Simulation and Experiment Study of Refuse Derived Fuel (RDF) Combustion in Atmospheric Conditions

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ABSTRACT

Treating solid waste through Refuse Derived Fuel (RDF) offers an effective solution for resource recovery, enhancing energy conversion efficiency, and mitigating environmental pollution. Simulating RDF combustion processes in the atmosphere provides crucial insights for modeling syngas generation in gasifiers. The results indicate that the combustible species CO, CH_4 and H_2 in syngas primarily form in a region with a rich mixture, where the gas temperature ranges from 700°C to 1050°C. The highest gas temperature was observed in front of the RDF flame. The heating values of syngas from RDF-Wood chip gasification were 0.11, 2.31, 5.14, and 7.64 MJ/kg, corresponding to excess air ratio (ER) values of 1.0, 0.5, 0.3, and 0.2, respectively. The optimal heating value of syngas was achieved when the ER ranged from 0.14 to 0.32. At an ER of 0.28, the heating values of syngas from RDF-Rice husk, RDF-MSW, and RDF-Wood chip gasification were 5.1, 5.3, and 5.7 MJ/kg, respectively.The deviation between the average temperatures predicted by simulation and those measured experimentally was 13%. It is possible to predict the composition and heating value of syngas from RDF gasification by analyzing the combustion of RDF pellets in air. This approach simplifies both the simulation and experimental processes in the gasifier.

1. INTRODUCTION

Solid waste management is a persistent challenge for most countries worldwide. Although traditional landfilling remains the predominant disposal method, it presents numerous serious limitations, including the occupation of large land areas [1], greenhouse gas emissions [2], leachate generation, odor emissions, and risks of fire, explosion, or landslides. These issues pose hazards to both the environment and human health [3]. Landfilling also hinders resource recovery, leading to the permanent loss of materials that could otherwise be repurposed or recycled [4].

In Vietnam, landfilling is currently the primary waste management solution, with most landfill sites becoming overloaded. This is particularly problematic in rural areas, where the treatment of solid waste generated from agricultural production and daily life is relatively low, causing significant environmental impacts. Therefore, finding a sustainable and comprehensive waste treatment solution is crucial. According to current environmental protection laws in Vietnam, solid waste must be sorted at the source, enabling the application of new technologies in subsequent waste treatment stages.

Traditional waste incineration methods are often inefficient and demand sophisticated, high-cost exhaust gas treatment systems. An emerging trend in solid waste management involves converting the combustible fraction of municipal solid waste into Refuse-Derived Fuel (RDF) for use as an alternative energy source [5,6]. The concept of RDF was developed in the early 1970s [7]. Converting waste into energy through RDF offers practical benefits, such as promoting the development of a circular economy, conserving land resources, enhancing resource utilization efficiency, and replacing fossil fuels with renewable energy [8]. Additionally, the source of waste is abundant and continuous, thus, converting waste into energy can reduce dependence on imported fuel sources [9]. Moreover, approximately 50% of the carbon content in household and industrial waste is of renewable origin [10], so using energy from solid waste contributes to reducing greenhouse gas emissions [11,12].

Refuse Derived Fuel (RDF) is widely used as a fuel source in the cement industry. However, direct RDF incineration has some limitations, including incomplete combustion leading to high CO levels, reduced flame temperature, and the generation of pollutants. Gasification of RDF presents a promising solution to these issues, enhancing the energy conversion efficiency from solid waste [13,14]. Compared to biomass, RDF from solid waste

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has a higher calorific value due to higher concentrations of combustible elements such as carbon and hydrogen [15]. Additionally, the lower moisture content in waste-derived fuel reduces the energy required for drying before subsequent processes. Moreover, the lower ash fusion temperature of RDF compared to biomass ash prevents furnace slagging during the thermal conversion process [16,17].

Numerous studies have explored the application of RDF as a fuel for various energy systems [18-20]. A common concern identified in these investigations is the high chlorine content often present in waste-derived fuels. In particular, impurities such as alkali chlorides in the resulting syngas can lead to severe corrosion in thermal systems due to their tendency to vaporize and subsequently condense on cooler surfaces [19,20].

