Int. J. Renew. Energy Dev. 2023, 12(3), 601-614

Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.undip.ac.id

Research Article

Simulation and experimental study of refuse-derived fuel gasification in an updraft gasifier

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Abstract. Refuse-derived fuel (RDF) made from the mixture of wood and loose rice husk increases the porosity of the fuel in the furnace to facilitate the gasification process. Simulation results show that CO is concentrated in the incomplete combustion zone and CO_2 forms mainly in the fully burned area; CH_4 forms in the reduction region, while H_2 forms in the region of high temperature of the furnace. When the mixture composition was f=0.3, the CO concentration in the syngas reached about 21%, the H_2 concentration reached about 2% and the CH_4 concentration was too low to be ignored. When the mixture composition increased to f = 0.5, the CO concentration reached about 26%, the H_2 concentration remained almost unchanged and the CH_4 content increased to 6%. The calorific value of the syngas reached a maximum when f = 0.5 and the temperature of the reduction zone is in the range of 900K to 1200K. Air humidity affects CO concentration but not much on CH_4 and H_2 concentration as well as the syngas calorific value. The difference between simulation and experimental results is not more than 10% for CH_4 concentration and not more than 14% for CO_2 concentration. The power of the spark ignition engine is reduced by 30% when running on syngas compared to when running on gasoline.

Keywords: Refuse-derived fuel; Gasification; Updraft gasifier; Syngas; Waste to energy

Received: 22nd Oct 2022; Revised: 15th April 2023; Accepted: 1st May 2023; Available online: 7th May 2023

1. Introduction

In recent years, the ever-increasing demand for using fossil fuel in industrial and transportation activities have led to serious consequences like depletion of fossil energy and global warming (Mohapatra *et al.*, 2022; Nguyen-Thi and Bui, 2023; Zhao *et al.*, 2020). Thus, the human is looking for alternative and renewable energy sources aiming to complement the depleting fossil energy and prevent the climate change (Hoang *et al.*, 2023; Nagarajan *et al.*, 2022; Ugwu *et al.*, 2022). However, alternative energy sources must be sustainable so that it could be used for a long term and they do not compete with other (Almutairi *et al.*, 2023; Ilham *et al.*, 2022). As reported in literature, the existing renewable energy sources such hydropower (Forouzi Feshalami, 2018; Li and Saracoglu, 2021), wind (Chen *et al.*, 2022; Hassoine *et al.*, 2022), solar (Shahzad Nazir *et al.*, 2021; Shi and Luo, 2018), biomass (Duc Bui *et al.*, 2023; Ortiz-Alvarez *et al.*, 2022), and hydrogen (Kharisma *et al.*, 2022; S. J. Wang *et al.*, 2023) are available and abundant. Additionally, the population in the world is increasing, showing a large number of wastes could be released into environment every day that also cause the threat to the living environment (Bigdeloo *et al.*, 2021; Wowrzeczka, 2021). Due to this reason, using waste for producing energy has been become an emerging trend in recent years aiming to satisfy two main purposes: diversification of the energy source and mitigation of environment pollution (Bin *et al.*, 2022; Hoang *et al.*, 2022).

Waste-to-energy technology has been developed for many years and is increasingly shown to be an effective technology for domestic solid waste treatment (Chandrasiri *et al.*, 2022; Rasaidi *et al.*, 2022). Household waste can be an alternative energy source on account of the high heat capacity substances contained in it such as paper, plastic, rubber, and cloth, etc. (Gutberlet and Uddin, 2017; Hoang *et al.*, 2020; Nguyen and Le, 2021; Zahra *et al.*, 2022), and organic wastes such as biomass and food waste (Atabani *et al.*, 2022; Prasertpong *et al.*, 2023; Son Le *et al.*, 2022). However, waste could be converted into energy through refuse-derived fuel (RDF) (Stępień *et al.*, 2019) because the high density of RDF makes it easier to store and transport to the point of use, and this increases the homogeneity of the fuel in the energy conversion process (Maj *et al.*, 2022; Streier *et al.*, 2023). Recent studies show that there are many factors affecting the characteristics of RDF including both processing and material properties (Jewiarz *et al.*, 2020; Sprenger *et al.*, 2018). A number of studies confirm that the moisture content of 8-12 % gives the pellets a higher density and quality because the present of water increases the contact surface between particles by the Van der Waal force (Shahab Sokhansanj *et al.*, 2005; Styks *et al.*, 2020). The optimal compression pressure during the production of pellets depends on the input conditions of material because the porosity of the pellets has a strong impact on the gasification process (Lee, 2022; Mani *et al.*, 2006). Due to the main advantages of RDF such as reduction of solid waste volume and easy heat recovery, this technology is increasingly interested in the industry (Gałko *et al.*, 2023; Tejaswini and Pathak, 2023). In addition, waste gasification for heat recovery has been developed for many decades (Rahma *et al.*, 2021; J. Wang *et al.*, 2023). The gasification process can reduce 70% weight and 90% volume of

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https://doi.org/10.14710/ijred.2023.53994
ISSN: 2252-4940/© 2023.The Author(s). Published by CBIORE

solid waste, reduce greenhouse gas emissions, and save land used for landfills (Putro *et al.*, 2020; Shahabuddin *et al.*, 2020; Valizadeh *et al.*, 2022). Solid waste gasification is based on the principle of fuel combustion in an oxygen-deficient environment to produce syngas consisting of the main components CO, H_2, CH_4, CO_2 and N_2 (Jamro *et al.*, 2022; Tang *et al.*, 2022; Zuo *et al.*, 2022). Regarding the application of syngas from biomass or solid waste gasification, recent studies show that syngas could be used for power generation (Ali *et al.*, 2023; Shahavi *et al.*, 2022; Zhang et al., 2022). The above reviews show that converting solid waste into RDF pellets to produce syngas for power generation engines is a worldwide trend. The composition of rural waste is remarkably diverse, the quantity of waste is not uniform, thus the treatment system needs to be flexible in size, convenient in installation and movement. The equipment available on the world market can hardly meet simultaneously those requirements. This work focuses on researching RDF gasification from daily rural solid waste to power small generators aiming towards the goal of contribution to develop the use of energy recovered from solid waste.

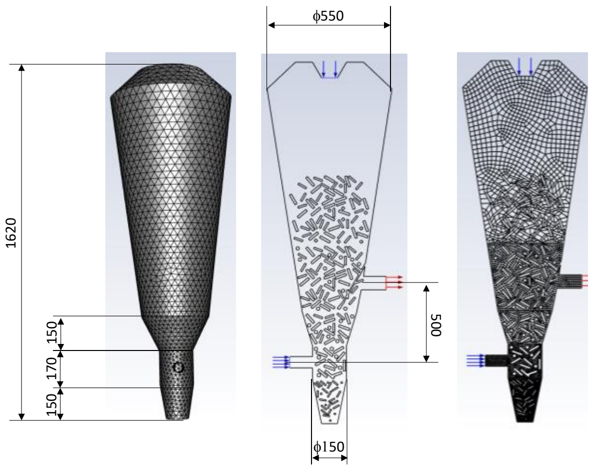


Fig 1. 3D simulation of gasifier (a), RDF distribution inside gasifier (b) and 2D spatial meshing of gasifier

2. Methodology

The study was conducted in an updraft gasifier with the basic dimensions shown in Figure 1a. The cylinder combustion chamber has a diameter of 150mm, and a height of 150mm. The reduction zone is cone-shaped with a height of 150mm. The pellet of RDF is cylindrical in shape with an average diameter of 10mm and a variable length. The combustion process of RDF, like other solid fuels, starts with a combustible mixture of the volatile organic compounds removed from the RDF and mixed with air. In this simulation the RDF pellets are randomly distributed in the gasifier owning variable surface temperature. To simplify the calculation, we simulate in 2D space as shown in Figure 1b.

The calculation space is divided into the following zones: ash pit zone, combustion zone, reduction zone, pyrolysis zone, drying zone and biomass storage zone. Thanks to the division of such areas, the parameters can be initially set up to investigate their influence on the gasification process. The boundary condition is defined as below:

- Fuel inlet: there is unique fuel inlet with the fluid flow Q_f and no combustion occurs (f=1, c=0),
- Air inlet: only air inlet with the flow Q_a and the combustion ignites once mixing with the fuel within the combustion limit (f=0, c=1). Q_a and Q_f are determined with a given equivalence ratio (ER) through the mixture composition f.
- The first mixture in the gasifier has an overall composition f according to the given ER.
- The temperature of different zones in the gasifier are set up aiming to study their effect on the gasification process
- Fuel composition is calculated according to the mass composition of the elements C, H, O and N specified in Table 1.

