *Fuel Processing Technology*, Volume 87(4), pp. 343–353
- Di Blasi, C., Branca, C., 2013. Modeling a Stratified Downdraft Wood Gasifier with Primary and Secondary Air Entry. *Fuel*, Volume 104, pp. 847–860
- Gai, C., Dong, Y., 2012. Experimental Study on Non-woody Biomass Gasification in a Downdraft Gasifier. *International Journal of Hydrogen Energy*, Volume 37(6), pp. 4935–4944
- Guo, F., Dong, Y., Dong, L., Guo, C., 2014. Effect of Design and Operating Parameters on the Gasification Process of Biomass in a Downdraft Fixed Bed: An Experimental Study. *International Journal of Hydrogen Energy*, Volume 39(11), pp. 5625–5633
- Houston, D.F., 1972. Rice Chemistry and Technology. St. Paul, MN. *American Association of Cereal Chemist*, pp. 301–340

- Koch, T., 2005. The TKE 3-stage Gasifier Gasification and Combine Heat and Power Production in Small Scale. *In: Presentation Trondheim*, pp. 256–263
- Ruiz, J.A., Juárez, M.C., Morales, M.P., Muñoz, P., Mendivil, M.A., 2013. Biomass Gasification for Electricity Generation: Review of Current Technology Barriers. *Renewable and Sustainable Energy Reviews*, Volume 18, pp. 174–183
- Surjosatyo, A., Vidian, F., Nugroho, Y.S., 2014. Experimental Gasification of Biomass in an Updraft Gasifier with External Recirculation of Pyrolysis Gases. *Journal of Combustion*. Volume 2014, pp. 1–6
- Susanto, H., Beenackers, A.A.C.M., 1996. A Moving-bed Gasifier with Internal Recycle of Pyrolysis Gas. *Fuel*, Volume 75(11), pp. 1339–1347
- Vargas-Moreno, J.M., Callejón-Ferre, A.J., Pérez-Alonso, J., Velázquez-Martí, B., 2012. A Review of the Mathematical Models for Predicting the Heating Value of Biomass Materials. *Renewable and Sustainable Energy Reviews*, Volume 16(5), pp. 3065–3083
- Wicaksono, R., 2013. Gasification Application Study on Pottery Industry: Effect of Fuel Mixture Percentage Coconut Shell and Rice Husk on Flame Stability in Downdraft Gasification System. *In: IMAT Proceeding 2013*, pp. 121–130
- Yoon, S.J., Son, Y.-I., Kim, Y.-K., Lee, J.-G., 2012. Gasification and Power Generation Characteristics of Rice Husk and Rice Husk Pellet using a Downdraft Fixed-bed Gasifier. *Renewable Energy*, Volume 42, pp. 163–167
- Zheng, J.-l., Zhu, X.-f., Guo, Q.-x., Zhu, Q.-s., 2006. Thermal Conversion of Rice Husks and Sawdust to Liquid Fuel. *Waste Management*, Volume 26(12), pp. 1430–1435