RDF gasification presents an effective alternative to mitigate the limitations of direct incineration. In this process, RDF is thermochemically converted into syngas, composed of CO, H_2, CH_4, H_2O, and other light hydrocarbons along with byproducts such as soot, char, and ash. Once cleaned, the syngas can be further processed to synthesize liquid hydrocarbon fuels, hydrogen, methanol, or ammonia, or be used directly as a fuel for internal combustion engines [21]. This process offers higher energy recovery efficiency compared to direct incineration, with lower emissions [22]. The oxidizing agent can be air, steam, oxygen-enriched air, or carbon dioxide [23].

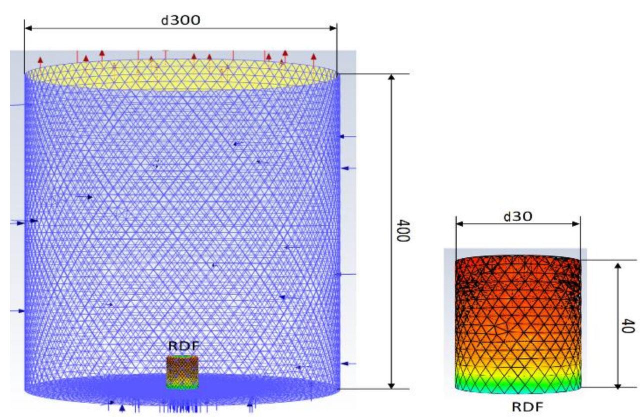
Saidi et al. [24] and Chen et al. [25] reported that increasing temperature enhances the gasification reaction rate and increases the hydrocarbon content. Down-draft gasifiers [26] can be divided into four different zones [27]: RDF storage zone with a temperature of 373K-423K, primary pyrolysis zone, secondary pyrolysis zone with a temperature of 423K-973K, combustion zone with a temperature of 973K-1773K, and reduction zone with a temperature of 1073K-1373K. Syngas is mainly formed in the reduction zone, and its composition can be adjusted by adding steam to this zone [27].

Gasification is a complex process that can be simulated using software [27]. The application of Ansys Fluent software for studying the gasification process is well-documented [26,28]. Comparisons between simulation results and experimental data of RDF gasification in gasifiers are presented in various studies [29,30]. In these studies, the air-fuel ratio is adjusted by controlling the fuel and air flow rates into the gasifier. The gasification rate depends on the velocities of the fuel and air.

To enhance the efficiency of simulating the gasification process, fundamental information about the combustion process of RDF pellets is required. This study focuses on simulating the basic combustion process of RDF pellets under rich mixture conditions. The geometric shape of the flame, temperature distribution, and concentration of species in the combustion products as the air-fuel ratio changes are analyzed. The combustion processes of three types of RDF-rice husks, wood chips, and municipal solid waste (MSW)-are simulated for comparison. The results of this fundamental research provide essential information for simulating the gasification process in actual gasifiers.

2. MATERIAL AND METHOD

The simulation of the fuel pellet combustion process was conducted using Ansys Fluent version 21R1. The focus of this study is on the fundamental investigation of the gasification process of the fuel pellet. The computational domain consists of a cylindrical fuel pellet with a diameter of 30mm and a height of 40mm placed in a computational domain representing air, which is also cylindrical with a diameter and height ten times larger than the dimensions of the pellet (Figure 1). Air is drawn into the computational domain from the bottom of the cylinder and around the computational domain due to gravity forces. The fuel pellet is assumed to have a porous structure containing the fuel components as specified in Table 1.



(a) (b)

Fig. 1. Meshing computational domain (a) and RDF pellet (b)

The fuel is introduced into the simulation by its elemental composition. Based on this composition, the air-fuel ratio on a mass basis (r) under theoretical complete combustion conditions can be calculated:

$$r = \frac{100}{23}\left(\frac{8x_C}{3} + 8x_H - x_O\right) \quad (1)$$

in which, x_C, x_H and x_O represent the mass fractions of C, H, O in the fuel according to Table 1 [31].