Note that the equivalence ratio (ER) in the simulation calculations can be defined as the actual air–fuel ratio (used in the gasification) to the stoichiometric air–fuel ratio for combustion and be determined through the mixture fraction f. Once the fuel composition was figured out, using the Coal Calculator in Fluent software for calculating the fuel molecular formula as well as the air-to-fuel ratio under theoretical combustion conditions. The fuels chosen in the simulation calculation are rice husk, biomass, coconut skull, wood, and domestic solid waste which own the composition of hydrogen and carbon element in increasing order and the oxygen element content in descending order. Therefore, the stoichiometric air-fuel ratio (A/F_{st}) calculated for rice husks, biomass, coconut skulls, wood, and municipal solid waste arrange in ascending order as shown in Table 1.

In this study, in addition to the use separately of the basic RDF mentioned above, a mixture of RDF from wood and rice husk was investigated for the aim of comparing the case of mixture with a single RDF. The gasification process is simulated through the local premixed combustion model, which is characterized by two constants quantities: the mixture composition f and the combustion process c being between values of 0 and 1. The air flow rate Q_a and the fuel flow rate Q_f are expressed by the value of ER. Figure 2 depicts the relationship between ER and mixture fraction f for rice husk, biomass, coconut skull, wood, and solid waste. In the simulation calculation, the ER value would be preselected corresponding to fuel, the mixture fraction f was determined next, and then the air-fuel ratio, as well as the mass flow rate of air Q_a and fuel Q_f, need to supply to the gasifier, would be calculated.

3. Experimental setup

3.1. Experimental system

The experimental equipment was set up as in Figure 3, in which the furnace (2) was designed in accordance with the updraft gasifier setting in simulation model. The ash discharging

Table 1
Composition and characteristics of fuels used in the simulation

Fuels	Element composition (%wt)				Fuel molecular formula	Stoichiometric air-fuel ratio (A/F_{st})
	C	H	O	N		
Rice husks	0.46	0.06	0.475	0.005	$C_{0,33}H_{2,85}O_{1,42}N_{0,0171}$	1.59
Biomass	0.48	0.06	0.457	0.003	$C_{0,41}H_{2,85}O_{1,37}N_{0,0102}$	2.05
Coconut skulls	0.502	0.057	0.434	0.007	$C_{0,50}H_{2,71}O_{1,30}N_{0,0239}$	2.47
Wood	0.5324	0.0636	0.4028	0.0012	$C_{0,62}H_{3,02}O_{1,20}N_{0,0041}$	3.65
Municipal solid waste	0.57	0.06	0.343	0.027	$C_{0,77}H_{2,85}O_{1,02}N_{0,0925}$	4.54

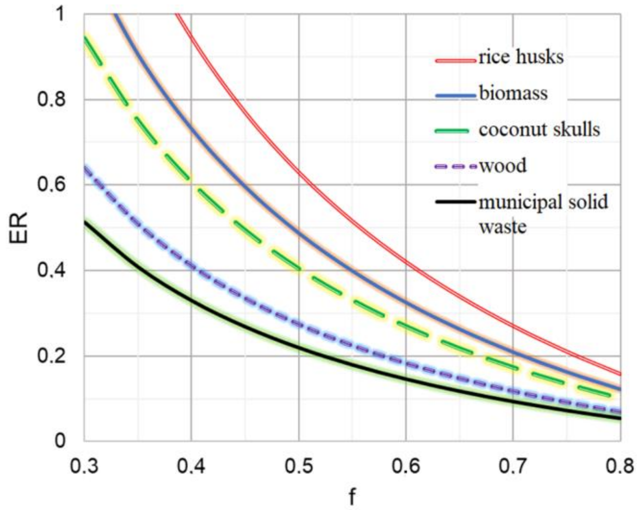


Fig 2. Relationship between ER and mixture fraction f for different feedstock

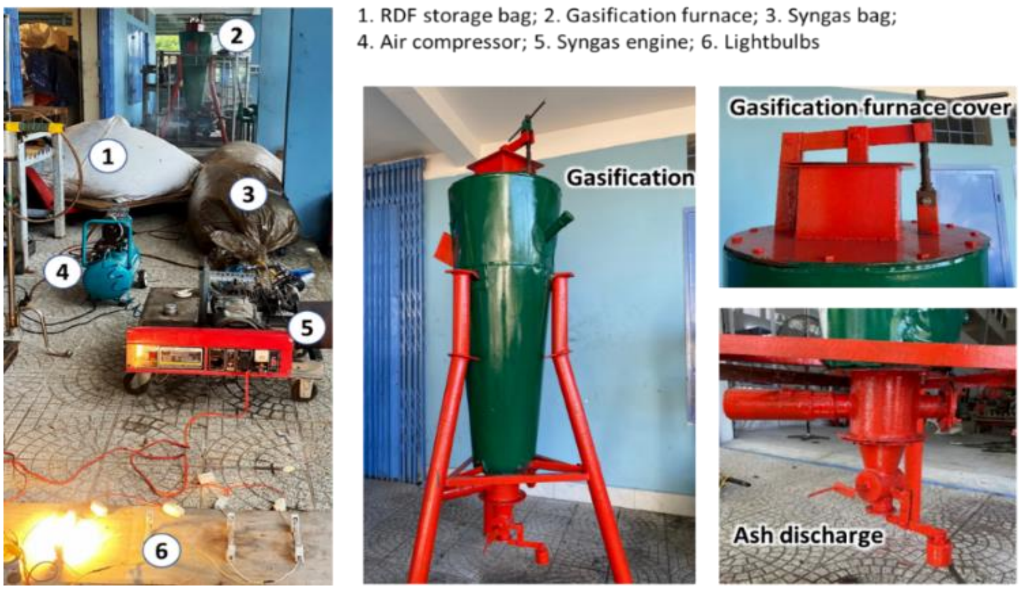


Fig 3. Experimental system of RDF gasification process

part is structured in the form of a reel with a closed lid based on the counterweight. RDF from bag 1 is supplied at the inlet. The syngas obtained from the gasification process is gathered into bag 3 before being pressurized by the air compressor 4 then fed into engine 5. The load capacity of the engine is measured through the electrical power consumed by 6 halogen lamps possess a total power of 2 kW.

3.2. Setting up the gasification furnace

Firstly, coating the furnace bottom with a layer of fine ash to prevent gas leakage during the operation of the furnace, then covering a layer of RDF to upper the fine ash layer. Start the furnace by burning about 0.5kg of RDF as a primer and put it inside the oven. Then put the mixture of RDF and rice husks into the oven. In each batch of experiments, putting 8kg of RDF into the oven mixed with 0.5kg of rice husk. Turn on the blower, adjust the air supply valve to the largest open position so that the air flow enters at a high speed to help the ignited RDF pellet primer easily spread to the main RDF in the furnace's combustion chamber. After closing the furnace lid, open the air supply valve to form combustion in the furnace until the amount of syngas generated can burn stably and maintain continuously. This takes about 5 minutes. Adjust air flow for best syngas quality (blue flame, steady burning). Once producing the syngas at their best quality, load them into the syngas bag. Note to periodically discharge the ash every 30 minutes. The syngas bag volume is around 964 litter. During the experiment, it is necessary to adjust the air blower at three different positions and measure the time to fill the syngas bag, aiming to calculate the syngas flow. In the process of loading syngas into the large bag, we extract a syngas part into the small bag for syngas analysis.

4. Results and discussion

4.1. Effect of raw materials on the quality of syngas

Figure 4 and Figure 5 present the contour lines of the variables affecting the gasification process like velocity, temperature, mixture fraction, and process variable, corresponding to RDF from solid waste and biomass with the same ER=0.35.

