EFFECT OF OXYGEN ENRICHMENT ON SYNGAS QUALITY IN SMALL-SCALE DOWNDRAFT GASIFICATION OF RDF–RICE HUSK

Do Phu Nguu*, Nguyen Minh Tien, Phung Minh Tung

The University of Danang - University of Technology and Education, Vietnam

*Corresponding author: dpnguu@ute.udn.com

(Received: December 16, 2025; Revised: January 05, 2026; Accepted: January 13, 2026)

DOI: 10.31130/ud-jst.2026.24(1).720E

Abstract - This study investigates the impact of supplementing 20% oxygen into the air supply during the gasification of a 65% RDF and 35% rice husk blend in a small-scale downdraft gasifier. The results demonstrate that oxygen enrichment significantly elevates combustion zone temperatures and reduces nitrogen dilution, leading to a substantial increase in combustible gas components. Specifically, comparative data reveal that at an Air Ratio (ER) of 0.3, CO concentration rises markedly from 23% to 44%, resulting in a total combustible fraction of approximately 70%. Similarly, at ER 0.4, CO levels increase from 20% to 34%, while at ER 0.5, they rise from 12% to 30%. These findings confirm that oxygen enrichment effectively enhances the heating value and quality of biomass-derived syngas.

Key words - HRES; Biogas; Syngas; Hydrogen; Flexible gaseous fuel engine

1. Introduction

The depletion of fossil fuels and the environmental consequences of their extraction and use - particularly greenhouse gas emissions and global warming - have searched for alternative energy sources increasingly urgent. Numerous scientific studies are directed toward meeting long-term carbon reduction goals, striving to limit the rise in global average temperature to 1.5°C and to pursue strategies to remain below 2°C, as stipulated in the Agreement at the COP26 Climate Change Summit [1]. Among the alternative solutions, enhancing carbon sequestration through afforestation and utilizing forest by-products, as well as renewable energy from biomass, has emerged as a promising pathway - especially for agricultural countries like Vietnam, where roughly 80% of the land area consists of hilly and mountainous regions, ideal for biomass energy development. However, conventional direct-combustion technologies still face limitations, particularly in controlling CO emissions, which remain a major technical challenge in gasification. Gasification has been proposed as a viable solution to improve the efficiency of biomass utilization. This technology not only enhances energy conversion efficiency but also provides better environmental control. Biomass gasification - converting solid biomass into a transportable and storable combustible gas mixture (syngas) - is considered cost-effective and scalable within a circular energy economy. Gasification offers greater potential for eliminating societal waste and plays a key role in the circular green economy. Municipal solid waste, plastics, wastepaper, agricultural and forestry residues, and various other waste streams contain molecules that can be gasified into syngas composed of hydrogen, producer gas, and bio-derived gasoline. Currently, biomass in the form of biofuels supplies approximately 10% of global energy [2]. Because it is formed through photosynthesis, using atmospheric carbon dioxide, biomass is regarded as a carbon-neutral resource [3]. Each year, around 20 billion tons of woody biomass waste are generated globally [4]. In many rural areas, most of this biomass is burned either outdoors or indoors [5], creating significant waste-management issues and contributing substantially to environmental pollution [6, 7]. Recycling biomass can therefore be an essential step toward achieving carbon-neutral energy.

The conversion of biomass, agricultural residues, and municipal solid waste into energy has been studied for decades and continues to attract attention both domestically and internationally. In Vietnam, biomass is increasingly recognized as a highly promising renewable energy resource, drawing substantial interest from researchers. Gasification technology has been shown to reduce the mass of solid waste by about 70% and its volume by up to 90%, while simultaneously lowering greenhouse gas emissions and decreasing dependence on landfills [8]. The gasification process relies on partial oxidation reactions in an oxygen-deficient environment, involving both reversible combustion reactions and reduction reactions. Optimal gasification performance is usually achieved when the Air Ratio (ER) ranges from 0.25 to 0.3, with operating temperatures around 680–700°C [8]. When air is used as the oxidizing agent, the typical volumetric composition of syngas includes 18–20% H_2, 18–20% CO, 2% CH_4, 11–13% CO_2, up to 50% nitrogen, water vapor, and trace pollutants [9], with a lower heating value of 4–7 MJ/Nm³ [10]. When steam or pure oxygen is used as the oxidizer, the resulting syngas attains a higher heating value, ranging from approximately 10 to nearly 30 MJ/Nm³ [11]. Syngas is a potential fuel source for industrial drying burners [12] and power generation applications [13, 14].

