

Experiment and Simulation of Rice husk Gasification Process with a Downdraft Gasifier

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In this study, the gasification of rice husk in a downdraft process is simulated by Aspen Plus software to predict an appropriate operation condition for designing small-scale equipment. Gibbs models of the reactions occurring in the process are applied for the simulation while tuning the equivalence ratio (ER) to forecast the syngas' compositions. Based on the analysis, ER value of 0.096 is selected to generate a syngas mixture consisting of CO (43.26 mol%), CH₄ (0.09 mol%), and H₂ (33.87 mol%), corresponding to the optimal calorific value of 8.92 MJ/kg and efficiency of 86.98 %. A real experiment is performed with the small-scale gasifier to evaluate the results obtained from the simulation. The pilot results show that not only the input air flow rate but other confounding factors also affect the combustion efficiency at some degree, which is compatible with the simulation model. The total energy value acquired from the conversion of 5.0 kg of dry rice husk was 86.82 MJ, while the energy value of the syngas obtained was 44.42 MJ syngas.

1. Introduction

The conversion of organic materials and hydrocarbons into syngas is known as gasification. Because of its capacity to generate greater energy sources of syngas and lower environmental effects (smoke, dust, fumes, volatile compounds, and toxic gases), this approach has the potential to replace existing combustion processes. (Mai and Nguyen, 2020). Syngas, including CO, CO₂, CH₄, and H₂, produced from biomass gasification can be optionally purified before being combusted. The combustion of gaseous fuels inherently has higher efficiency than solid matters. That is because the oxidation of a solid object in oxygen/air is gradually happening from its outer surface into the inner layers, which can be described as a heterogeneous process, while a combustive gas like syngas can be burned at a very high mass transfer rate in a homogeneous process (Mai and Nguyen, 2020). There are three main types of equipment, depending on the arrangement of the biomass flow and the gasifier agent that enters the device: updraft, downdraft, and cross draft. This study uses the downdraft device for rice husk gasification, with atmospheric air as the gasification agent.

Rice husk is an agricultural by-product of the rice growing process. After the harvest, rice husks are left in the field. Raw materials are abundant and cheap. Rice husk has a small density and low moisture content, which is suitable for combustion.

The gasification reaction is generally described in Eq(1) (Mai and Nguyen, 2020):



As a consequence of the aforementioned process, ash and tar are produced.

The raw material is rice husk, which is simulated by a non-conventional component consisting of carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and sulfur (S), and ash. Rice husk is fed at the top of the down-draft gasifier crossing reaction zones, including drying (250 °C), pyrolysis (250 – 500 °C), combustion (800 – 1,000 °C), and reduction zone (800 – 600 °C) (Rollinson, 2016) to transform into syngas. The reactions are defined according to the reaction region and the temperature of that region (Saleh and Samad, 2021).

This study uses the Aspen plus V.10 software to simulate the gasification process. The Gibbs free energy model is applied to the combustion and gasification regions to simplify the simulation. The equilibrium equations were synthesized and added to the model on Aspen software without adding other kinetic parameters. The reaction was carried out under Gibbs energy conditions suitable for gasification of the feedstock.

A tiny gasifier (gasification capacity of 5 kg rice husk/batch) is also set - up in an experiment on a modest production scale. The data is obtained in order to compare the control to the simulation software's result. These reports could provide preliminary assessment of the simulation model's relevance as parameters for the scale-up process and huge production.

2. Materials and methods

2.1 Material

Rice husk is collected from Thai My commune, Cu Chi district, Ho Chi Minh City, Vietnam. The material is dried before being brought to the lab and stored in a dry environment. The National Renewable Energy Laboratory methodology is used to analyse the fiber material component (NREL).

In Aspen Plus, Rice husk is described by non-conventional composition. In solids process modeling, the elemental components in Table 1 are entered in the software to determine the material.

2.2 Simulation description

Aspen plus software is being used to model the gasification process. As shown in Figure 1, this process is split into four processes corresponding to four reaction zones: drying, pyrolysis, combustion, and reduction.