The mixture fraction f is 0.4 and 0.6 for solid waste RDF and

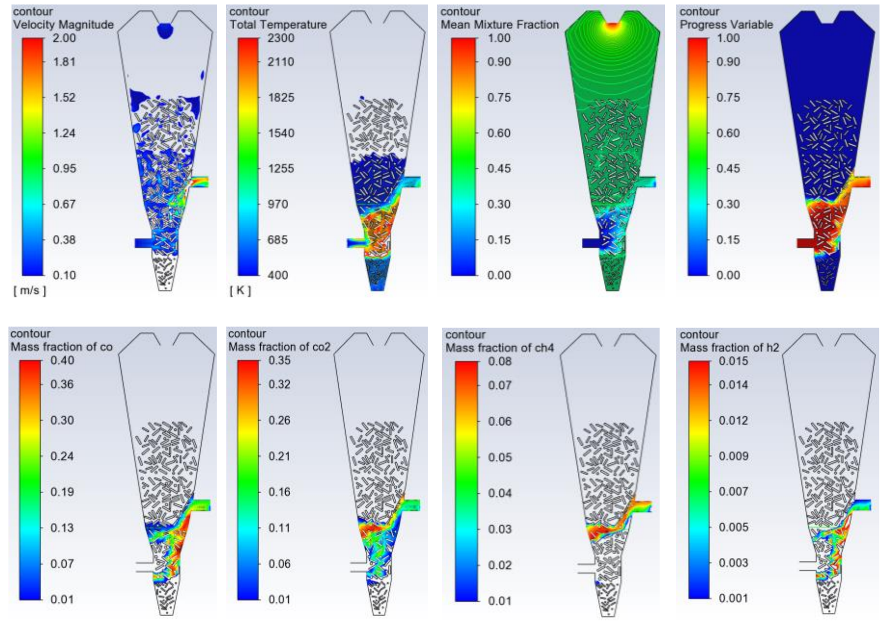


Fig 4. Contour lines of velocity V, temperature T, mixture fraction f, combustion process variable c and mass concentrations of CO, CO_2, CH_4, H_2 in syngas obtained from municipal solid waste with Qs=10g/s, f=0.4

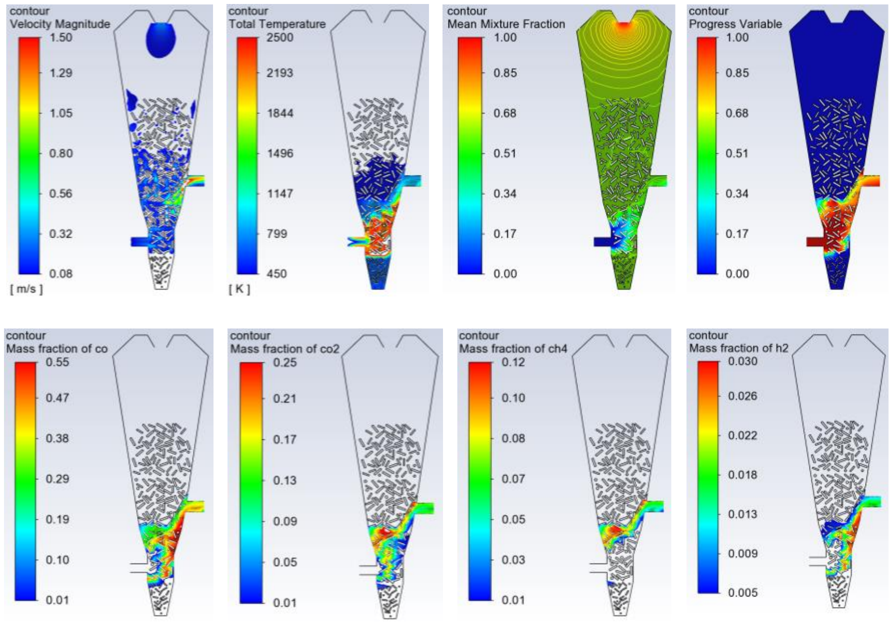


Fig 5. Contour lines of velocity V, temperature T, mixture fraction f, combustion process variable c and mass concentrations of CO, CO_2, CH_4, H_2 in syngas obtained from domestic solid waste with Qs=10g/s, f=0

biomass RDF, respectively. The result shows that there are no significant differences in the distribution of these variables in the gasification chamber operating at the same ER. However, the maximum value of the mixture fraction in the combustion zone and the reduction zone is different. The maximum concentrations of CO, CH_4 and H_2 in the combustion and reduction zones in the case of the RDF from biomass are all higher than the corresponding values in the case of one from domestic solid waste but the CO_2 concentration is the opposite (Kaniowski *et al.*, 2022; Tulu *et al.*, 2022). This is because, to achieve the same ER value, the Q_a/Q_f ratio of domestic solid waste RDF and biomass RDF is 3/2 and 2/3, respectively. The amount of air supplied to the furnace is superior in the case of domestic solid waste, leading to the complete combustion reaction to produce CO_2 being more favorable than the reduction reaction to create other components in the syngas (Kardaś *et al.*, 2018).

Figure 6 (a-d) compares the composition and calorific value of syngas obtained from RDF gasification of domestic solid waste (a), (b) wood, (c) biomass, and (d) rice husks with the same excess air coefficient ER=0.35. To ensure this value is kept constant, the mixture fraction f of RDF from domestic solid waste, biomass, wood, and rice husks is 0.4, 0.45, 0.6 and 0.65, respectively. This means the Q_a/Q_f ratio decreases gradually. According to the results proven in Figure 4 and Figure 5, when Q_a/Q_f is gradually reduced, the possibility of a complete combustion reaction decreases while the reduction reaction ability increases, so the CO_2 content decreases while the CO content increases. The content of CH_4 and H_2 in the syngas changes slightly according to the mixture fraction (Galvagno *et*

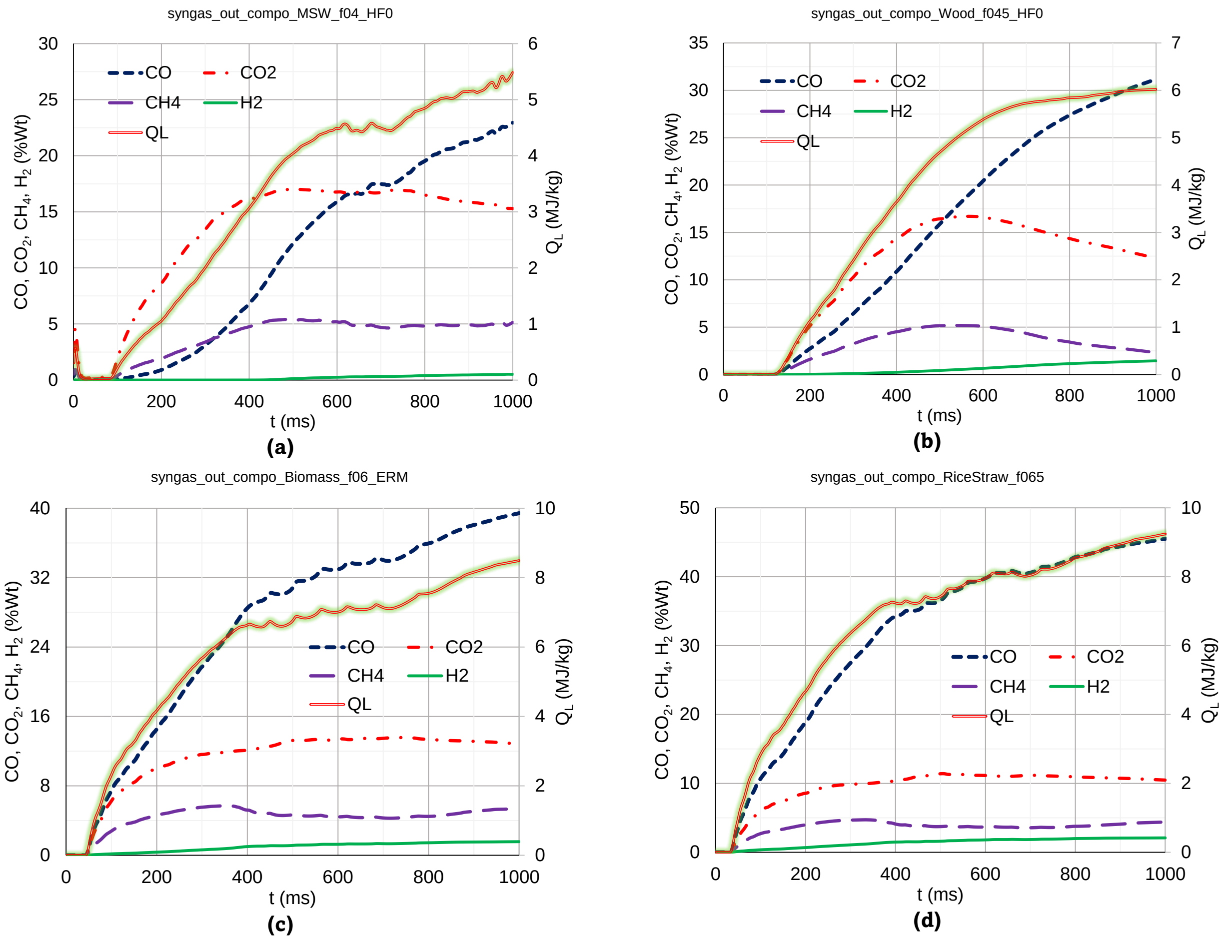


Fig 6. Comparison of the concentration of substances in the syngas and the calorific value of the fuel obtained from the RDF gasification of domestic solid waste (a), wood (b), biomass (c) and rice husk (d) with the same ER=0,35

al., 2006; Sittisun *et al*., 2019). Therefore, the calorific value of syngas when RDF gasification of domestic solid waste, biomass, wood, and rice husk at the same excess air coefficient ER = 0.35 is 5.5, 6, 8.5, and 9 respectively. When the mixture fraction f given is the same, the higher air–fuel ratio the fuel (A/F_{st}), the richer the mixture.

