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Performance analysis of a co-gasifier for organic waste in agriculture

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Abstract

Background: Agricultural waste has been proposed as an alternative energy resource to meet fossil fuel crisis, green house emission, and other environmental impacts worldwide. In Iran, rice husk and bagasse are main resources of biomass which can be used to produce syngas. This paper deals with a simplified model of combined gasification of coal and biomass processes considering chemical equilibrium.

Results: It should be noticed that the CO₂ which is produced from agricultural waste gasification is natural because the biomass absorbs CO₂ from nature and gives it back after gasifying; however, mixing agricultural waste with coal leads to enrich syngas quality and gasifier efficiency.

Conclusions: In this regard, an advanced coding was developed to simulate the thermodynamics of the co-gasifier and to find the produced syngas composition. The effects of moisture content, steam-to-biomass ratio, and gasifier temperature are then discussed on the system performance. Additionally, co-gasification of rice husk/coal was compared with co-gasification of bagasse/coal. The results indicated that adding coal to biomass increases lower heating value of syngas from 4,694 kJ/Nm³ to 5,321 kJ/Nm³ and gasifier efficiency from 71.29% to 77.85%.

Keywords: Agricultural waste, Bagasse, Co-gasification, Performance analysis, Rice husk

Introduction

The high consumption rate of fossil fuels strongly accelerates the depletion of world energy resources as well as causes environmental damage in terms of global warming. Therefore, several attempts have been considered to tackle environmental impacts. It is widely known that the development of biomass gasification plants to replace fossil fuels is one of the best strategies. Nowadays, gasification of organic waste in agriculture is not common because the heating value of syngas is not rich enough; therefore, co-gasification of biomass and coal may be a solution to use agricultural wastes.

Gasification is the heating up of solid or liquid carbonaceous material with some gasifying agent to produce gaseous fuel. It includes partial oxidation of fuel and hydrogenation. In partial oxidation process, the gasifying agent (also called the oxidant) could be steam, carbon

dioxide, air or oxygen, or some mixture of two or more gasifying agents. The gasifying agent is chosen according to the desired chemical composition of the syngas and efficiency (Ahmed and Gupta 2009).

Gasification essentially converts a potential fuel from one form to another (Basu 2010). This transformation causes to increase the heating value of the fuel by rejecting noncombustible components such as nitrogen and water. Additionally, it removes sulfur and nitrogen such as when burnt gasified fuel does not release them into the atmosphere and reduces the carbon-to-hydrogen (C/H) mass ratio in the fuel. As an alternative to simple biomass gasification, the combined usage of biomass and coal has several advantages. With reference to coal-based processes, the addition of the biomass not only reduces the CO₂ emissions, but also mitigates the critical issues of high coal sulfur content and adverse properties of ash. Moreover, adding the coal to the biomass is appealing in order to overcome the limitation of the low energy density of biomass and to substitute part of the biomass feedstock when it is temporarily in short supply, for instance, in the case of seasonally produced agricultural residues (Miccio et al.

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2011). An interesting difference between coal and biomass lies in the composition of their organic matter; woody biomass contains typically around 50 wt.% carbon and 45 wt.% oxygen, whereas coal contains (depending on coal rank) 60 to 85 wt.% carbon and 5 to 20 wt.% oxygen (Prins et al. 2007).