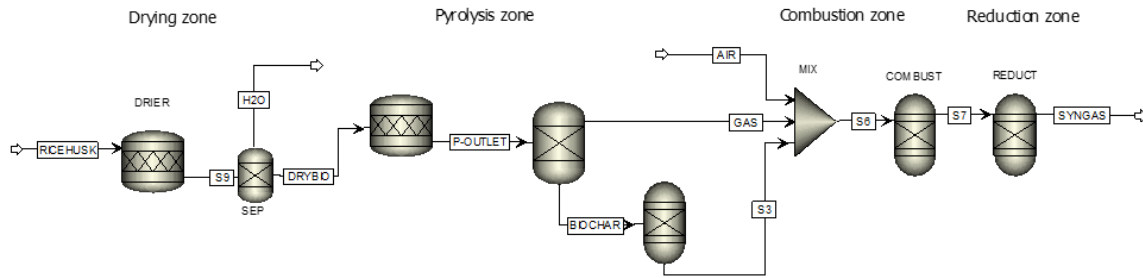
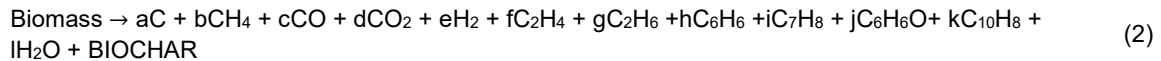


Figure 1: Aspen plus flowsheet of the downdraft gasification model

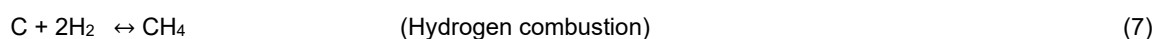
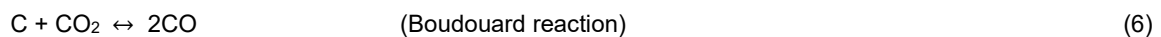
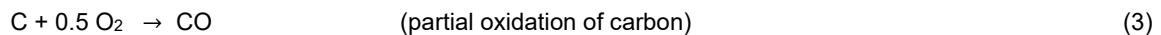
Drying zone: the moisture in the raw material is removed by heating it with temperature of 250 °C.

Pyrolysis zone: The material is pyrolyzed to diverse low molecular compounds and BIOCHAR - Eq(2) under the influence of high temperature (setting value of 500 °C) (Puig-Gamero et al., 2021). This biochar is split into smaller, non-equivalent components, produced in a mixture of H₂, O₂, N₂, C, and ash.



with a, b, c, d, e, f, ..., k, l are the numbers of moles C, CH₄, CO, CO₂, H₂, C₂H₄, C₂H₆, C₆H₆, C₇H₈, C₆H₆O, C₁₀H₈, and H₂O, and these are calculated according to the adjustment of moles mass balance (Neves et al., 2011).

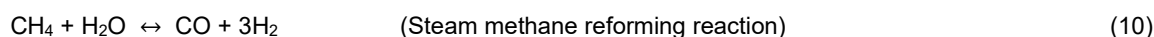
Combustion zone: the Gibbs free energy model is used to calculate the behavior of the mixture in this zone based on the reaction equilibrium coefficient (Jarungthammachote and Dutta, 2008). Under temperature of 1 000 °C, Oxygen gas in the air will react with intense combustion according to Eq(3), Eq(4) and (Eq5) at the reaction center. The product gases will react with carbon according to Eq(6) and Eq(7) but the reaction is an equilibrium reaction so it is slower.



Reduction zone: this zone occurs when carbon and carbon dioxide are reduced according to Eq(8) and Eq(9). For this reactions, the Gibbs free energy model is used to describe the process (Barba et al., 2011).