Figure 7 (a and b) compares the concentration by volume, concentration by mass and calorific value of syngas obtained from the gasification of rice husk, wood, and domestic solid waste with f=0.5. The A/F_{st} value for rice husk, wood and domestic solid waste is 1.59, 3.65 and 4.54 respectively (as shown in Table 1). With this ratio of 1.59, the rice husk is gasified in a poor mixture where CO_2 and H_2O have the condition to be converted into CO and H_2, so the CO_2 concentration is reduced. When the mixture is too rich, for example in the case of municipal solid waste owning A/F_{st} = 4.54, the reduction conditions become poor, CO is generated due to incomplete combustion and H_2O is converted to CH_4. For wood, with f = 0.5, the ER is in the range of 0.2 to 0.4, so it is an ideal gasification condition, thus the syngas calorific value reaches the highest value (Sharma *et al*., 2022b).

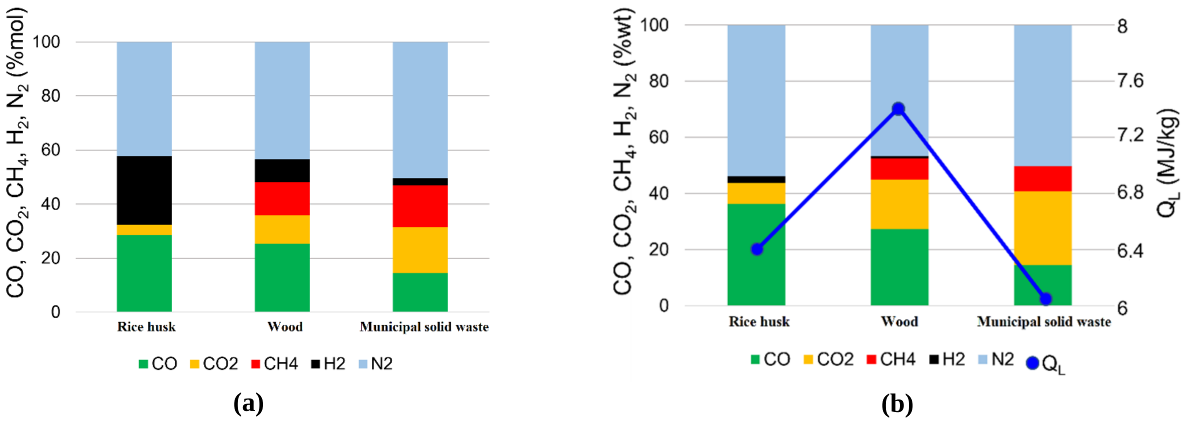


Fig 7. Comparison of volume concentration (a), mass concentration and calorific value (b) of syngas obtained from RDF gasification of rice husk, wood, and municipal solid waste f=0.5)

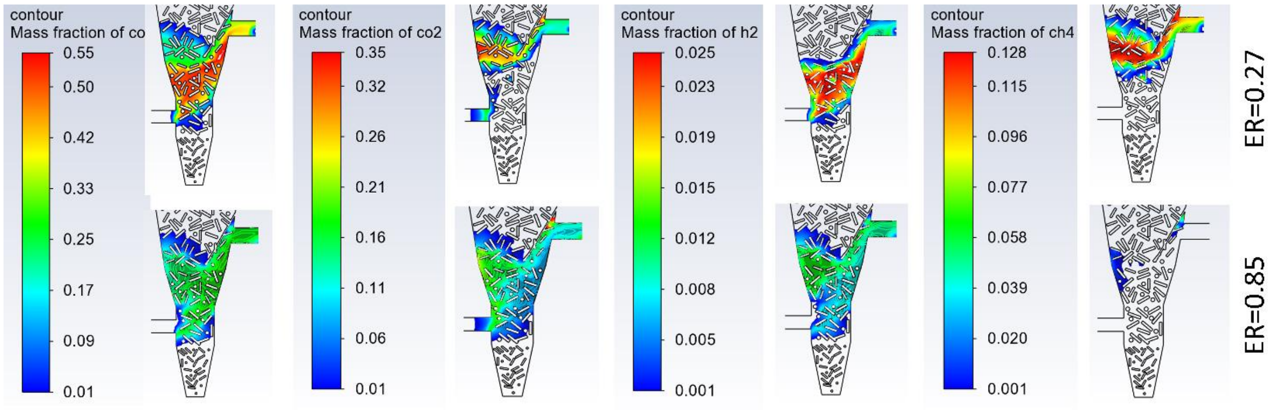


Fig 8. Comparison of the contour lines of CO, CO_2, H_2 and CH_4 concentration in syngas during gasification of coconut skull is with ER=0.27 and ER=0.85

4.2. Effect of the mixture fraction f

Figure 8 introduces the concentration contour lines of CO, CO_2, CH_4 and H_2 when gasification of coconut skull with ER = 0.27 and ER = 0.85. The fuel combustion process is concentrated near the air inlet area. The reaction zone includes both the burning area and the reduction area (where the data of the combustion process is shown in red in Figure 8). The simulation results have shown that the highest concentration of CO is concentrated in the incomplete combustion zone (lack of air), as well as the reduction zone where CO_2 converts to CO. A residual amount of CO_2 is concentrated in the upper part of the reduction area. Similar CO, H_2 forms in the high-temperature region, in the reduction section (Ferreira *et al.*, 2021; Rosha and Ibrahim, 2022). The results obtained from two cases of different ER values displayed that when the mixture is poor, the concentrations of CO, CH_4, H_2 are lower than in the case of rich mixture (Cai *et al.*, 2021). Especially when the mixture is poor, the zone of CO_2 production becomes enlarged, and the gasification zone restricts since a large amount of air inlet leads to completely burning most of the fuel (Veses *et al.*, 2020).

