Process Simulation of Inverted Downdraft Gasifier for Tar Reduction Using in Situ Process

Maha Hidayatullah Akbar\textsuperscript{1}, Yohanes Bobby Sanjaya\textsuperscript{1}, Hafff Dafiqurrohman\textsuperscript{1}, Yuswan Muharam\textsuperscript{2}, Adi Surgosatyo\textsuperscript{1,3}\textsuperscript{*}

\textsuperscript{1}Department of Mechanical Engineering, \textsuperscript{2}Department of Chemical Engineering, \textsuperscript{3}Tropical Renewable Energy Center, \{Faculty of Engineering - Universitas Indonesia, Kampus UI Depok, 16424, Indonesia\}

E-mail: *adisur@eng.ui.ac.id

Abstract. Biomass gasification is a topic that is currently popular technology which convert biomass to another form of energy. Unfortunately, gasification has many challenges specially to reduce tar in significant amounts which will be discussed in this journal. Regular updraft gasifier can produce 10\% - 30\% volatile tar while many gasifiers produce so much tar that gas cleaning cost is more than the actual gasifier. In-situ method is used for reducing tar amount inside the reactor. One of the solutions is inverted downdraft gasifier implementation, which typically produces much less tar, about 1-5\%. In this research, the inverted downdraft gasification was simulated by Aspen Plus which provides an overview optimal condition for less tar syngas. The result gives us highest value of syngas, 6.05 MJ/Nm\textsuperscript{3} for Coal and 6.24 MJ/Nm\textsuperscript{3} for MSW (Municipal Solid Waste) which both of them have ER 0.20. In Aspen Plus, we can discover several main parameters that can be done by finding both mass flow rate and contents in syngas which contains \textit{CH}_4, \textit{H}_2, \textit{CO}, \textit{CO}_2, \textit{O}_2, \textit{H}_2\textit{S}, \textit{N}_2 and \textit{H}_2\textit{O}.

1. Introduction

Gasifiers can be distinguished based on the direction of air flow in gasification. The gasifier designs can use is fixed bed: updraft and downdraft, and also fluidized bed: bubbling and circulating [1, 2] Unfortunately updraft gasifier has a weakness which is the large amount of tar, Tar condenses in the gasifier’s low temperature zone, clogs gas lines, and causes system damages[3, 4]. If the syngas is used for electricity-producing gas engines, intensive gas cleaning will be required which is intended for reducing tar as much as gas cleaning system can clean [5].

The population in Jakarta is 10,177,924, which was rising at a rate of 1.20\% in 2015 Depok makes an estimated 1120 tons of urban waste daily, 76.61\% of which is organic. The existing waste management facilities in Depok comprise one landfill known as the Cipayung Landfill, which covers 10.6 ha and can handle 55-58 garbage lorries per day, each with a capacity of up to 12 m\textsuperscript{3} [6]. It is absolutely an alarm for waste problem in urban areas. These urban waste problems make researcher look for ways to solve this environmental problem [7], but on the other hand the need for energy also increases for urban communities. This led to the magnified municipal solid waste generation at an alarming rate on a global scale. Municipal solid waste seems to be an economically viable and attractive resource to produce green fuels through different waste-to-energy conversion.
Inverted downdraft gasification forces volatile gases out of a solid fuel and burns them separately from the solid body that can reduce harmful emission production which it refers tar [8]. Inverted downdraft gasifier answers not only the demand of energy but also the need of clean energy. Municipal Solid Waste (MSW) can be converted into pellet and this pellet can be used as feedstock for gasification. The primary goal is to break down municipal solid waste (MSW) into multiple gaseous species, including synthetic gases, hydrocarbons and tar compounds [9]. The research that is conducted by James et al claims that tar can be reduced by Inverted Downdraft Gasifier from 79.4 to 13 g/m$^3$ by increasing its burning rate.

On this research, we simulated inverted downdraft gasifier in Aspen Plus. MSW will be compared to lignite as the feed stock in this simulation. This will create a clear picture of the energy potential of urban waste which we will compare with lignite coal which is still widely used as a fuel source for gasification.

2. Methodology Research

The Inverted Downdraft Gasifier has different direction on both directions of combustion and direction of combustion compared to the fixed bed downdraft gasifier that is stated in methodology. Model created in Aspen One is based on the actual gasifier. it will show the reactions that take place inside gasifier in systematical order as shown in figure below. In gasification, gasification performance is affected by Equivalence ratio, gasifier temperature, ultimate analysis of feedstock and proximate analysis of feedstock. The Peng-Robinson equation of state with PR-BM (Boston-Mathias) modification is chosen as base property method.