In this reduction zone, CH_4 and H_2O (steam) can react with each other according to a reaction called steam methane reforming (SMR) - Eq(10). With the downdraft gasifier when the agent is air, the steam in reduction zone generated consists of the moisture of the raw material and a smaller amount of steam generated in the combustion zone according to reaction 4. Because the Gibbs model will give preference to reactions 8 and 9, the amount of steam supplied is insufficient for SMR reaction. The temperature of the combustion zone and gasification zone is very large, in range 600 – 1,000 °C, the water in the feedstock has been rapidly vaporized and passed rapidly through the device. So in the above gasification model, it will be based on the SMR reaction theory to occur little and can be ignored when simulating the reduction zone.



In the SYNGAS flow, the product gas is produced at the end of the conversion process.

2.3 Experiment setup for rice husk gasification by air

Figure 2a shows the process flow diagram. Rice husk gasifier in the form of downdraft equipment with a batch yield of 5 kg.

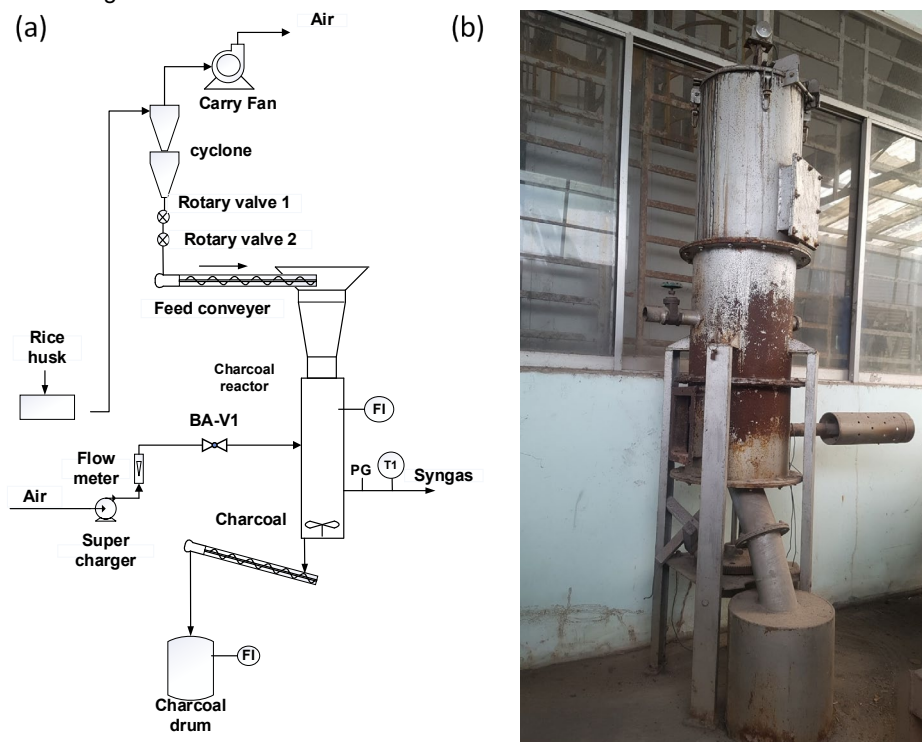


Figure 2: (a) Process flow diagram and (b) gasifier of the downdraft pilot-scale fixed-bed gasification.

The real gasifier is filled with rice husk (Figure 2b), and the gasification agent (air). The air is controlled by flow through the flowmeter. The syngas gas is cooled to room temperature (about 30 °C) before being analysed for components. In a charcoal drum, ash and burning material are not entirely contained at the bottom of the device. When gas flow is controlled in a flow meter with values of 0.5, 1, 1.5, and 2 $\text{Nm}^3 \cdot \text{h}^{-1}$, the device is run on equivalence ratio (ER) parameters of 0.032, 0.063, 0.095, and 0.127. The gasifying agent being air at a temperature of approximately 30 °C. The syngas composition in this experiment is analyzed with a TESTO 350XL gas meter.