Figure 9 presents the variation of the CO, CO_2, CH_4, H_2

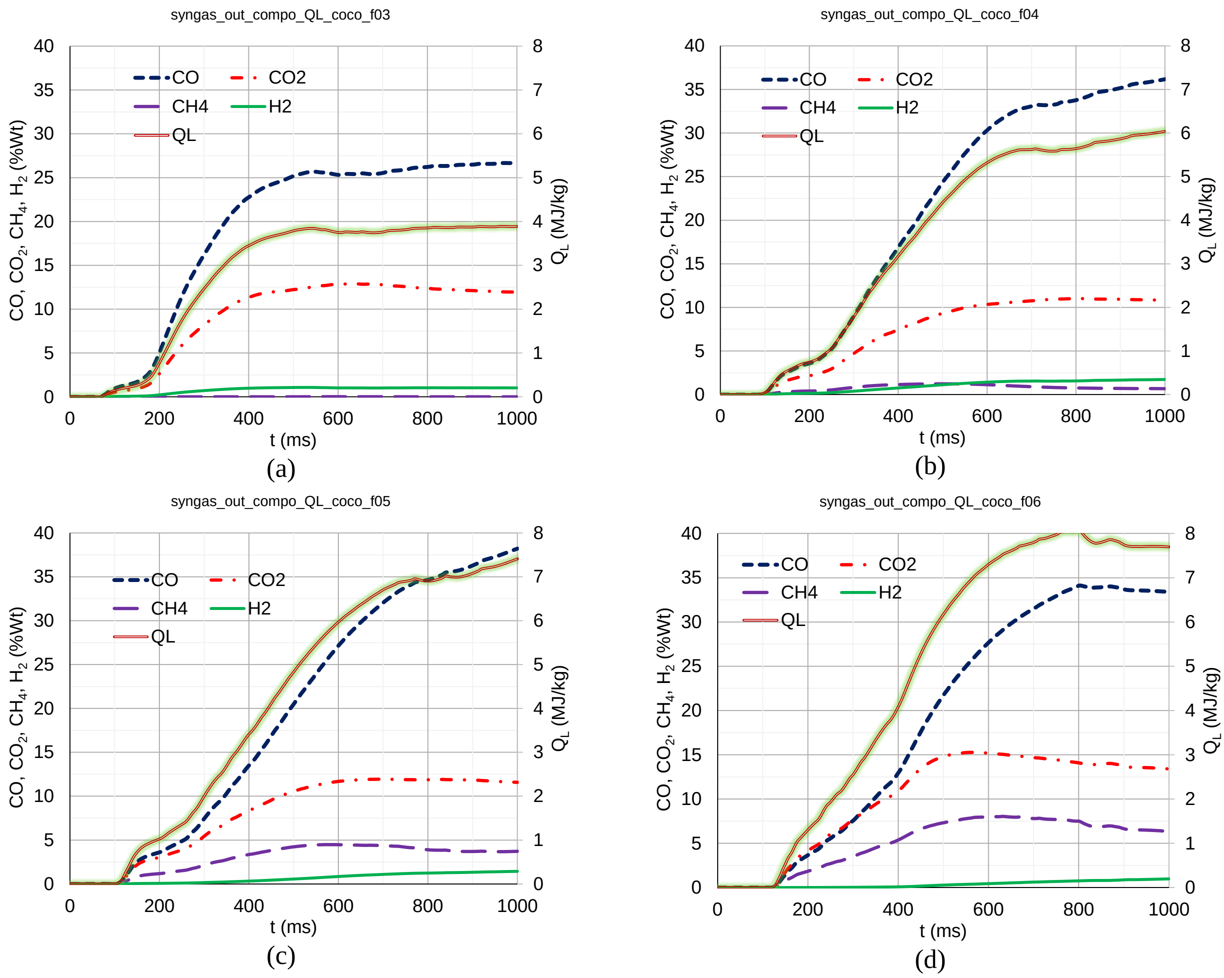


Fig 9. Composition and calorific value of syngas obtained from gasifying coconut skull with f=0.3 (a), f=0.4 (b), f=0.5 (c) and f=0.6 (d)

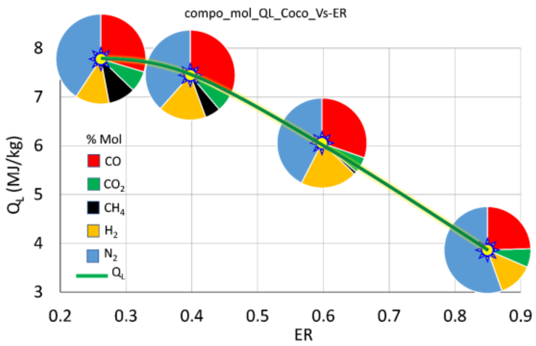


Fig 10. Variation of syngas composition and fuel calorific value according to ER during gasification of coconut skull

concentration in the syngas over the calculated time correlating with the different value of the mixture fraction f. It can be seen that the syngas composition remains a stable value after just about 100ms with the fuel supply condition mentioned above. When the mixture fraction f = 0.3, the CO concentration in the syngas reaches about 20%, the H_2 concentration reaches about 2% and the CH_4 concentration is very low, can almost be ignored.

When the mixture fraction increased to f = 0.5, the CO concentration reachs about 37%, the H_2 concentration remains almost unchanged and the CH_4 content increases to 4%. This result justifies that when the mixture is rich, the CO concentration increases, one side due to incomplete combustion, other side due to the conversion of combustion products. When gasification process takes place in dry conditions, H_2 is produced mainly due to the decomposition of substances in combustion products. A part of H_2 is formed during combustion, but soon it reacts with CO or C and procedures CH_4. In thermodynamic equilibrium, the concentration of H_2 increases once the concentrations of CO and CH_4 decrease (Wang *et al.*, 2022).

Figure 10 illustrates the variation in the syngas composition as well as the calorific value of the fuel according to the excess air coefficient ER when gasifying the coconut skull. When the ER decreases, the CH_4 content in the syngas increases and the H_2 content decreases. The fuel calorific value increases rapidly when ER is reduced from 0.9 to 0.4. If ER continues to decrease, the calorific value of syngas is almost insignificant due to the decrease in H_2 and the increase in CO_2. Therefore, it is necessary to choose the ER value between 0.3 and 0.4 to ensure the efficiency of gasification process.

4.3. Effect of temperature in the gasification zones

Figure 11 presents the variation of syngas composition corresponding the mixture fraction f=0.5 and the temperature at the reduction zone T_k=800K (Figure 11a) and 1190K (Figure 11b), respectively. It can be found that the temperature of the reduction zone has almost a very slight effect on CH_4 and H_2 content but strongly affects the conversion of CO_2 to CO. At the temperature T_k=800K, the CO concentration is about 25% and the CO_2 concentration is about 24%. When the reduction temperature increases to 1190K, the CO concentration reaches 30% and the CO2 concentration decreases to 19%.

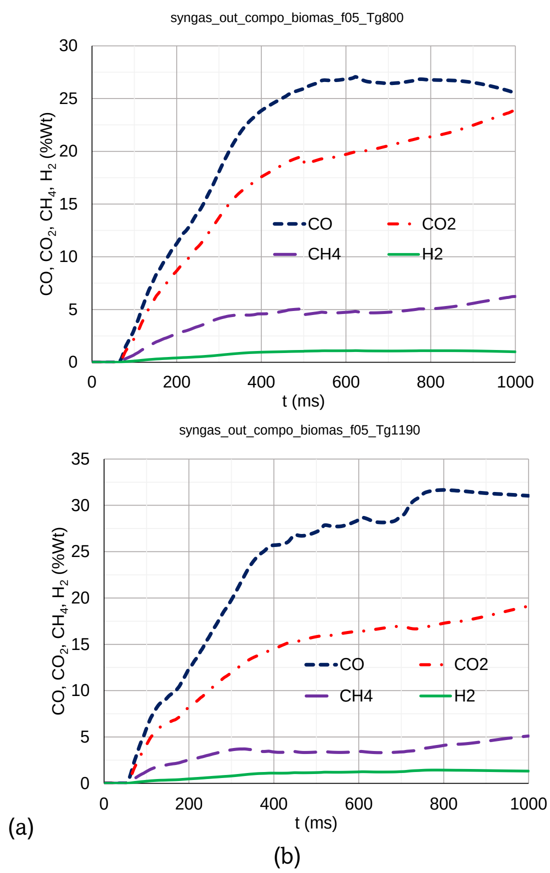


Fig 11. Effect of temperature at the reduction zone on the syngas composition, (a) Tk=800K, (b) 1190K

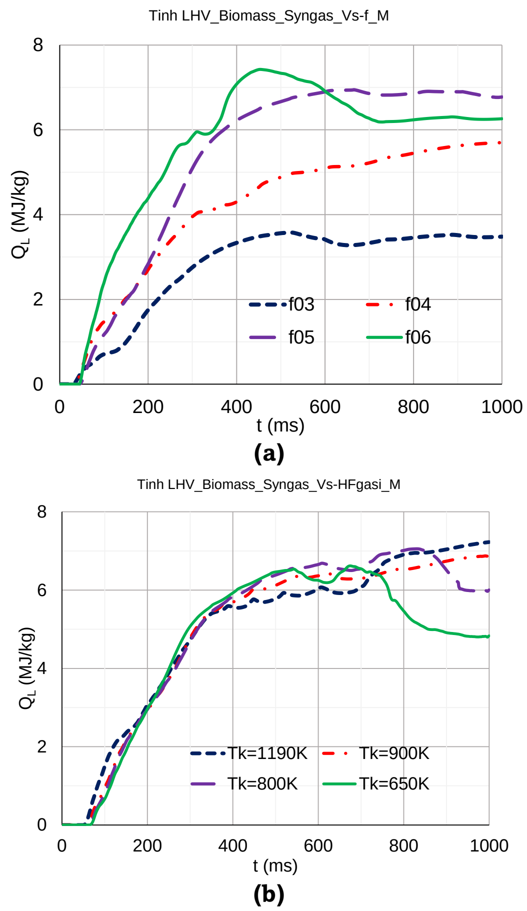


Fig 12. Effect of the mixture fraction f, (a) and the temperature of the reduction zone (b) on the calorific value of syngas