In this study, the k-ε turbulence model and Partially Premixed Combustion model were selected. In the simulation, the air introduced into the computational domain has a combustion progress variable c=1 and a mixture fraction f=0, while inside the RDF c=0 and f=1. The mixture fraction f of RDF pellet can be selected in the range from 0 to 1 to simulate the effects of the equivalence ratio (□) on gasification process. The value of □ is determined as follows:

$$\emptyset = \frac{fr}{1-f} \tag{2}$$

In this work, the excess air ratio ER=1/ ϕ is used.

Table 1. Fuel Composition in RDF pellet

Fuel pellet	Fuel composition (% by mass)			
	C	H	O	N
RDF-Husk	0.46	0.06	0.475	0.004
RDF-Solid waste	0.57	0.0636	0.343	0.027
RDF-Wood chips	0.532	0.064	0.4028	0.0012

3. RESULTS AND DISCUSSION

3.1. Distribution of temperature and concentration of species in RDF flames

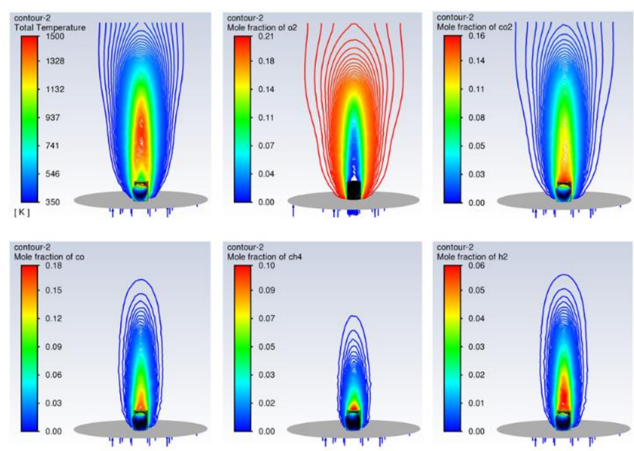


Fig. 2. Contours of temperature, concentrations of CO, H_2, CH_4, and H_2 in the RDF-Rice husk Flame on yz direction (ER=0.3).

Figure 2 illustrates the temperature contours and concentrations of CO, CO_2, CH_4, and H_2 in the RDF-Rice husk. It can be observed that the high-temperature region is concentrated in the flame front area, which also corresponds to the high-concentration zone of the combustion products. Under rich mixture conditions, incomplete combustion occurs, leading to the partial conversion of carbon and hydrogen into CO_2 and H_2O. Consequently, the concentrations of combustible gases such as CO, CH_4, and H_2 in the combustion products increase. The concentrations of these species are determined based on the thermodynamic reaction equilibrium. Under stable combustion conditions of the RDF-Rice husk, the maximum molar concentrations of CO, CH_4, and H_2 are 18%, 10%, and 6%, respectively, as shown in Figure 2.