2.4 Calculation formula

The equivalence ratio (ER) effect on gasification (Figuroa et al., 2014) is calculated using Eq(11).

$$ER = \left(\frac{A}{Y}\right)_{supply} / \left(\frac{A}{Y}\right)_{Stoi} \quad (11)$$

where: $\left(\frac{A}{Y}\right)_{supply}$ and $\left(\frac{A}{Y}\right)_{Stoi}$ is the amount of air supplied to the actual gasifier and according to the analytical method Shown in Eq(12).

$$\left(\frac{A}{Y}\right)_{Stoi} = \left(1 + \frac{y}{4} - \frac{z}{2}\right) \left(\frac{M_{O_2} + 3.76 M_{N_2}}{M_{biomass}}\right) \quad (12)$$

where M is the molecular mass (g/mol), the biomass has the molecular formula $C_xH_yO_z$.

The high heating value ($HHV_{biomass}$) and the low heating value ($LHV_{biomass}$) of biomass are calculated based on a dry ingredient according to Eq(13) and Eq(14) (Kirsanovs and Žandeckis, 2015).

$$HHV_{biomass} = 339.1C_{dr} + 1178.3H_{dr} + 100.5S_{dr} - 103.4O_{dr} - 15.1N_{dr} - 21.1 A_{dr} \text{ (MJ/kg)} \quad (13)$$

$$LHV_{biomass} = HHV_{biomass} (1 - M) - 2.44M \text{ (MJ/kg)} \quad (14)$$

where C_{dr} , H_{dr} , O_{dr} , S_{dr} , N_{dr} : the Fuel chemical composition on dry basis, %; A_{dr} : ash content in the Fuel on dry basis, %; h_{fg} : specific heat of vapor; M: the wet basis moisture content, %.

The low heating value (LHV) of syngas is the percentage of gas constitutes from our equilibrium model as shown in Eq(15).

$$LHV_{syngas} = 10.7H_2 \% + 12.6CO \% + 35.8CH_4 \% \text{ (MJ/kg)} \quad (15)$$

Cold gas efficiency (CGE) is the percentage of the energy of syngas gas at standard temperature conditions compared to the energy of biomass in theory shown in Eq(16).

$$CGE = (\omega \cdot LHV_{syngas} / LHV_{biomass}) \cdot 100 \text{ (\%)} \quad (16)$$

where ω is the weight of syngas production (including the weights of the gases CO, CO₂, and H₂) per the dry biomass.

3. Results and discussion

3.1 Components of rice husk

The elements C, H, N, O, and S are found in the rice husk and are listed in Table 1 below. The analysis indicated that rice husk represents a source of energy-seeking raw materials for the gasification process, containing up to 40.94 wt% carbon content. The water component for reactions in the reduction zone to generate H₂ and CO is provided by the moisture content of the material, which is 10.6 wt% (Pellegrini and de Oliveira, 2007).

Table 1: The characteristic properties of rice husk

Item	Value	Item	Value
Proximate analysis (wt%)		Elemental analysis (wt%)	
Moisture	10.6	C	40.94
Volatile matter	56.8	H	4.6
Fixed carbon	20.1	N	0.7
Ash	12.5	O	30.6
		S	0.06
$HHV_{biomass}$ (MJ/kg)	14.94	$LHV_{biomass}$ (MJ/kg)	13.02

3.2 The composition change of syngas according to the ERs ratio on Aspen plus simulation

When the ER changes, the syngas components in the product line differ significantly, as shown in Figure 3a. When the ER goes from 0 to 0.127, the CO content increases, indicating that the ER is rising and the CO content is declining. The initial CO₂ level is shallow (less than 1.0 mol%), then rapidly increases when the ER is more than 0.127.

In the combustion zone, when starting with a low rate of ERs, the amount of O₂ gas provided is moderate for reactions (3) and (4) to occur, further raising the ER, implying that more air volume, the amount of oxygen will be more than enough to fulfill all three reactions (3), (4), and (5), leading to a decline in H₂ levels and the creation of more CO and CO₂. At this point, the reactions will occur in the backward direction to rebalance the amounts

of H₂, resulting in additional CO₂ in reaction (8), and this CO continues to convert into CO₂ in reaction (9). The CH₄ gas content is low (less than 0.2 mol). In the reaction (7), just a tiny CH₄ is released.