Among fixed-bed gasification systems, downdraft gasifiers can reduce tar content to below 10 mg/Nm³ [15]. In this configuration, both fuel and air flow downward in the same direction, enabling syngas to pass through high-temperature zones; consequently, tar is oxidized, and other impurities are significantly reduced, producing cleaner gas that makes downdraft gasifiers more suitable for practical applications [16, 17]. Although downflow gasifiers exhibit limited flexibility with respect to biomass type and recycled fuel pellet (RDF) size, they remain suitable for small-scale syngas production. This study employs a laboratory-scale downflow gasifier to systematically examine the combined influence of RDF–rice husk biomass properties and oxygen-enriched air on syngas composition. The novelty of this work lies in the controlled adaptation of locally available Vietnamese biomass characteristics together with oxidizer enrichment, aiming to enhance syngas fuel quality. The findings provide new insights into syngas optimization and broaden the practical applicability of small-scale downflow gasification systems.

2. Research Methodology

2.1. Simulation Study

In this work, both simulation and experimental studies were conducted and compared to evaluate the results. The simulation was carried out using ANSYS Fluent software. The gasification process was modeled as a diffusion combustion process, in which the fuel and air are supplied from separate sources. The fuel inlet conditions include the fuel composition and temperature, while the air inlet conditions consist of air pressure and temperature. The fuel-air mixture composition (f) is assumed and assigned initial values corresponding to the characteristics of the input fuel pellet. The air ratio ER is the ratio of the actual (air/fuel) ratio divided by the theoretical (air/fuel) ratio.

This study selects the k-ε turbulent model and the Partially Premixed Combustion model, using a downdraft, with the basic dimensions illustrated in Figure 1. The combustion chamber is conical, with a fuel inlet diameter of 240 mm, a maximum chamber diameter of 400 mm, and a height of 110 mm. The RDF (wood-rice husk RDF) used in this study is cylindrical in shape, with an average diameter of 10 mm, while the length varies. Similar to other solid fuels, the volatile components in RDF are released before combustion and mix with air to form a combustible mixture. In the simulation, RDF pellets are randomly distributed within the gasifier, the air surrounding the pellets has a combustion process parameter c=1, while inside the pellets, c=0, and their surface temperatures vary. To simplify the calculations, the authors performed the simulation in 2D, as shown in Figure 1. The computational domain is divided into five regions: ash zone, combustion zone, reduction zone, drying zone, and fuel bed zone. This zoning allows the initial conditions to be configured individually in order to investigate their influence on the gasification process.

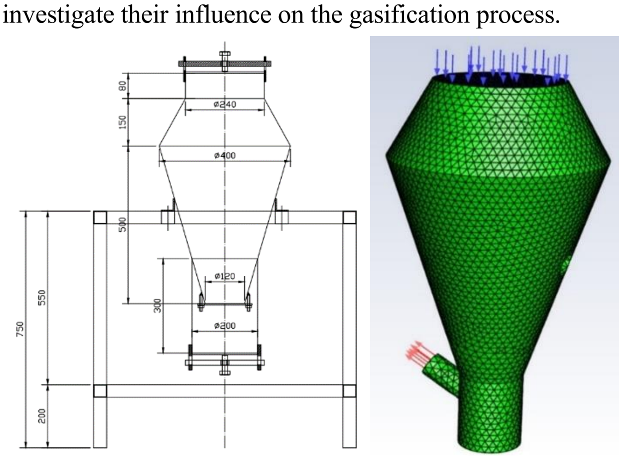


Figure 1. *Dimensions of the downdraft gasifier and the computational domain mesh model*

Boundary conditions were defined as follows: Fuel inlet: Only fuel is present, no combustion occurs (f = 1, c = 0), with a fuel flow rate of Q_f. Air inlet: Only air is present, and combustion occurs only when air comes into contact with fuel within flammability limits (f = 0. c = 1), with an air flow rate of Q_a. Here, c is the progress variable representing combustion, and the f variable represents the fuel fraction. The values of Q_a and Q_f are determined based on the specified Air Ratio (ER) using the predefined mixture fraction f. The initial fuel–air mixture in the gasifier is thus set according to the desired ER. Temperatures in each zone of the gasifier were also assigned to investigate their effects on the gasification process. The elemental composition of the RDF fuel, including carbon (C), hydrogen (H), oxygen (O), and nitrogen (N), is presented in Table 1. Once the fuel composition is known, the Coal Calculator tool in ANSYS Fluent was used to determine the empirical formula of the fuel and the theoretical air-to-fuel mass ratio under complete combustion conditions (denoted as r).