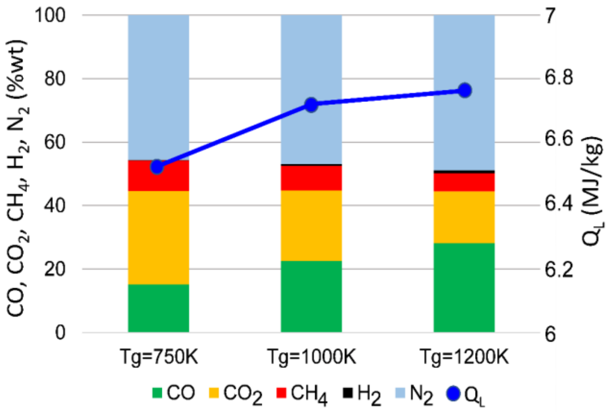


Fig 13. Effect of temperature of the reduction zone on the composition and calorific value of syngas from wood corresponding with f=0.45

The calorific value of syngas is instituted from the specific calorific value of CO, CH_4 and H_2. The low calorific value of CO, CH_4 and H_2 is 10 MJ/kg, 50 MJ/kg and 120 MJ/kg, respectively. Therefore, the syngas calorific value can be calculated easily once knowing the mass composition of the syngas. Figure 12a introduces the influence of the mixture fraction on the syngas calorific value when the temperature of the reduction zone is Tk=1000K. It can be seen that the calorific value increases from f=0.3 to f=0.5. When f increases beyond 0.5, the calorific value of the syngas begins to decrease. The low calorific value of syngas obtained from RDF biomass gasification is in the range of 6 to 7 MJ/kg and reaches the maximum value when the temperature of the reduction zone is in the range of 900K to 1200K (Figure 12b). When the temperature of the reduction zone is less than 900K, the syngas calorific value decreases rapidly.

Figure 13 introduces the effect of the temperature of the reduction zone on the composition and calorific value of syngas obtained from wood gasification corresponding with a mixture fraction f=0.45. The results show that when the temperature of the reduction zone increases, the CO content increases but the CH_4 content decreases. When the temperature of the reduction is greater than 1000K, the calorific value of syngas has only a

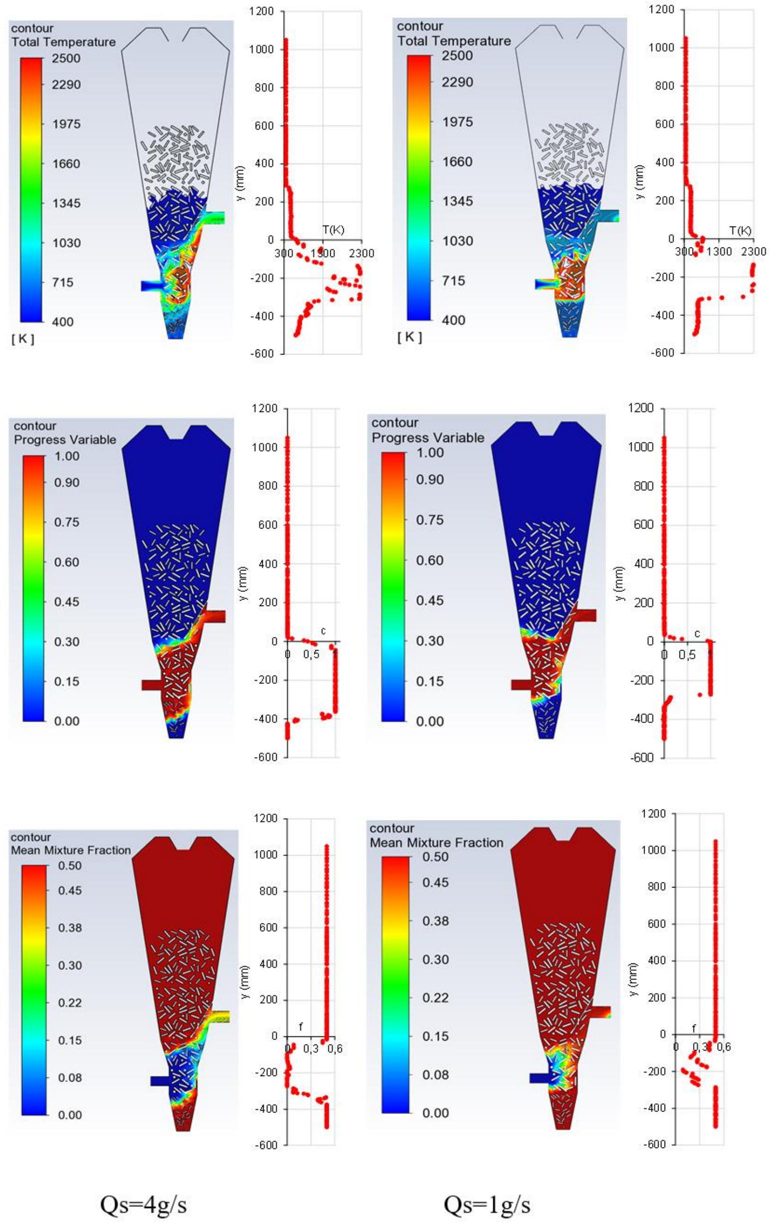


Fig 14. Effect of syngas flow on gasification process (with rice husk – RDF and mixture fraction f=0.5)

very slight increase. This is due to the calorific value of CH_4 is much larger than the calorific value of CO (B. Wang *et al.*, 2023). Therefore, these results confirm that the optimal temperature of the reduction zone for biomass gasification is in the range of 900K-1000K.

4.4. Effect of air flow rate supplied into the furnace on the quality of syngas

Figure 14 shows that when increasing the air flow and keeping the ER value unchanged, the combustion zone is expanded, expressed in the zone where f=0 or c=1. When the syngas flow is 1g/s, the zone where f=0 is narrow, concentrated near the inlet gate. At this condition, the temperature of the combustion zone is almost homogeneous. But when the syngas flow increases to 4g/s, the area with f=0 almost envelopes the whole combustion chamber, the burning area is deflected to the opposite side of the inlet gate and the temperature upper the symmetry axis of the furnace in the burning area fluctuates sharply (James R *et al.*, 2018). The expansion of the combustion zone when increasing the flow rate of air supplied to the furnace can disrupt the reduction zone and affect the quality of the syngas (Ren *et al.*, 2022). Therefore, to keep the combustion area stable, the ash discharge rate must be increased so that the RDF drops faster.

Figure 15 introduces the effect of flow rate (2g/s (Figure

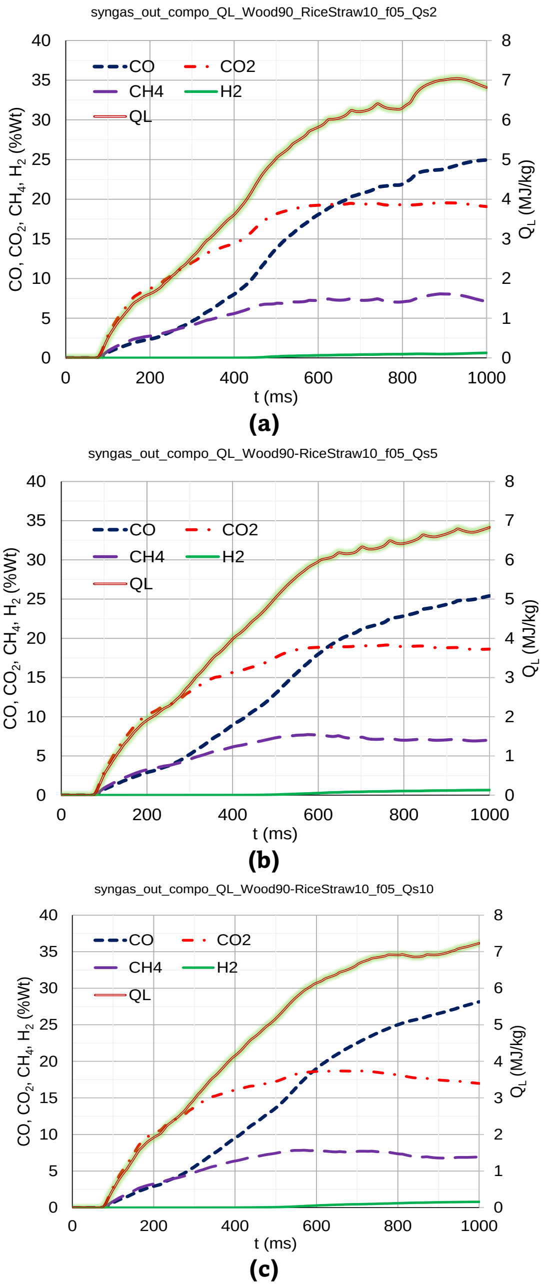


Fig 15. Variation of the concentration of substances in the syngas when gasifying a mixture of 90% wood RDF and 10% rice husk RDF with the airflow rates of 2g/s (a), 5g/s (b) and 10g/s (c)