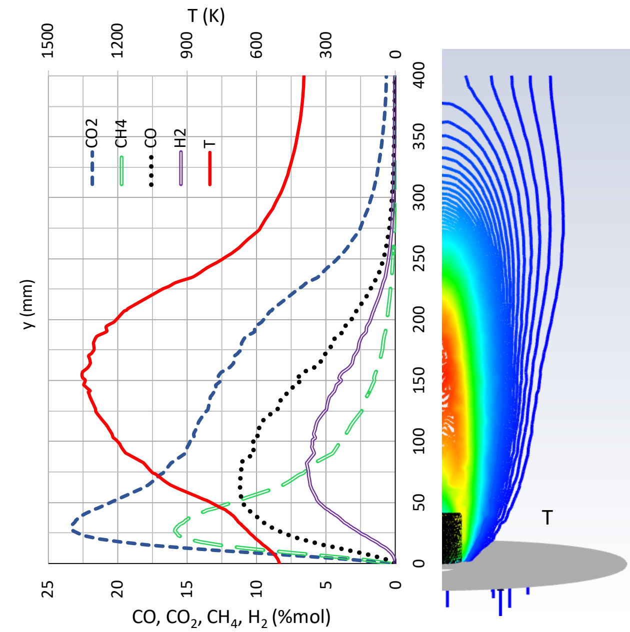


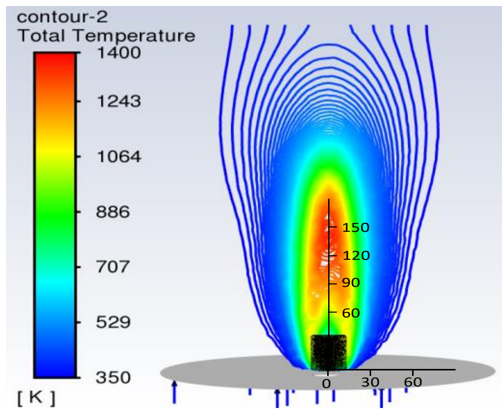
Fig. 3. Distribution of H_2, CH_4, CO, CO_2 concentration and temperature T on y-axis of RDF-MSW flame.

Figure 3 presents the variation of temperature and species concentrations along the y-axis of RDF-MSW pellets. The result inidcated that the maximum species concentrations are located closer to the RDF pellet compared to the temperature. This is because near the RDF pellet, the fuel-air mixture is rich, resulting in a lower combustion temperature but higher concentrations of incomplete combustion products. The gaseous fuel components CO, CH_4, and H_2 tend to reach their maximum concentrations when 25 mm < y < 75 mm, corresponding to a combustion temperature range between 700°C and 1050°C.

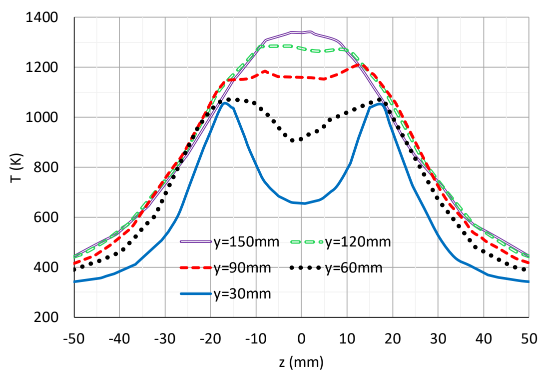
In addition, by observing Figures 3, it is evident that the temperature variation curve (T) of the pellet combustion process reaches its peak in the core region of the flame. In this area, oxygen from the air diffuses into the vaporized fuel from the RDF pellets, mixes evenly, and undergoes complete combustion.

Where xCO, xCH_4, and xH_2 represent the mass fraction (g/g) of CO, CH_4, and H_2 in the combustion products.

Figure 4a presents the temperature contour of the RDF-Wood chip flame. During combustion, oxygen from the diffusing air reacts with the vaporized fuel from the RDF, resulting in the flame front being located outside the edge of the RDF pellet. When y<90 mm, the T(x) curve has two peaks corresponding to the flame positions on the left and right sides of the pellet (Figure 4b). When y>90 mm, the T(x) curve shows only one peak at the top of the flame. The highest flame temperature occurs when y is in the range of 90 mm to 150 mm. This region can be considered a well-mixed zone between the vaporized fuel from the RDF pellet and air. When y>150mm, the gas temperature decreases rapidly due to the diffusion of air into the combustion products.



(a)



(b)

Fig. 4. Temperature distribution in flame of RDF-Wood chip. (a) Contour of temperature in section yz, (b) Variation of temperature in z direction at different heigh y of flame (ER=0.3).