The equivalence ratio is very important gasifier design parameter. It is the ratio of the actual air-fuel ratio to the stoichiometric air-fuel ratio [10]. In this model, absolute pressure will be use. For coal gasification simulation, the pressure is 35 bar [11] meanwhile MSW uses 1 bar for MSW gasification simulation [9].

During the gasification process, atmospheric air containing oxygen is pushed by a fan into the fuel section because it converts the rice husks into carbon-rich char and through thermo-chemical reactions that makes combustible gases which includes: carbon monoxide, hydrogen, and methane gases [12]. The chemical reactions of oxidation process are taken from Basu et al [10] meanwhile The chemical reactions of gasification process are taken from Eikland et al [13].
Table 1. Gasification Reaction and Oxidation Reaction in Gasifier Reactor

| Gasification reactions | Oxidation reactions          |
|------------------------|-------------------------------|
| Water gas reaction:    | Carbon oxidation:             |
| C\(_s\) + H\(_2\)O \rightarrow CO + H\(_2\) | C\(_s\) + O\(_2\) \rightarrow CO \(_2\) |
| CO + H\(_2\) \rightarrow C\(_s\) + H\(_2\) | Carbon monoxide oxidation:   |
|                        | CO + 0.5O\(_2\) \rightarrow CO \(_2\) |
| Boudouard reaction:    | Methane oxidation:           |
| C\(_s\) + CO\(_2\) \rightarrow 2 CO | CH\(_4\) + 2O\(_2\) \rightarrow CO\(_2\) + 2H\(_2\)O |
| 2 CO \rightarrow C\(_s\) + CO\(_2\) | Water gas shift reaction:    |
|                        | Hydrogen oxidation:          |
|                        | H\(_2\) + 0.5 O\(_2\) \rightarrow H\(_2\)O |
| Methanation reaction:  | Methane-reforming:           |
| 0.5C\(_s\) + H\(_2\) \rightarrow 0.5 CH\(_4\) | CH\(_4\) + H\(_2\)O \rightarrow CO + 3H\(_2\) |
| 0.5 CH\(_4\) \rightarrow 0.5C\(_s\) + H\(_2\) | CO + 3H\(_2\) \rightarrow CH\(_4\) + H\(_2\)O |

Table 2. Inverted downdraft Block’s Functions in Aspen Plus

| Block   | Model | Function                                      |
|---------|-------|-----------------------------------------------|
| Drying  | RYield| Simulate biomass drying based on the water content value in proximate analysis of coal |
| Pyrolysis| RYield| Simulate biomass pyrolysis based on the results of pyrolysis experiment |
| Char-Dec| RStoic| Decompose char into C, H\(_2\), O\(_2\), N\(_2\), S, and ash in order to easily deal with solid reaction in the simulation of char gasification and combustion |
| Gasif   | REquil| Simulate char gasification                     |
| Oxi     | REquil| Simulate oxidation                            |
| Sep-1...3| Sep2 | Separate the gas and solid                    |
| Mix     | Mixer | Mix air, pyrolysis gas and gasification gas that will combusts in Oxidation Reactor |

After the data is collected. Several data comparison will be shown. LHV (Low Heating Value) that will be rated as one of the main parameters of heating value in syngas. LHV can be obtain by this calculation with LHV expressed in MJ/Nm\(^3\) and CO, H\(_2\) and CH\(_4\) will be expressed in % of mass fraction [23, 24]

\[
LHV = \frac{13.622 \cdot CO + 10.788 \cdot H_2 + 35.814 \cdot CH_4}{100} 
\]  

3. Result

In this section, the result of the simulation of inverted downdraft gasifier will be presented. Our objective is to discuss the effect of Equivalence Ration (ER) on the composition of the produced gas and to identify key aspects that determine the quality of produced gas. In this simulation for both coal gasification and MSW gasification, the oxidation temperature will be set at 1500\(^\circ\)C (1773 K) while gasification zone has temperature 627\(^\circ\)C (900 K), the gas produced by the gasifier will be recorded then the simulation will be repeated by varying the value of ER. The result
The amount of N\textsubscript{2} corresponds to the amount of air that reacts with the fuel within gasifier that reactions shown at table 1 have already taken place. The amount of N\textsubscript{2} increases the amount of nitrogen increases as the ER increases. this can happen because nitrogen is the most dominant gas agent in air, so this has an impact on the addition of ER where ER, which contains air flow, makes nitrogen yield number increases. Either in coal gasification or in MSW gasification shows an increase in N\textsubscript{2} nitrogen percentage. N\textsubscript{2}’s Yield increases from 0.4082 (40.82%) to 0.5628 (56.28%) in coal gasification in the other hand. N\textsubscript{2}’s Yield increases from 0.2012 (20.12%) to 0.3530 (35.40%) in MSW gasification.
Figure 4. Effect of ER to syngas’s Tar content