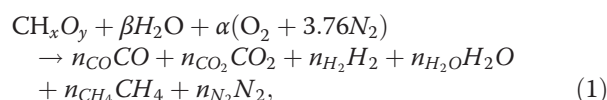
In the former years, there has been much research done regarding co-gasification systems with the aim of investigating the performance of different designs and capacities. Sjoström et al. (1999) reported synergies in fluidized bed co-gasification of wood and coal mixtures at small particle sizes with maximum feed rates of 5.2 kg/h and maximum pressures of 15 bar. Pan et al. (2000) investigated the co-gasification of many biomass/coal combinations. They confirmed that the feasibility of co-gasification process for pine woodchips blends with poor quality coals. When black coal was considered, a minimum of 25% of pine woodchips was needed to significantly enrich the overall efficiency; the product gas lower heating value (LHV) and the carbon conversion also increased. McLendon et al. (2004) reported on a series of air-blown fluidized bed and entrained bed co-gasification tests with coal and straw. Pressures in the larger unit (based on U-Gas design) were up to 14.2 bar, and feed rates of the feedstock were a maximum of 720 kg/h. Feeding presented problems, but some synergies were noted. Madhukar et al. (2007) observed in their study that combined steam and air gasification gave much higher H₂ yield than air gasification alone. Doherty et al. (2009) studied the effects of varying equivalence ratio, temperature, level of air preheating, biomass moisture and input steam on syngas composition, and gas heating value. Li et al. (2010) discussed the effect of temperature on the amount of hydrogen production. They found that a higher temperature caused higher hydrogen production and syngas yield. Loha et al. (2011) investigated the alternation of hydrogen production, the LHV of syngas, energy and exergy efficiencies by varying the steam-to-fuel ratio, and temperature of gasifier. Industrial scale experience with coal and biomass or waste co-gasification is reported for several plants, e.g., the Buggenum plant in the Netherlands, where efforts of co-gasification of up to 50% w/w of biomass were undertaken to generate a high proportion of green energy (Howaniec et al. 2011).

Methods

In this study, the simulation of a steam–air gasifier was developed by means of the Equation Engineering Solver software (F-chart Software, LLC, Madison, WI, USA). Thermodynamic equilibrium calculation is independent of the gasifier design; therefore, it is convenient for studying the influence of fuel and process

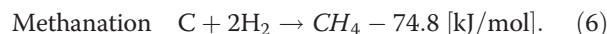
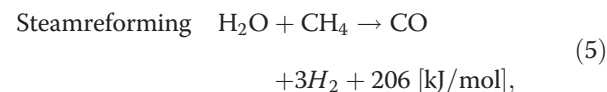
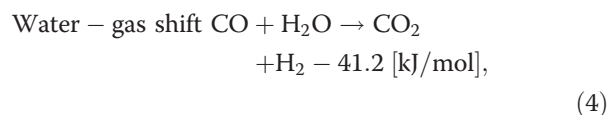
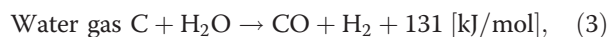
parameters. Chemical equilibrium is determined by either of the equilibrium constant and the minimization of the Gibbs free energy. In equilibrium modeling, it is assumed that biomass is dry and ash free and contains of C, H, and O; the elements nitrogen and sulfur were not considered because biomass contains a negligible amount of both in comparison with carbon, hydrogen, and oxygen, while these are significant elements in coal. In this research, nitrogen and sulfur content of coal is also neglected for simplicity of the global reaction. Therefore, the chemical formula of the biomass and coal is represented as CH_xO_y; where *x* and *y* are the numbers of atoms of hydrogen and oxygen per single atom of carbon in biomass and coal. It calls for ultimate and proximate analyses of the obtained fuel.

In general, the global reaction of gasification process with steam and air as gasifying agent can be written as Equation 1:



where *α* and *β* are moles of air and steam supplied per moles of mixed fuel, respectively. Numbers of moles which are produced in the reaction are indicated by *n_i*.

The main reactions which occur in the gasifier are indicated in Equations 2 to 6:



The above-mentioned reactions show that gasification is an endothermic process; therefore, some parts of feedstock are burnt to supply the required heat. On the right hand side, *n_{H₂}*, *n_{CO}*, *n_{CO₂}*, *n_{H₂O}*, *n_{N₂}*, and *n_{CH₄}* are the unknown numbers of moles of hydrogen, carbon

Table 1 Values of \bar{h}_f^0 (kilojoules per kilomole) and coefficients of the empirical equation for $\Delta\bar{g}_{f,T}^0$ (kilojoules per kilomole)