Table 1. *Fuel Composition and Properties Used in the Simulation*

Fuel	Elemental composition (%wt)				Molecular formula	r
	C	H	O	N		
Rice husk	0.46	0.06	0.475	0.005	C0.33H2.85O1.42 N0.0171	1.59
Biomass	0.48	0.06	0.457	0.003	C0.41H2.85O1.37 N0.0102	2.05
Coconut shell	0.502	0.057	0.434	0.007	C0.50H2.71O1.30 N0.0239	2.47
Wood	0.5324	0.0636	0.4028	0.0012	C0.62H3.02O1.20 N0.0041	3.65
Solid waste	0.57	0.06	0.343	0.027	C0.77H2.85O1.02 N0.0925	4.54

The selected fuels for simulation calculations include rice husk, biomass, coconut shell, wood, and municipal solid waste (MSW), arranged in ascending order of hydrogen and carbon content, and descending order of oxygen content. Consequently, the theoretical air-to-fuel mass ratio (r) for complete combustion follows the same increasing order: rice husk, biomass, coconut shell, wood, and MSW, as presented in Table 1. In addition to the individual RDFs listed above, a mixed RDF composed of wood and rice husk is also considered in this study to compare its behavior with that of the individual RDFs.

The gasification process is simulated using the Partially Premixed Combustion (PPC) model, characterized by two conserved scalars: the mixture fraction f and the progress variable c, both ranging from 0 to 1. The air flow rate Qa and fuel flow rate Qf are expressed through the Air Ratio (ER). The relationship between ER, the Equivalence Ratio ϕ, the mixture fraction f, the theoretical air-to-fuel ratio $(Q_a/Qf)_{lt}$, and the actual air-to-fuel ratio $(Q_a/Q_f)_{tt}$ is given by the following expressions:

$$ER = \frac{1}{\phi} \quad (1)$$

$$f = \frac{\phi}{\phi + r} \quad (2)$$

$$r = \left(\frac{Q_a}{Q_f}\right)_{lt} \quad (3)$$

$$\phi = \frac{(Q_f/Q_a)_{tt}}{(Q_f/Q_a)_{lt}} \quad (4)$$

In the simulation calculations, a suitable value of the Air Ratio (ER) corresponding to the gasified fuel is selected. Based on this ER, the mixture fraction f is determined, and the mass flow rates of air Q_a and fuel Q_f supplied to the gasifier are subsequently calculated.

2.2. Experimental Study

***Figure 2.** Experimental setup diagram of the downdraft gasifier*

The experimental study was conducted by gasifying agricultural residues and RDF blended at specific ratios, following the setup illustrated in Figure 2. A small-scale downdraft gasifier, designed and fabricated with dimensions similar to those shown in Figure 1, was utilized for this purpose. The syngas outlet pipe was installed at a 45° incline relative to the gasifier body. Temperature sensors were placed at corresponding positions along the gasifier body and the syngas outlet pipe to monitor the temperature at multiple locations throughout the gasifier.

An air pump and a flow meter were installed at the air inlet to control and measure the supplied airflow, enabling the calculation of the corresponding air–fuel ratio (A/F). Industrial-grade oxygen from a pressurized cylinder was introduced into the airflow to assess the effect of oxygen as an oxidizing agent on the final syngas composition. The composition of the resulting syngas fuel was measured and analyzed using a Gasboard Gas Analyzer.