The combustion products, CO$_2$ and H$_2$O are increasing due to produced gas from gasification zone reacted with O$_2$ in oxidation zone resulting in drop of produced gas yield, For example, H$_2$ yield decreases from 0.0725 (7.25%) to 0.0305 (3.05%) in coal gasification and from 0.0472 (4.72%) to 0.0283 (2.83%) in MSW gasification simulation. CO gives similar trend which is compatible with H$_2$ trend CO yield decreases from 0.4125 (41.25%) to 0.2152 (21.52%) in coal gasification simulation and from 0.4540 (45.40%) to 0.3094 (30.94%) in MSW gasification simulation. These correlation between increasing value of ER and the decreases H$_2$ and CO yield’s from producer gas, has shown a match with Michailos et al research [16]. In both simulations, CH$_4$ is almost depleted in produced gas indicating that all Methane gases produced from gasification zone are burned in oxidation zone.

In order to determine the quality of produced gas, one must understand the reliable parameters to assess it. The first one is Tar, which is a dark brown or black viscous liquid of hydrocarbons and free carbon, obtained from a wide variety of organic materials through destructive distillation. Usually, Tar can be produced from coal, wood, petroleum, or peat. Tar is considered as harmful substance that is poisonous to human and may causes problem for...
syngas utilization. In this simulation, Tar is represented by Benzene, \( \text{C}_6\text{H}_6 \) that is bioproduct from pyrolysis zone that aren’t capable to react in gasification zone. However, tar can be reduced via combustion in oxidation zone. The second parameter is LHV or the amount of chemical energy stored in the produced gas that are useful for various application. Ideally, we want the producer gas to have highest LHV possible with lowest tar content. Based from simulation’s result and calculating from LHV formula we can obtain correlation between ER and Tar content and producer Gas LHV as shown in figures below;

The graphs show that increase in value of ER results in decrease in both Tar content and syngas’s LHV. These results are to be expected as both Tar (Benzene) and Syngas undergo oxidation in the inverted downdraft reactor. As for the value, Tar can be reduced unto below 5% on coal gasification and 6.5% in MSW Gasification, by the increasing number of ER, these results match from the Liu et al journal [17]

The quality of the producer gas can be seen from the heat content, which is LHV (Lower Heating Value). The lower heating value (also known as net calorific value) of producer gas is defined as the amount of heat released by combusting a specified quantity. In this simulation, The LHV is also decreased from 6.05 MJ/Nm\(^3\) to 3.05 MJ/Nm\(^3\) for Coal gasification simulation and The LHV is decreased from 6.24 MJ/Nm\(^3\) to 4.21 MJ/Nm\(^3\) for MSW gasification simulation. This is due to the reduced percentage yield of combustible gases such as \( \text{H}_2 \) (hydrogen) and \( \text{CH}_4 \) (methane). Since both graphs have almost similar slope, it can be estimated that the optimum ER is around 0.3-0.35.

4. Conclusion

In this work, ASPEN Plus is used for inverted downdraft gasification simulation. Parametric analysis was performed by varying gasification Equivalence ratio from 0.20 to 0.50. The combustible gas, like \( \text{H}_2 \) and CO, is decreased because ER increases. \( \text{H}_2 \) yield decreases from 0.0725 (7.25%) to 0.0305 (3.05%) in coal gasification simulation meanwhile the situation is similar in MSW simulation which \( \text{H}_2 \) yield decreases from 0.0472 (4.72%) to 0.0283 (2.83%) in MSW gasification simulation. CO yield decreases from 0.4125 (41.25%) to 0.2152 (21.52%) in coal gasification simulation. On the other hand, MSW simulation which CO yield decreases from 0.4540 (45.40%) to 0.3094 (30.94%) in MSW gasification simulation. before determining the effect on gasification performance that contains LHV effect, gas yield effect and tar effect. The crucial results will follow: the lower ER is the higher LHV, it reflects in this simulation both coal gasification simulation and MSW gasification simulation. The LHV is decreased from 6.05 MJ/Nm\(^3\) to 3.05 MJ/Nm\(^3\) for Coal gasification simulation and The LHV is decreased from 6.24 MJ/Nm\(^3\) to 4.21 MJ/Nm\(^3\) for MSW gasification simulation. Tar, in this simulation, is reduced by the increasing number of ER. From these results we can also conclude that in situ tar reduction in inverted downdraft is in parallel with the producer gas’s LHV, hence the Gasifier Performance.

Acknowledgments

Thank you to the Directorate of Research and Community Service (DRPM) Universitas Indonesia, who provided research grant [grant number NKB-4971/UN2.RST/HKP.05.00/2020].