	CO	CO ₂	H ₂ O	CH ₄
\bar{h}_f^0 (kJ·kmol ⁻¹)	-110.5	-393.5	-241.8	-74.8
a' (kJ·kmol ⁻¹)	5.619×10^{-3}	-1.942×10^{-2}	-8.950×10^{-3}	-4.62×10^{-2}
b' (kJ·kmol ⁻¹)	-1.190×10^{-5}	3.122×10^{-5}	-3.672×10^{-6}	1.13×10^{-5}
c' (kJ·kmol ⁻¹)	6.383×10^{-9}	-2.448×10^{-8}	5.209×10^{-9}	1.319×10^{-8}
d' (kJ·kmol ⁻¹)	-1.846×10^{-12}	6.946×10^{-12}	-1.478×10^{-12}	-6.647×10^{-12}
e' (kJ·kmol ⁻¹)	-4.891×10^2	-4.891×10^2	0	-4.891×10^2
f' (kJ·kmol ⁻¹)	8.684×10^{-1}	5.270	2.868	14.11
g' (kJ·kmol ⁻¹)	-6.131×10^{-2}	-1.207×10^{-1}	-1.722×10^{-2}	-2.234×10^{-1}

monoxide, carbon dioxide, steam, nitrogen, and methane, respectively, which are presented in the produced syngas. Four mass balance equations are then presented to obtain these unknowns as Equations 7 to 10:

$$C : 1 = n_{CO} + n_{CO_2} + n_{CH_4}, \quad (7)$$

$$H : x + 2\beta = 2n_{H_2} + 2n_{H_2O} + 4n_{CH_4}, \quad (8)$$

$$O : y + \beta + 2\alpha = n_{CO} + 2n_{CO_2} + n_{H_2O}, \quad (9)$$

$$N : 2 \times 3.76\alpha = 2n_{N_2}. \quad (10)$$

In the above equations, there are five unknown parameters because only gaseous products are considered. Therefore, by calculating the equilibrium constants of reactions 4 and 6 (Equations 4 and 6), the unknown numbers were determined as follows:

$$K_1 = \frac{P_{CO_2}P_{H_2}}{P_{CO}P_{H_2O}} = \frac{n_{CO_2}n_{H_2}}{n_{H_2O}n_{CO}}, \quad (11)$$

$$K_2 = \frac{P_{CH_4}}{P_{H_2}^2} = \frac{n_{CH_4}n_{total}}{n_{H_2}^2}. \quad (12)$$

Table 2 The coefficients of specific heat for the empirical equation

C ₃	C ₂	C ₁	C ₀	Gas
-0.454	1	-0.46	1.1	CO
0.39	-1.27	1.67	0.45	CO ₂
-0.71	0.75	3.25	1.2	CH ₄
-0.42	0.96	-0.48	1.11	N ₂
-0.33	0.54	0	0.88	O ₂
3.79	-6.85	4.6	13.46	H ₂

The equilibrium constant and the Gibbs free energy of reactions were calculated according to Equations 13 and 14:

$$\ln k = -\frac{\Delta G_T^0}{RT}, \quad (13)$$

$$\Delta G_T^0 = \sum_i v_i \Delta \bar{g}_{f,T,i}^0, \quad (14)$$

where, R is the universal gas constant (8.314 kJ·kmol⁻¹·K⁻¹), ΔG_T^0 is the standard Gibbs function of reaction, and $\Delta \bar{g}_{f,T,i}^0$ represents the standard Gibbs function of formation at a given temperature T of the gas species i which can be expressed by the empirical Equation 15 (Jarunthammachote and Dutta 2007):

$$\Delta \bar{g}_{f,T}^0 = \bar{h}_f^0 - a'T \ln T - b'T^2 - \left(\frac{c'}{2}\right)T^3 - \left(\frac{d'}{3}\right)T^4 + \left(\frac{e'}{2T}\right) + f' + g'T. \quad (15)$$