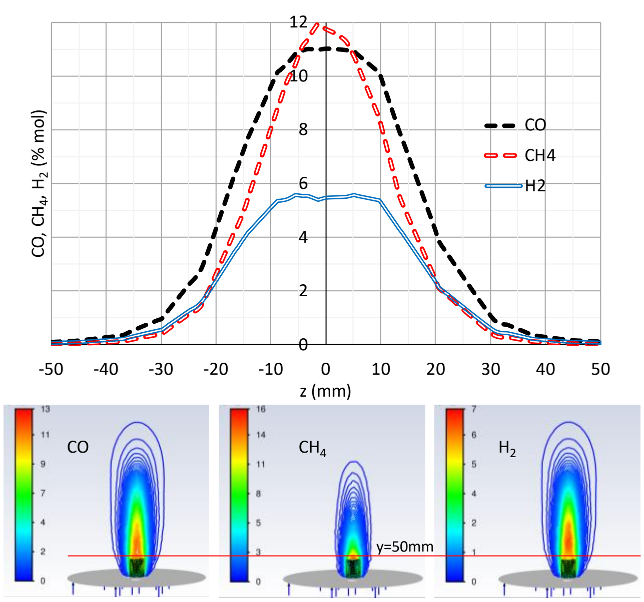


Fig. 5. Distribution of specie concentrations in z direction at y=50mm of RDF-MSW flame.

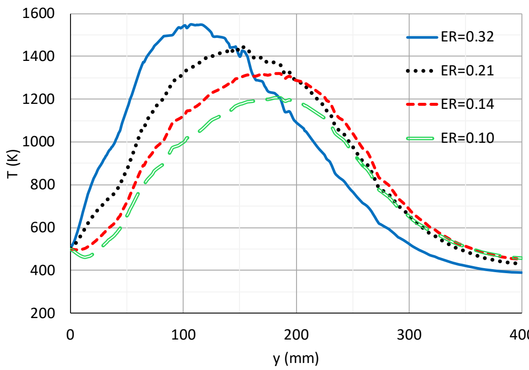
The variation of CO, CH_4, and H_2 concentration along the z direction is similar to the variation of flame temperature. Figure 5 present the profils of species concentration at y=50mm. The results indicate that the CO, CH_4, H_2 formation primarily occurs in the flame front. After that, CO, CH_4, and H_2 rapidly diffuse into the surrounding air, thus, their concentrations fall down to zero outside the flame edge.

3.2. Effect of ER on the composition and heat value of syngas from RDF gasification

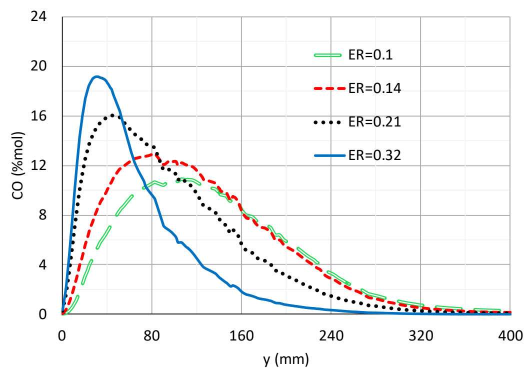
Figures 6a, b, c, and d illustrate the influence of the equivalence ratio (ER) on the variation of temperature and the concentrations of CO, H_2, and CH_4 along the y-axis of the RDF-MSW flame. The initial mixture fraction fff is varied to achieve different ER values. It can be observed that at ER = 0.32, the concentrations of CO and H_2, and the combustion temperature reach their maximum values. In contrast, the concentration of CH_4 peaks at ER = 0.14. As the ER decreases (indicating a richer mixture), the combustion temperature drops due to incomplete combustion. The heat value of syngas is proportional to the concentrations of combustible species in the fuel. Therefore, the optimal heat value of syngas corresponds to an ER range from 0.14 to 0.32.

Figure 6e illustrates the contours of temperature and concentrations of CO and H_2 in the yz section of the RDF-MSW flame. When ER = 1 (stoichiometric mixture), combustion is complete, and the highest combustion temperature reaches 1900K, with the concentrations of CO and H_2 being practically negligible. Both the temperature and the concentrations of CO and H_2 increase at ER = 0.32 and then decrease at ER = 0.14 due to the mixture becoming too rich.