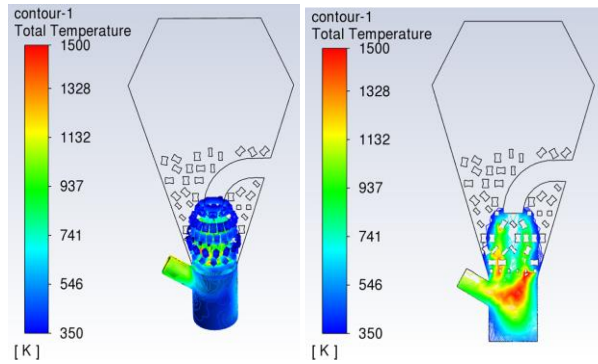
3. Results and Discussion

3.1. Simulation of Temperature Variation in the Gasifier

Figure 3 illustrates a simulation of the combustion process of agricultural residues and RDF inside the gasifier. Ambient air is introduced into the gasifier at the midpoint indicated in the simulation, where the airflow moves downward and encounters char particles that have undergone pyrolysis. This interaction forms a combustion zone with temperatures ranging from approximately 1200^{0}C to 1400^{0}C. The gas stream then continues downward through the hot char layer, where the gasification reactions take place. Ash generated during the process falls to the bottom of the reactor together with the produced gases.

The heat source originates from the ignition flame at the beginning of the gasification process, as shown in Figure 3a. The combustion zone subsequently expands as its temperature gradually increases, reaching peak values of up to 1500^{0}C in certain regions. However, temperatures in surrounding areas remain comparatively lower, especially at the upper section of the gasifier where the agricultural residue–RDF mixture has not yet undergone gasification, as indicated by the temperature distribution and color gradients in Figure 3b.

In Figure 3b, the combustion zone continues to intensify and spread, representing the hottest region inside the gasifier. Once formed, the syngas flows through this high-temperature zone toward the outlet. The elevated temperatures promote the oxidation of tar compounds into CO, which is why the downdraft gasifier design inherently results in a syngas product with relatively low tar content.



(a) *(b)*

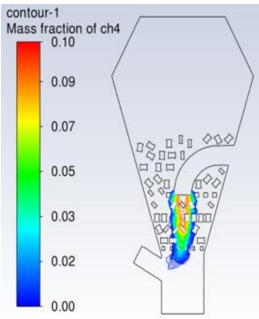
***Figure 3.** Temperature variation in the downdraft gasifier firing 65% RDF–35% rice husk with air (ER = 0.3)*

3.2. Effect of Injector Position

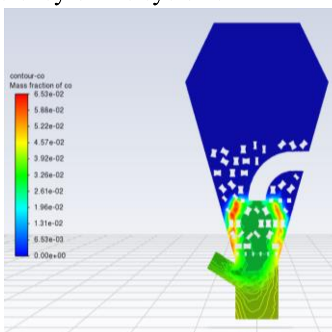
Figure 4 illustrates contour plots of CO, CH_4, and H_2 concentrations within the combustion zone of the gasifier. When ambient air is used as the oxidizing agent, the concentrations of combustible gases produced in the resulting syngas are relatively low. The concentrations of these combustible species are determined based on the thermodynamic equilibrium conditions of the gasification reactions. As shown in Figure 4a, the simulated CH_4 concentration forms only in very small amounts and is mainly concentrated near the air inlet region. In contrast, CO is generated at noticeably higher concentrations, with peak levels occurring near the outer boundary of the combustion-zone cross-section, as depicted in Figure 4b. Hydrogen, shown in Figure 4c, tends to form near the central portion of the combustion zone, particularly along the boundary layer where the oxidizing agent is introduced.

Figure 5a presents the simulation results showing that the concentrations of CO and H_2 increase significantly when oxygen-enriched air is used as the oxidizing agent in the gasification process (Figures 5b and 5c). This increase is particularly notable for CO concentration. The reason is that enriching the oxidizing air with additional oxygen increases the oxygen content while substantially reducing the nitrogen content in the oxidizer, thereby decreasing the amount of nitrogen present in the produced syngas. Nitrogen is an inert, non-combustible gas, and its reduction leads to a higher relative concentration of combustible gases such as CO and H_2, which in turn enhances the lower heating value of the fuel.