When the ER rate increases from 0 to 0.096, LHV slowly declines from 9.85 to 8.93 MJ/kg. As the ER increases, LHV decreases quickly, and at 0.253, LHV is only 4.97 MJ/kg (Figure 3b). The change is based on a percentage of syngas gas moles (Including CO, CH₄, and H₂). When ER is lower than 0.096, the amount of CO rises, and CH₄ and H₂ decrease slowly, resulting in a subdued reduction in LHV. As the ER rises, the amount of CO₂ generated rises, and the amount of N₂ (inert component loaded in the air) increases rapidly, reducing the amount of CO, CH₄, and H₂. As a result, the LHV lowers significantly.

The initial ω value is 1.07 kg/kg (ER = 0), which comes to a peak value of 1.26 kg/kg (ER = 0.096), then dropped (Figure 3b). Cold gas efficiency (CGE) reached a peak of 86.98 % at the same ω value. So the optimal ER ratio design would be 0.096, with CO (43.26 mol%), CH₄ (0.09 mol%), and H₂ as syngas components (33.87 mol%).

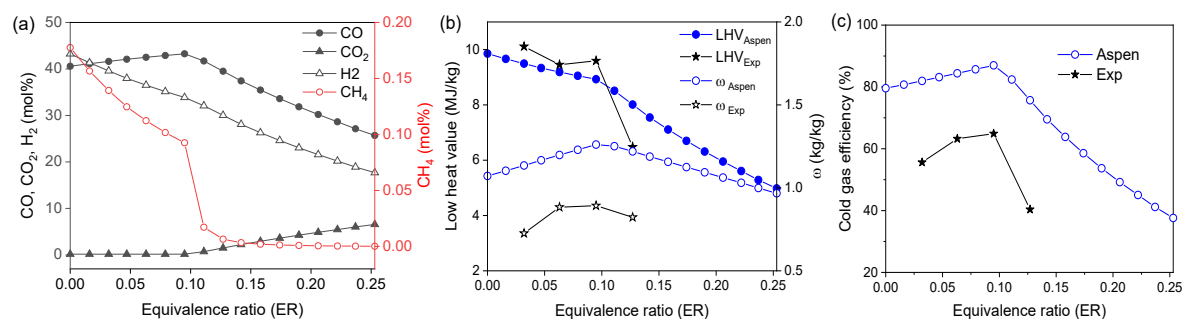


Figure 3: (a) Effect of ER on syngas composition in the Aspen Plus model, (b) Low heat value (LHV) and syngas production per weight biomass (ω) and (c) Cold gas efficiency of Aspen model and experimental model

3.3 Experimental results for rice husk gasification

The simulation model has described the change in gas composition of the real gasifier. In the process of gasification by down-draft gasifier, CO and H₂ accounted for the largest amount with CO accounted more than 40 mol% and H₂ is more than 30 mol%. Figures 4a and 4c show similarity in CO and H₂ concentrations in different ERs of the simulation model and the experiment gasifier. The differences are mostly less than 10 %. The CO₂ and CH₄ concentrations of the two models have a relatively large difference (probably more than 50 %), and the concentrations of CH₄ and CO₂ tend to change in the same way with increasing ER (Figure 4b, 4d). Since the concentration in the gas mixture is very small, with CO₂ concentrations less than 2 mol%, and CH₄ less than 0.5 mol%. The difference in measurement methods is the main cause. The very low concentration of CH₄ also supports the original assumption when simulating the gasification process, in the reduction region ignoring the SMR reaction. The highest concentration of CH₄ obtained by the real gasifier is 0.49 mol%, so the SMR reaction is not significantly affected until the syngas composition can be ignored to simplify the simulation. The LHV value of the experimental model corresponds to the Aspen model. The difference is less than 7 % at the ERs of 0.032 to 0.095 (Figure 3b). At ER of 0.127, more air supply leads to a rapid increase in N₂ content, which reduces the LHV value, which is similar as predicted by the Aspen model. The ω values of the two models differ by about 30 %. Part of the syngas is not collected in the product stream from the real gasifier, so the real gasification efficiency is lower than the simulated model. At ER of 0.096, ω value is 0.89 kg/kg, the highest efficiency is 64.88 % (Aspen Model is 86.98 %) for experiment model (Figure 3c).