References

[1] P. Sharma, B. Gupta, M. Pandey, K. Singh Bisen, and P. Baredar, “Downdraft biomass gasification: A review on concepts, designs analysis, modelling and recent advances,” Mater. Today Proc., no. xxxx, 2020, doi: 10.1016/j.matpr.2020.08.789.

[2] T. Kirch, P. R. Medwell, and C. H. Birzer, “Natural draft and forced primary air combustion properties of a top-lit up-draft research furnace,” Biomass and Bioenergy, vol. 91, pp. 108–115, 2016, doi: 10.1016/j.biombioe.2016.05.003.
[3] K. B. Sutar, S. Kohli, M. R. Ravi, and A. Ray, “Biomass cookstoves: A review of technical aspects,” Renew. Sustain. Energy Rev., vol. 41, pp. 1128–1166, 2015, doi: 10.1016/j.rser.2014.09.003.

[4] J. Zeng et al., “Evaluating tar production via the release of volatile matters for H2-rich syngas production,” Int. J. Hydrogen Energy, vol. 45, no. 6, pp. 3712–3720, 2020, doi: 10.1016/j.ijhydene.2019.08.251.

[5] G. N. Shelke and P. Mahanta, “Feasibility study on utilization of biomass briquette in a conventional downdraft gasifier,” Int. Energy J., vol. 15, no. 4, pp. 157–166, 2015.

[6] U. Gasification and O. F. Eucalyptus, “Updraft gasification of,” no. part 3, p. 2013, 2013.

[7] G. A. Kristanto and W. Koven, “Estimating greenhouse gas emissions from municipal solid waste management in Depok, Indonesia,” City Environ. Interact., vol. 4, no. 2019, p. 100027, 2019, doi: 10.1016/j.cacint.2020.100027.

[8] S. Nanda and F. Berruti, “A technical review of bioenergy and resource recovery from municipal solid waste,” J. Hazard. Mater., vol. 403, no. August 2020, p. 123970, 2021, doi: 10.1016/j.jhazmat.2020.123970.

[9] P. S. Anderson and T. B. Reed, “Biomass Gasification: Clean Residential Stoves, Commercial Power Generation, and Global Impacts,” Energy Sources, vol. 11, no. 5, pp. 1–13, 2004, doi: 10.1080/009083190913584.

[10] A. Tungalag, B. J. Lee, M. Yadav, and O. Akande, “Yield prediction of MSW gasification including minor species through ASPEN plus simulation,” Energy, vol. 198, 2020, doi: 10.1016/j.energy.2020.117296.

[11] P. Basu, Biomass Gasification and Pyrolysis. 2010.

[12] Aspen Technology, “Aspen Plus Model for Moving Bed Coal Gasifier,” 2010.

[13] I. Osei, F. Kemausuor, M. K. Comneh, J. O. Akowuah, and L. Owusu-Takyi, “Design, Fabrication and Evaluation of Non-Continuous Inverted Downdraft Gasifier Stove Utilizing Rice husk as feedstock,” Sci. African, vol. 8, p. e00414, 2020, doi: 10.1016/j.sciaf.2020.e00414.

[14] M. S. Eikeland, R. K. Thapa, and B. M. Halvorsen, “Aspen Plus Simulation of Biomass Gasification with Known Reaction Kinetic,” Proc. 56th Conf. Simul. Model. (SIMS 56), October, 7-9, 2015, Linköping Univ. Sweden, vol. 119, pp. 149–156, 2015, doi: 10.3384/ecp15119149.

[15] A. R. Proto et al., “Energetic Characteristics of Syngas Obtained from Gasification of Hazelnut Prunings,” Procedia - Soc. Behav. Sci., vol. 223, pp. 835–840, 2016, doi: 10.1016/j.sbspro.2016.05.288.

[16] Y. II Son, S. J. Yoon, Y. K. Kim, and J. G. Lee, “Gasification and power generation characteristics of woody biomass utilizing a downdraft gasifier,” Biomass and Bioenergy, vol. 35, no. 10, pp. 4215–4220, 2011, doi: 10.1016/j.biombioe.2011.07.008.

[17] Z. Liu, “Gasification of municipal solid wastes: a review on the tar yields,” Energy Sources, Part A Recover. Util. Environ. Eff., vol. 41, no. 11, pp. 1296–1304, 2019, doi: 10.1080/15567036.2018.1548508.

[18] S. Michailos and A. Zabaniotou, “Simulation of Olive Kernel Gasification in a Bubbling Fluidized Bed Pilot Scale Reactor,” J. Sustain. Bioenergy Syst., vol. 02, no. 04, pp. 145–159, 2012, doi: 10.4236/jsbs.2012.40201.