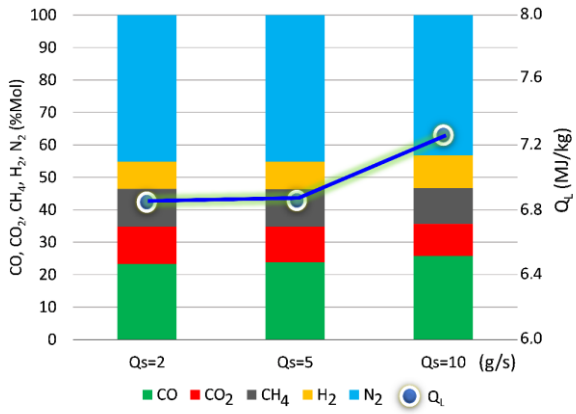


Fig 16. Variation of the concentration of substances in the syngas and change of calorific value according to flow rate of syngas obtained when gasifying the mixture of 80% wood RDF and 20% rice husk RDF with f=0.5

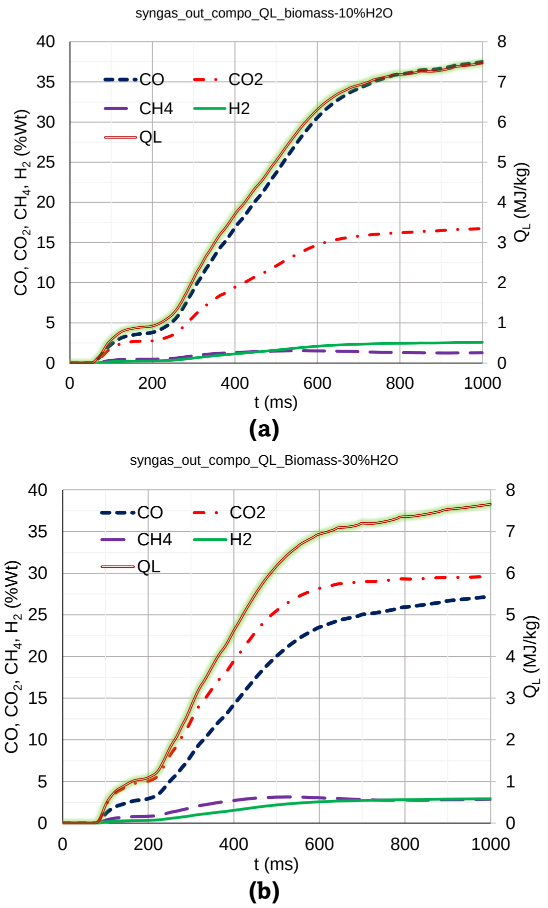


Fig 17. Composition and calorific value of syngas corresponding with the air humidity of 10% (a) and 30% (b) (with biomass RDF, f=0.5)

15a), 5g/s (Figure 15b) and 10g/s (Figure 15c)) on the gasification of the mixture of 90% wood RDF and 10% rice husk RDF. Apparently, when the flow rate is below 5g/s, the syngas composition and the calorific value do not have a significant variance. But when the flow rate is greater than 5g/s, the contents of CO and H_2 augment slightly, leading to an increase of about 6% of the syngas calorific value. This can be explained by the fact that when the airflow increases, the burning rate augments, which rises to the temperature of the reaction zone, making the gasification process more favorable (Mondal, 2022).

Figure 16 introduces the variation of the syngas composition and the calorific value of the fuel according to flow rate of syngas obtained when gasifying the mixture consisting of 80% wood RDF and 20% rice husk RDF. As the flow rate increases, the molar concentrations of CO and H_2 increase while the concentration of CH_4 decreases slightly. When the syngas flow is less than 5g/s, the syngas calorific value is almost unchanged. When the syngas flow is greater than 5 g/s, the syngas calorific value increases slightly. Thus, simulation calculations show that the gasifier gives a stable calorific value when the flow of syngas generated is in the range from 5 m^3/h to 30 m^3/h.

4.5. Effect of air humidity

Figure 17 compares the syngas composition when supplying the air humidified at value of 10% (Figure 17a) and 30% (Figure 17b). It can be found that when the air humidity increases from 10% to 30%, the H_2 content is almost unchanged, but the CH_4 content increases by nearly 50%, the CO content decreases by 30% and the CO_2 content increases by nearly 80%. Although the calorific value of syngas increases by about 1% when the air humidity increases from 10% to 30%, a high CO_2 concentration in syngas affects its combustion quality when applied to internal combustion engines. Therefore, increasing the humidity of the air supplied into the gasification of the biomass RDF is not beneficial (Sharma *et al.*, 2022a).

Figure 18a shows that the CO_2 concentration increases very rapidly with the air humidity while the CO content decreases. In return, the concentrations of CH_4 and H_2 in the syngas increase, so the calorific value of the syngas hardly changes significantly. This can be explained by the evaporation of the humidity content in supplied air, which lowers the temperature of the combustion zone and the reduction area, which affects the gasification process.

Figure 18b shows that when increasing the humidity of the air, the temperature of both combustion and reduction zones decreases. This leads to a diminution in the reaction rate of CO formations. However, the presence of a higher water vapor content in the reaction area improves the H_2 and CH_4 concentrations in the syngas. When the temperature in the gasification area rises, the CO content in the syngas increases while the CO_2 concentration decreases being connected with the favorable reduction reactions (Zhao *et al.*, 2021). However, this has the drawback that the CH_4 content decreases, resulting in the syngas calorific value hardly changing significantly, as shown in Figure 19a (T =1197K) and Figure 19b (T =1395K).

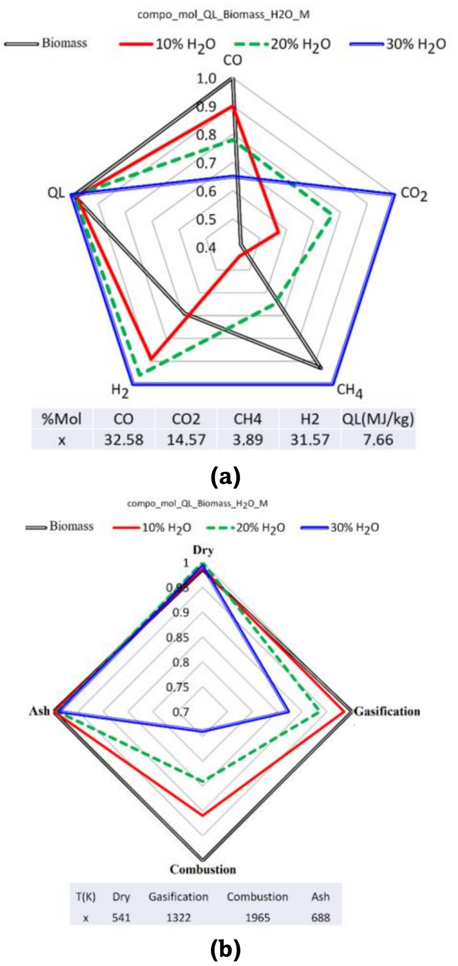


Fig 18. Effect of air humidity on the calorific value and composition of the syngas (a) and on the temperature of different zones in the gasifier (b) (biomass RDF, f=0.5)