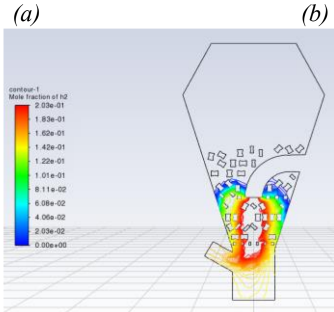
The peak combustion temperature also rises, as shown in Figure 5d, and the main combustion zone shifts toward the side opposite the air inlet. The maximum combustion temperature exceeds 2000^{0}K when 20% O_2 from an industrial oxygen cylinder is added to the air supply, compared to a maximum of about 1500^{0}K when only ambient air is used. The elevated temperature provides the necessary energy for pyrolysis-cracking reactions and localized oxidation processes, facilitating the decomposition of tar compounds into gases such as CO and H_2. The reduction in tar production results in a cleaner gas mixture, which helps protect downstream application equipment - such as internal combustion engines and gas turbines - from clogging and corrosion, while also improving the overall efficiency of the system.



(a)

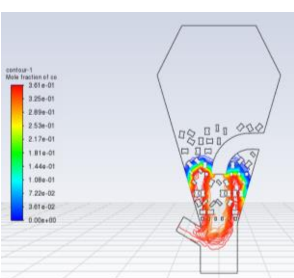


(b)

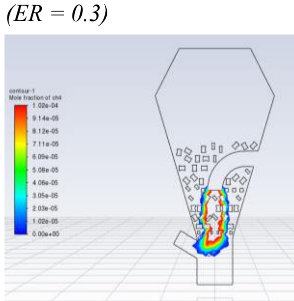


(c)

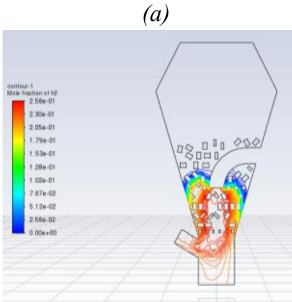
Figure 4. *Contour plots of CO, CH_4, and H_2 concentrations in the downdraft gasifier firing 65% RDF – 35% rice husk with air as oxidizer (ER = 0.3)*



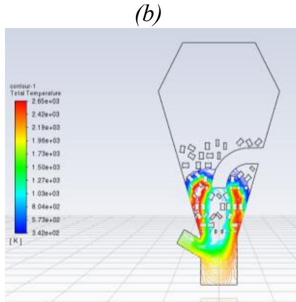
(a)



(b)



(c)

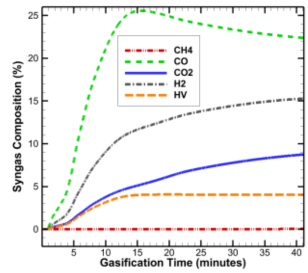


(d)

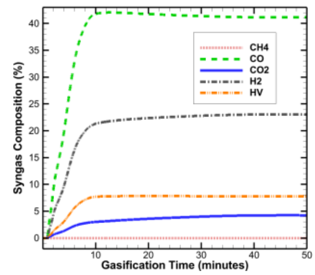
Figure 5. *Contour plots of CO, CH_4, and H_2 concentrations in the downdraft gasifier firing 65% RDF – 35% rice husk with air enriched with 20% oxygen (ER = 0.3)*

3.3. Effect of Oxygen Content in Air as an Oxidizing Agent on Syngas Quality in the Gasification Process

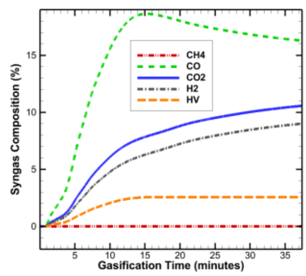
Figure 6 presents the simulation results of syngas composition after gasifying a 65% RDF – 35% rice husk mixture at ER = 0.3, 0.4, 0.5, and at ER = 0.3, 0.4, 0.5 with 20% O_2 enrichment. In the case where the oxidizing agent is solely ambient air, the concentrations of combustible gases such as CO, CH_4, and H_2 remain low (Figures 6a, 6c, 6e), and the simulation results show relatively poor stability. In contrast, when oxygen is added (Figures 6b, 6d, 6f), the concentrations of fuel components in the syngas increase and exhibit a more consistent linear trend.