Figure 7 compares the effects of ER on the compositions and heat value of syngas produced from RDF-Wood chip. The compositions of the species are determined by their highest values in the computational domain. The heat value of syngas is calculated based on the mass compositions of the species, representing the highest value attainable under specific combustion conditions. The heat values of syngas from RDF-Wood chip gasification are 0.11, 2.31, 5.14, and 7.64 MJ/kg, corresponding to ER values of 1.0, 0.5, 0.3, and 0.2, respectively. These values are lower than the respective heating values of syngas obtained from RDF gasification in a gasifier [29,30]. This difference can be attributed to the fact that when RDF burns in air, the combustible species produced in the flame front quickly disperse into the surrounding environment, resulting in a reduction of their concentrations.



(a)



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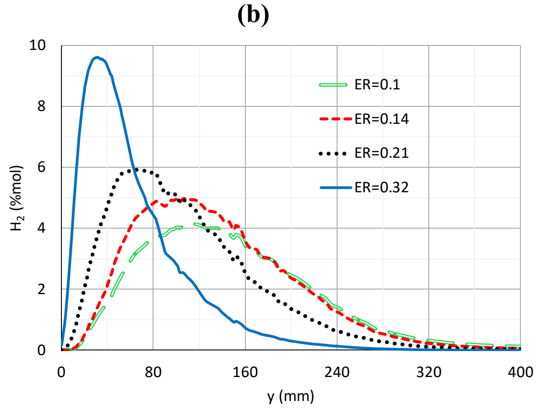
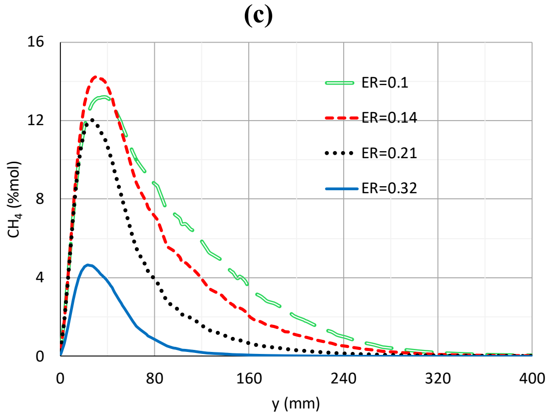
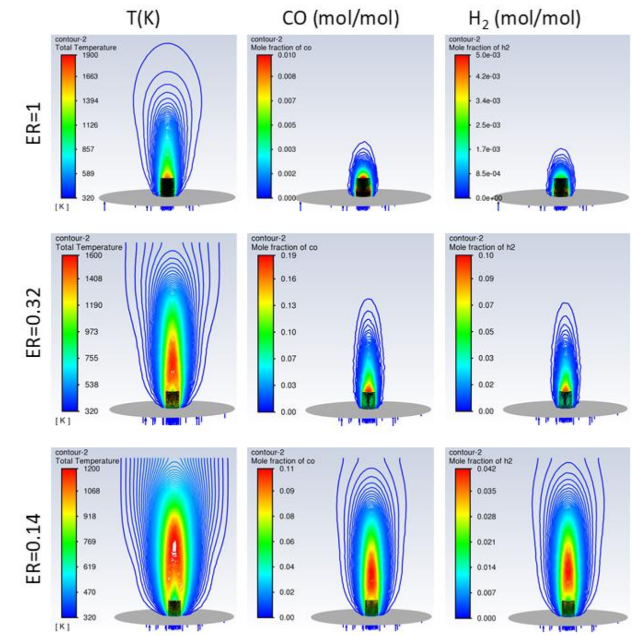


(c)



(d)



(e)

Fig. 6. Effects of ER on flame of RDF-MSW. Variation of temperature(a) and concentration of CO (b), H_2 (c), CH_4 (d) on y axis of RDF-MSW flame; Contours of temperature and concentrations of CO, H_2 in yz section as ER=1, ER=0.32 and ER=0.14 (e).