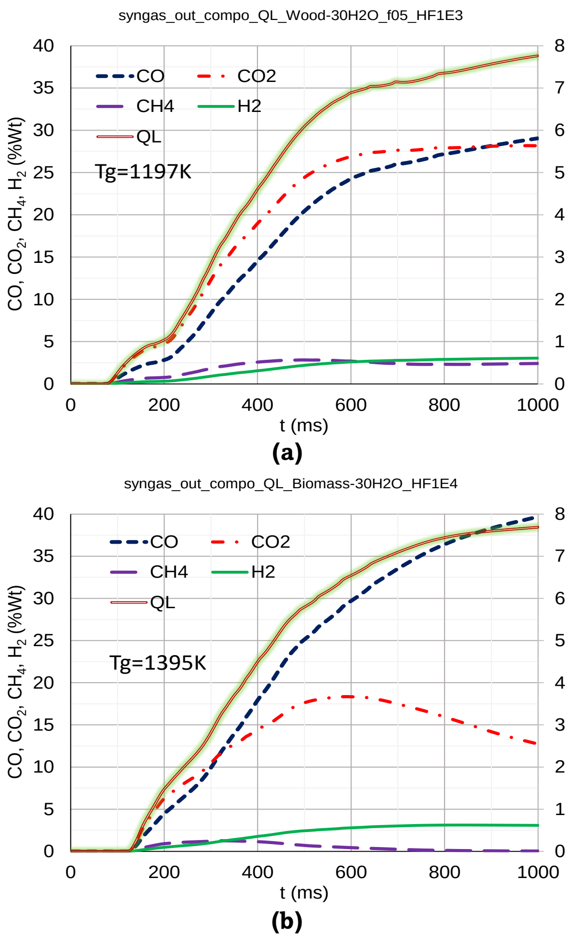
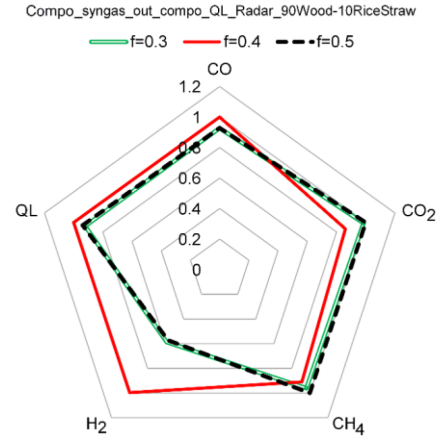
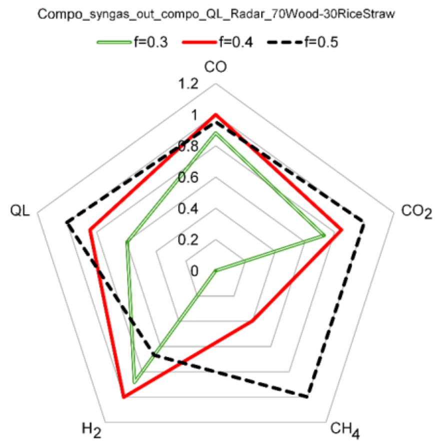


Fig 19. Effect of the gasification temperature on syngas composition and calorific value when gasifying biomass with air at 30% of humidity and f=0.5



%wt	CO	CO_2	CH_4	H_2	Q_L (MJ/kg)
x	26.87	19.08	7.11	1.12	7.26

(a)



%wt	CO	CO_2	CH_4	H_2	Q_L (MJ/kg)
x	30.48	17.3	6.13	1.48	7.15

(b)

Fig 20. Effect of the mixture fraction f on syngas composition and calorific value when gasifying the mixture of 90% RDF wood+10% rice husk (a) and the mixture of 70% RDF wood mixed 30% rice husk (b)

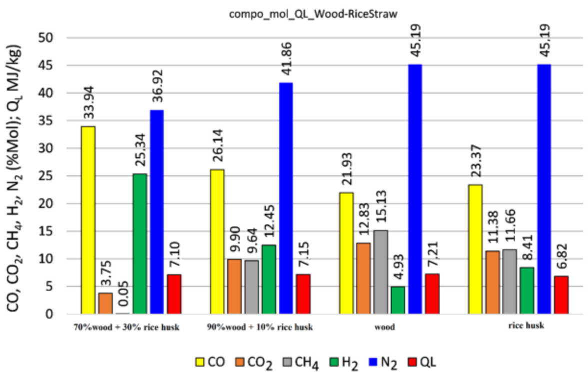


Fig 21. Effect of RDF constitution on composition and calorific value of syngas in case of Qs=2g/s and f=0.5)

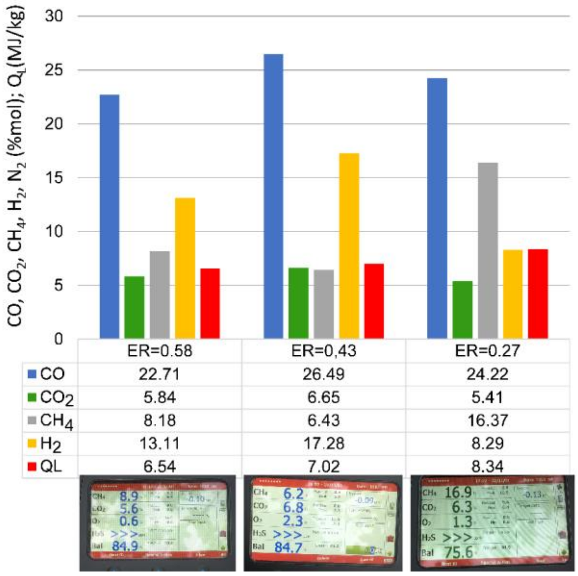
4.6. Effect of RDF mixture on the gasification process

The raw materials used to produce RDF have a wide range of physicochemical properties. For the gasification process, the ER coefficient affects the parameters controlling furnace (Hongrapipat *et al.*, 2022). A study of the effect of RDF mixture on syngas quality was carried out with a typical mixture containing 90% wood and 10% rice husk and 70% wood mixed with 30% rice husk.

Figure 20a introduces the influence of the mixture fraction f on the composition and calorific value of syngas obtained from the gasification of the RDF prepared from a mixture of 90% wood mixed with 10% rice husk. When f = 0.4, the CO and H_2 contents in the syngas are higher and the CO_2 content are lower than in the case of f = 0.3 and f = 0.5. Thus, for this kind of RDF mixture, the optimal mixture fraction f is about 0.4. Similarly, Figure 20b shows the effect of f on the composition and calorific value of syngas when gasifying the RDF mixture of 70% wood and 30% rice husk. In this case, when the constitution of rice husk in the RDF mixture increases, the CH_4 concentration in the syngas decreases very quickly with f, that leading to a strident decrease in the calorific value of the syngas.

Figure 21 presents the effect of the RDF constitution on syngas composition and calorific value. It can be found that RDF produced from rice husk gives higher CO and H_2 content than that from wood while on the opposite side, CH_4 content in wood RDF syngas is higher than in rice husk RDF syngas. The calorific value of syngas from rice husk RDF gasification is smaller than that of syngas from wood RDF gasification (6.82 MJ/kg versus 7.21 MJ/kg). When gasifying the mixture of 70% wood RDF and 30% rice husk RDF, the CO and H_2 components in the syngas increased, but the CH_4 content present in the syngas was almost negligible. When reducing the rice husk content to 10%, both CO and H_2 decreased and the CH_4 concentration increased. The syngas calorific value increases as the RDF composition decreases.

This result shows that when gasifying the mixture of wood and rice husk RDF, the H_2 content increases, generally. The increase of this component in the syngas will improve the combustion quality (Dakhel Alhassany *et al.*, 2023). Therefore,



The difference between the experiment and simulation in concentration of CH_4 and CO_2 (%)			
CH_4	8	3,5	3
CO_2	4	2	14

Fig 22. Comparison between the simulation and experimental results with different ER values

in case it is necessary to increase the combustion rate, especially in high-speed engines, the solution of gasifying the mixture of wood and rice husk RDF instead of gasifying these RDF components separately can be chosen.

Figure 22 compares simulation and experimental results of CH_4 and CO_2 content in produced syngas corresponding with three different excess air values from lean to rich mixture (Yang *et al*., 2021; Yousef *et al*., 2023). It can be observed that in all these cases, the difference between the experiment and simulation is not more than 14% in CO_2 concentration and is not more than 10% in CH_4 concentration.

5. Conclusions

The research results allow to draw the following conclusions: The mixture of wood and loose rice husk RDF increases the porosity of the material loading in the furnace resulting in the gasification process taking place facility. During the gasification process, CO concentrates in the incomplete combustion zone, while CO_2 forms mainly in the fully burned area; CH_4 forms in the reduction area, while H_2 forms in the region of high temperature. When the mixture fraction f=0.3, the CO concentration in the syngas reaches about 21%, the H_2 concentration reaches about 2% and the CH_4 concentration is very low, which can be ignored. When the mixture fraction increased to f=0.5, the CO concentration reached about 26%, the H_2 concentration remained almost unchanged and the CH_4 content increased to 6%. The syngas calorific value reaches its maximum when f=0.5 and the temperature of the reduction area is in the range of 900K to 1200K. Air humidity affects CO concentration but not much on CH_4, H_2 concentration and syngas calorific value. The difference between simulation and experiment is not more than 10% for CH_4 concentration and not more than 14% for CO_2 concentration.

Acknowledgments

The authors wish to express their appreciation to the NAFOSTED Program for supporting this research under the project NCUD.02-2019.22 entitled "Small Modular On-grid Power Production from Waste in Rural Areas".

Conflicts of Interest: The authors declare no conflict of interest.

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