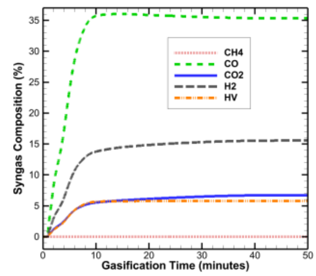
(a) ER = 0.3



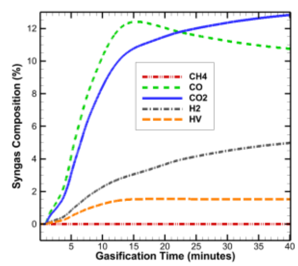
(b) ER = 0.3 (20% O_2 enrichment)



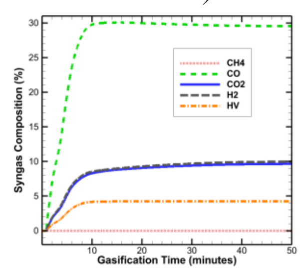
(c) ER = 0.4



(d) ER = 0.4 (20% O_2 enrichment)



(e) ER = 0.5



(f) ER = 0.5 (20% O_2 enrichment)

Figure 6. *Comparison of CO, CO_2, CH_4, and H_2 Concentrations in Gasification of 65% RDF–35% Rice Husk (ER = 0.3, 0.4, 0.5 with 20% O_2 Enrichment)*

With the addition of 20% oxygen, the concentrations of the combustible components increase steadily. At ER = 0.3, CO rises from 23% to 44%, while H_2 and CH_4 increase slightly from 15%–20% and 0%–5%, respectively, maintaining stability until the end of the gasification process. Similarly, at ER = 0.4, CO increases from 20% to 34%, and H_2 and CH_4 rise slightly from 7%–15% and 0%–5%. At ER = 0.5, the syngas fuel components reach their lowest levels, with CO, H_2, and CH_4 lower than at ER = 0.3 and ER = 0.4. However, when 20% oxygen is added, CO still increases significantly from 12% to 30%, H_2 rises modestly from 4%–10%, while CH_4 remains relatively low.

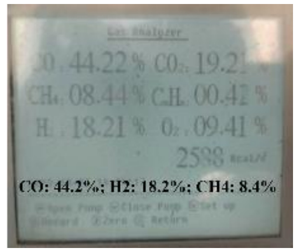
Oxygen enrichment of the air supplied to the gasifier raises the combustion temperature, which subsequently increases the temperature in the reduction zone. At the same time, the nitrogen concentration in the oxidizer decreases, thereby increasing the concentrations of combustible gases in the syngas and consequently enhancing the fuel's heating value. The elevated combustion temperature intensifies the reduction-zone reactions, promoting thermodynamic equilibrium among CO_2, CO, CH_4, H_2, and H_2O. Tar oxidation also becomes more pronounced, breaking down tar compounds into CO, which explains the increase in CO concentration when oxygen is added. H_2 increases slightly due to enhanced steam-reforming reactions. Under the condition of a fixed oxygen enrichment level, varying the ER demonstrates that CO concentration in the syngas changes accordingly as the ER increases from 0.3 to 0.5.

3.4. Experimental Evaluation of Oxygen-Enriched Gasification on Syngas Quality

The syngas fuel produced from the gasification of agricultural residues, including rice husk, sawdust, and RDF pellets blended at specific ratios, was used in this study. A small-scale downdraft gasifier was fabricated for the experimental investigation. The experimental setup is illustrated in Figure 7. This configuration ensures the production of cleaner syngas, making it suitable for use in internal combustion engines. After exiting the gasifier, the syngas is cooled and passed through a filtration system to remove remaining tar compounds and moisture. The cleaned syngas is then collected in gas storage bags for direct use or compressed into cylinders, enabling convenient transport and allowing the fuel to be utilized for various applications.

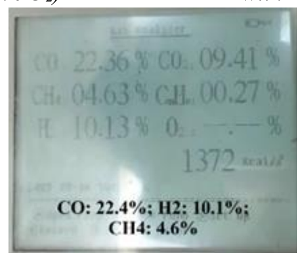
***Figure** 7. Experimental setup for gasification of syngas from waste by-products*

The final composition of the syngas fuel was measured using a Gasboard syngas analyzer (Figure 8). Each experimental run was conducted over a period of one hour, and multiple repetitions were performed to ensure reliability and minimize measurement errors.