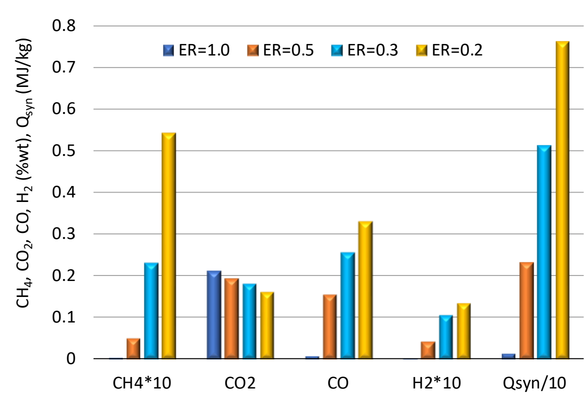


Fig. 7. The effect of ER on the composition of CH_4, CO_2, CO, H_2, and the heating value of syngas (RDF-Wood chip).

3.3. Effect of biomass properties on compositions and heat value of syngas

Figure 8 compares the maximum concentrations of species in the combustion products of RDF-Rice husk, RDF-MSW, and RDF-Wood chip at ER = 0.28. The concentrations of H_2 and CH_4 in the flame of RDF-Wood chip are the highest among the three types of RDF, while the concentrations of these gases in the flame of RDF-Rice husk are the lowest. This is because both the carbon and hydrogen contents in RDF-Rice husk are lower than those in the other RDF types (Table 1). Although the carbon content in RDF-Wood chip is lower, its hydrogen content is higher compared to RDF-MSW. Since the heat value of CO is much lower than that of H_2 and CH_4, the calorific value of syngas from RDF-Wood chip is higher than that from RDF-MSW. Figure 8 shows that at ER = 0.28, the heat values of syngas from RDF-Rice husk, RDF-MSW, and RDF-Wood chip gasification are 5.1, 5.3, and 5.7 MJ/kg, respectively.

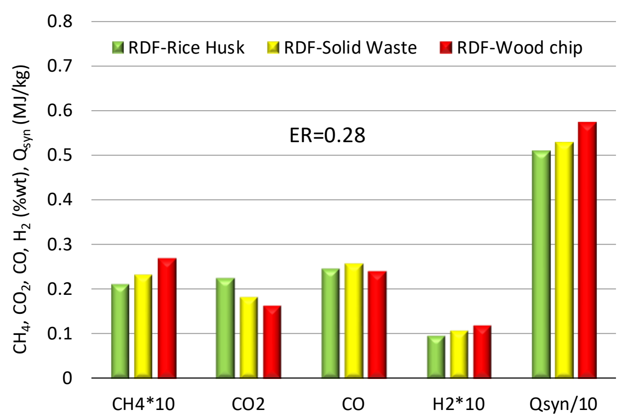


Fig. 8. Comparison of compositions and heat value of syngas produced by gasification of RDF-Rice husk, RDF-MSW and RDF-Wood chip with ER=0.28.

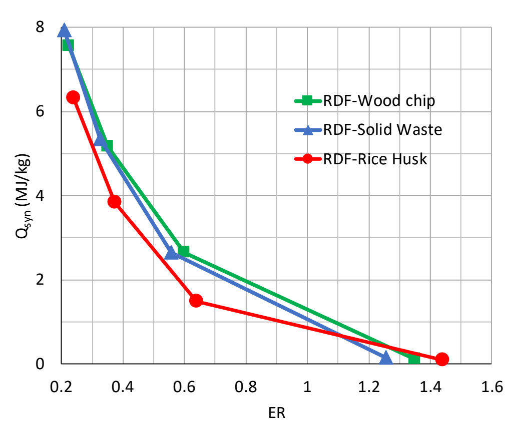


Fig. 9. Effects of biomass on variation of heat value with ER of syngas produced by gasification process.