The values of coefficients a' to g' and enthalpy of formation of the gases are presented in Table 1 (Jarunthammachote and Dutta 2007):

The temperature of the gasification zone needs to be calculated in order to calculate equilibrium constants Equations 13 to 15. For this aim, either energy or enthalpy

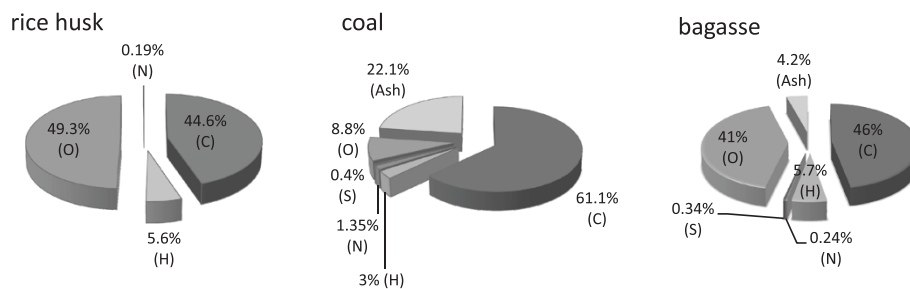


Figure 1 Ultimate analysis of rice husk, coal, and bagasse base on dry basis.

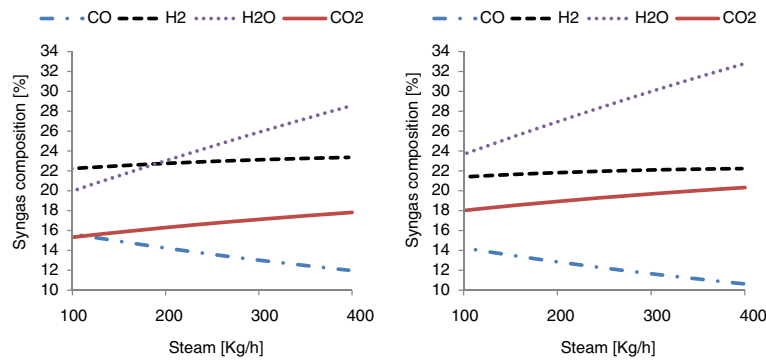


Figure 2 Effect of steam mass flow on gasifier performance for bagasse and rice husk.

balance was carried out for the gasification process, which was usually assumed to be an adiabatic process (Zainal et al. 2001). When the temperature in gasification zone is T and the temperature at inlet state is assumed to be 298 K, the overall energy balance for the gasification of 1 kg of biomass can be expressed as follows:

$$E_{in} = E_{out}, \quad (16)$$

$$E_{in} = H_{biomass}^0 + W(H_{f,H_2O(l)}^0 + H_{vap}) + X_g(H_{O_2}^0 + 3.76H_{N_2}^0), \quad (17)$$

$$E_{out} = \left(\frac{0.007}{2} + 3.76X_g\right)(H_{f,N_2}^0 + \Delta h) + n_{CH_4}(H_{f,CH_4}^0 + \Delta h) + n_{H_2O^2}(H_{f,H_2O}^0 + \Delta h) + n_{CO}(H_{f,CO}^0 + \Delta h) + n_{H_2}(H_{f,H_2}^0 + \Delta h) + n_{CO_2}(H_{f,CO_2}^0 + \Delta h). \quad (18)$$

In Equation 17, $H_{biomass}^0$ is the lower heating value of solid fuel which is estimated from the high heating value (HHV) formula:

$$LHV = HHV - 9h_{vap}H. \quad (19)$$

The HHV is converted into the LHV using the enthalpy of evaporation for the water formed during combustion; therefore, H is the mass fraction of hydrogen in solid fuel, and h_{vap} is the enthalpy of vaporization of water. The formulas for higher heating value in joules per kilogram (Souza Santos 2010) are as follows:

For fuel with the cases of coal,

$$HHV = 2.326 \times 10^5 (144.5C + 610H - 62.5O + 40.5S) \times (1 - Ash).$$

For Wood or other biomass,

$$HHV = 4.184 \times 10^5 (81.848C + 263.38H - 28.645(O + N) - 3.658Ash + 0.16371),$$

where C, H, N, O, and Ash are mass fraction elements in solid fuel.