(a) (ER=0.3 supplemented with 20% O_2)

(b) (ER=0.4 supplemented with 20% O_2)



(c) (ER=0.5 supplemented with 20% O_2)

***Figure 8.** Results of measuring the concentration of CO, CO_2, CH_4, H_2 from gasification of 65%RDF-35%rice husk (ER=0.3; 0.4; 0.5 and supplemented with 20% O_2) using Gasboard gas analyzer*

The experiments demonstrated a strong agreement between the simulated and actual gasification parameters. Under the same operating conditions with ER = 0.3 and ER = 0.4, and with 20% oxygen enrichment in the oxidizing air, the measured concentrations of CO and H_2 were 44.22% CO and 18% H_2, and 34.12% CO and 14.6% H_2, respectively. These values closely matched the simulation results, which predicted 44% CO and 22% H_2 at ER = 0.3, and 35% CO and 15% H_2 at ER = 0.4.

For ER = 0.5, the difference in CO concentration between simulation and experiment was approximately 8%, while CH_4 and H_2 concentrations remained largely consistent between simulation and experiment.

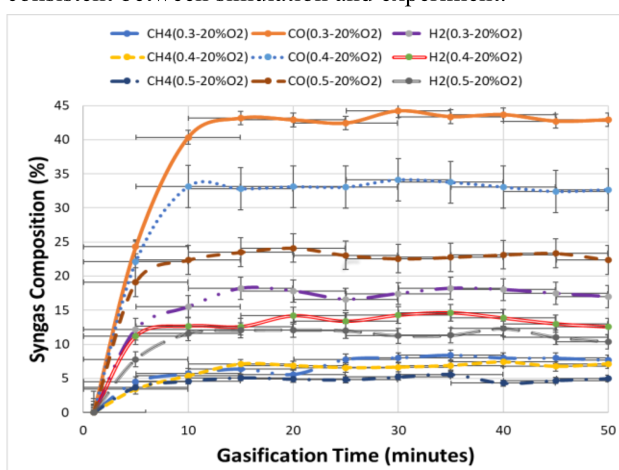


***Figure 9.** Experimental results of CO, CH_4 and H_2 concentrations analysis from gasification supplemented with 20% oxygen*

Overall, the combined simulation and experimental results confirm that enriching the oxidizing agent with 20% oxygen significantly increases the CO content in the produced syngas. The elevated oxygen concentration raises the temperature in the reaction zone, promoting the oxidation of tar compounds into CO. In particular, for downdraft gasifiers, this enhancement improves syngas quality, thereby increasing its potential as a renewable fuel (Figure 9). Oxygen enrichment substantially increases the combustion-zone temperature, which poses significant challenges to refractory material durability and increases the risk of ash melting (slagging) in fixed-bed gasifiers, issues not addressed in the present study.

4. Conclusion

Based on the above research results, the following conclusions can be drawn:

- The study demonstrated that using air enriched with 20% oxygen during the gasification of a mixed biomass (65% RDF – 35% rice husk) in a small-scale downdraft gasifier significantly improves syngas quality.

- Both simulation and experimental results show that oxygen enrichment substantially increases the combustion-zone temperature (reaching up to 2200K at ER = 0.3), promoting tar decomposition and gasification reactions. This leads to higher concentrations of combustible gases, particularly CO, which rises from 23% to 44%. At the same time, H_2 and CH_4 concentrations also increase slightly and remain stable.

- The reduction in N_2 content combined with the elevated reaction temperature raises the total fraction of combustible gases to 70% at ER = 0.3, thereby significantly enhancing the heating value of the syngas.

- These results confirm that oxygen-enriched air gasification is an effective approach to improve both the efficiency and quality of gaseous fuel derived from biomass, expanding its potential applications in renewable energy systems.

- Oxygen enrichment raises the combustion-zone temperature above 2200K, posing unresolved challenges related to refractory durability and slagging in fixed-bed gasifiers.

Acknowledgments: This research is funded by Funds for Science and Technology Development of the University of Danang under project number B2023-DN06-05.

REFERENCES

[1] United Nations, "COP 26: United Nations Climate Change Conference", *SEC Center in Glasgow, Scotland, UK*, 2021.

[2] S. Safarian, R. Unnthorsson, and C. Richter, "Simulation and Performance Analysis of Integrated Gasification–Syngas Fermentation Plant for Lignocellulosic Ethanol Production", *Biomass and Bioenergy*, vol. 138, p. 105603, 2020. doi: 10.1016/j.biombioe.2020.105603.