Figure 9 compares the variation of heat values of syngas from RDF-Rice husk, RDF-MSW, and RDF-Wood chip gasification as a function of ER. It can be seen that the heat values of syngas in all three cases decrease sharply with increasing ER. When ER exceeds the stoichiometric value, the heat value of syngas becomes negligible because the fuel in the RDF is almost completely burned. For all ER values, the calorific value of syngas from RDF-Wood chip is the highest, followed by that from RDF-MSW. The calorific value of syngas from RDF-Rice husk always remains the lowest among the three types of RDF considered.

3.4. Experimental study of RDF combustion in the air

Figure 10 compares the flame shape of flame of RDF-Rice husk provided by simulation and experimentation. Since the flame burns in an open-air environment, its front oscillates (like an oil lamp flame). However, the basic shape of the RDF combustion flame is similar to a pen-like shape of a fuel gas jet flame. Heat radiation from soot in the flame makes the it is bright. It can be observed that the simulated flame shape is similar to the experimental flame. This confirms the appropriate initial hypothesis of simulating the RDF combustion: burning of the vaporized fuel emitted from the RDF pellet.

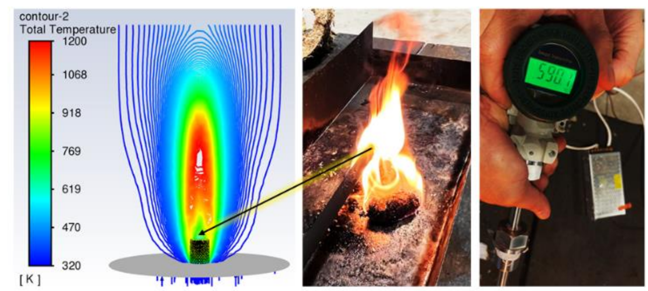


Fig. 10. Comparison of flame shape between simulation and experiment.

The average temperature of RDF combustion was measured by thermocouple. This is a specialized tool used to measure temperature in boilers or gasifiers. Figure 11 presents the the average temperature inside the RDF-Rice husk pellet. The experimental value is 738K as compared to the simulation value of 850K. The average temperature deviation is thus, 13%.

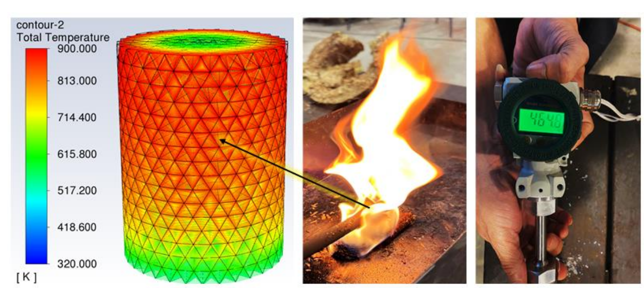


Fig. 11. Comparison average temperature given by simulation and experiment of RDF-Rice husk flame.

4. CONCLUSIONS

The research findings lead to the key points as follows:

- The combustible species CO, CH_4, and H_2 in syngas primarily formed in a region with a rich mixture, where the gas temperature ranged from 700°C to 1050°C while the highest gas temperature was observed in front of the RDF flame.
- The heating values of syngas from RDF-Wood chip gasification were 0.11, 2.31, 5.14, and 7.64 MJ/kg, corresponding to excess air ratio (ER) values of 1.0, 0.5, 0.3, and 0.2, respectively. The optimal heating value of syngas was achieved when the ER ranged from 0.14 to 0.32.

- At ER = 0.28, the heating values of syngas from RDF-Rice husk, RDF-MSW, and RDF-Wood chip gasification were 5.1, 5.3, and 5.7 MJ/kg, respectively.
- The deviation between the average temperatures predicted by simulation and those measured experimentally was 13%.
- It is possible to predict the constituent and heating value of syngas from RDF gasification by analyzing the combustion of RDF pellets in air. This approach simplifies both the simulation and experimental processes in the gasifier.

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