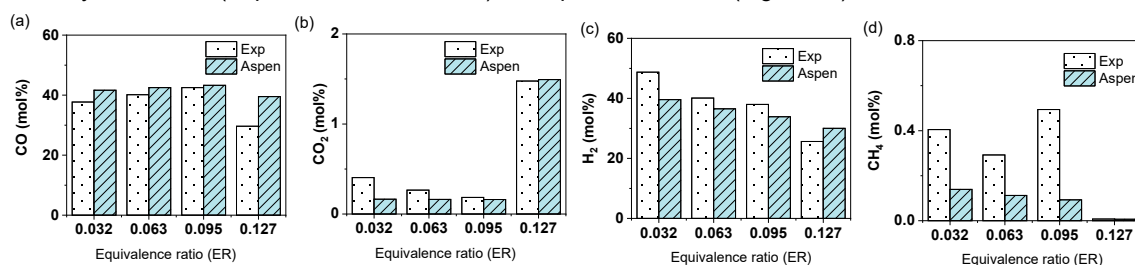


Figure 4: Comparison of (a) CO, (b) CO₂, (c) H₂, and (d) CH₄ concentrations between ASPEN PLUS and experiment model

Energy balance is also a part of checking energy flow (Table 2). Calculating total balanced energy based on the law of energy conservation, described according to Eq(17).

$$\text{Input energy [E}_{\text{rice husk}}(66 \text{ MJ}) + \text{E}_{\text{fan}}(1.11 \text{ MJ}) + \text{E}_{\text{conveyer}}(8.7 \text{ MJ}) + \text{E}_{\text{super-Charger}}(4 \text{ MJ}) + \text{E}_{\text{charcoal}}(6.97 \text{ MJ}) + \text{E}_{\text{air}}(0.04 \text{ MJ})] = \text{Output energy [(E}_{\text{syngas}}(41.42 \text{ MJ}) + \text{E}_{\text{ash}}(0.71 \text{ MJ}) + \text{E}_{\text{biomass loss}}(0.73 \text{ MJ}) + \text{E}_{\text{Heat loss}}(40.92 \text{ MJ})] = 86.82 \text{ MJ} \quad (17)$$

Table 2: Material and energy balance for the experimental model.

Stream/ Device	Input Weight (kg)	Energy (MJ)	Stream/ Device	Output Weight (kg)	Energy (MJ)
Rice husk	5.53	66.01	Syngas	4.63	44.42
Air	3.78	0.04	Ash	0.84	0.71
Fan	-	1.11	Inter gas	3.40	0.03
Coveyer	-	8.70	Biomass loss	0.06	0.74
Super-charger	-	4.00	Heat loss	-	40.92
Charcoal	-	6.97	-	-	-

4. Conclusions

The component analysis study indicated that rice husks are a potential biomaterial for syngas production. Down-draft gasifier simulation on Aspen plus, with ER of 0.096, syngas gas in the product line with the LHV of 8.92 MJ/kg, the ω value of 1.27 kg/kg, CGE peaking at 86.98 %. The experiment collected evidence proving that the simulation model on the software is aligned with actual fact when the ER is 0.096, the ω value of is 0.89 kg/kg, the LHV is 9.59 MJ/kg (CGE is 64.88 %), and the experiment's worse performance is due to loss and incomplete combustion. With 5.0 kg of dry rice husk, 4.63 kg of syngas with an energy value of 44.42 MJ is obtained.

Acknowledgments

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