[3] A. Favero, A. Daigneault, and B. Sohngen, "Forests: Carbon sequestration, biomass energy, or both?", *Science Advances*, vol. 6, no. 14, p. eaay6792, 2020. doi: 10.1126/sciadv.aay6792.

[4] Y. M. Bar-On, R. Phillips, and R. Milo, "The biomass distribution on Earth", *Proceedings of the National Academy of Sciences (PNAS)*, vol. 115, no. 25, pp. 6506-6511, 2018. doi: 10.1073/pnas.1711842115.

[5] W. Phairuang *et al.*, "The influence of the open burning of agricultural biomass and forest fires in Thailand on the carbonaceous components in size-fractionated particles", *Environmental Pollution*, vol. 247, pp. 238-247, 2019. doi: 10.1016/j.envpol.2019.01.001.

[6] K. Uranishi, F. Ikemori, H. Shimadera, A. Kondo, and S. Sugata, "Impact of field biomass burning on local pollution and long-range transport of PM2.5 in Northeast Asia", *Environmental Pollution*, vol. 244, pp. 414-422, 2019. doi: 10.1016/j.envpol.2018.09.061.

[7] S. Yin *et al.*, "Influence of biomass burning on local air pollution in mainland Southeast Asia from 2001 to 2016", *Environmental Pollution*, vol. 254, p. 112949, 2019. doi: 10.1016/j.envpol.2019.07.117.

[8] U. Arena, "Process and technological aspects of municipal solid waste gasification. A review", *Waste Management*, vol. 32, no. 4, pp. 625-639, 2012. doi: 10.1016/j.wasman.2011.09.025.

[9] C. D. Rakopoulos and C. N. Michos, "Development and validation of a multi-zone combustion model for performance and nitric oxide formation in syngas fueled spark ignition engine", *Energy Conversion and Management*, vol. 49, no. 10, pp. 2924-2938, 2008. doi: 10.1016/j.enconman.2008.02.011.

[10] M. Fiore, V. Magi, and A. Viggiano, "Internal combustion engines powered by syngas: A review", *Applied Energy*, vol. 276, p. 115415, 2020. doi: 10.1016/j.apenergy.2020.115415.

[11] A. Molino, S. Chianese, and D. Musmarra, "Biomass gasification technology: The state of the art overview", *Journal of Energy Chemistry*, vol. 25, no. 1, pp. 10-25, 2016. doi: 10.1016/j.jechem.2015.11.005.

[12] T. Lieuwen, V. McDonell, D. Santavicca, and T. Sattelmayer, "Burner Development and Operability Issues Associated with Steady Flowing Syngas Fired Combustors", *Combustion Science and Technology*, vol. 180, no. 6, pp. 1169-1192, 2008. doi: 10.1080/00102200801963375.

[13] A. Pradhan, P. Baredar, and A. Kumar, "Syngas as An Alternative Fuel Used in Internal Combustion Engines: A Review", *Journal of Pure and Applied Science & Technology*, vol. 5, no. 2, pp. 51-66, 2015.

[14] V. G. Bui, T. T. X. Nguyen, Q. T. Nguyen, and D. P. Nguu, "Simulation combustion characteristics of syngas-biogas-hydrogen dual fuel engine", *Transport and Communications Science Journal*, vol. 75, no. 2, pp. 1213-1226, 2024. doi: 10.47869/tcsj.75.2.1.

[15] E. B. Machin, D. T. Pedroso, A. B. Machín, N. Proenza, and J. Carvalho, "Clean syngas generation by the application of the primary method for tar elimination in downdraft biomass gasification reactor," in *Proc. 13th Lat.-Am. Congr. Electr. Gener. Transm. (CLAGTEE)*, Santiago, Chile, Nov. 2019.

[16] M. T. Phung, V. G. Bui, and T. S. Tran, "Simulation and Experimental Study on Refuse Derived Fuel Gasification in a Downdraft Gasifier", in *Proceedings of the 3rd Annual International Conference on Material, Machines and Methods for Sustainable Development (MMMS2022)*, Cham: Springer Nature Switzerland, 2024, pp. 369-378. doi: 10.1007/978-3-031-48933-4_44.

[17] A. Surjosatyo, F. Vidian, and Y. S. Nugroho, "A Review On Gasifier Modification For Tar Reduction In Biomass Gasification", *Jurnal Mekanikal*, vol. 41, pp. 20-35, 2018.