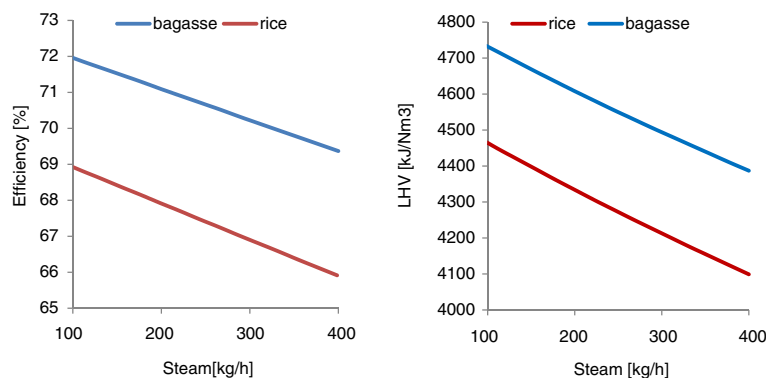


Figure 3 Effect of steam mass flow on efficiency and LHV.

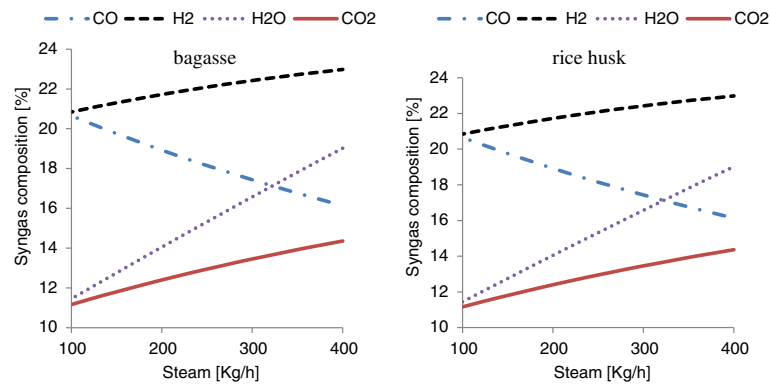


Figure 4 Effect of steam mass flow on gasifier performance for mixing bagasse/coal and rice husk/coal.

In Equation 18, h_f is the enthalpy of formation in kilojoules per kilomole, and its value is 0 for all chemical elements at a reference state (298 K, 1 atm), and ΔH represents the enthalpy difference between any given state and at a reference state. It can be approximated by the following :

$$\Delta \bar{h}_T = \int_{298}^T C_p(T) \cdot dT, \quad (20)$$

where C_p is the specific heat at constant pressure in kilojoules per kilogram Kelvin and is a function of temperature. It can be defined by the empirical equation below:

$$C_p = C_0 + C_1\theta + C_2\theta^2 + C_3\theta^3, \quad (21)$$

where T is the temperature in Kelvin and

$$\theta = \frac{T}{1000}, \quad (22)$$

where C_0 , C_1 , C_2 , and C_3 are the specific gas species coefficients, which are shown in Table 2 (Sonntag

et al. 2002). In this study, the efficiency is defined as follows:

$$\eta = \frac{LHV_{syngas} \times Q_g}{LHV_{fuel} \times m_{fuel}}, \quad (23)$$

where LHV_{syngas} is the lower heating value of syngas, Q_g is the volume flow rate of syngas, LHV_{fuel} is the low heating value of the fuel which is gasified, and m_{fuel} is the solid fuel consumption.

By adjusting the input data, the syngas composition, flue gas composition, LHV and efficiency of the process will be determined. The gas composition of mixed fuel which consists of 50% biomass and 50% coal was compared with the syngas composition of rice husk and bagasse. The moisture content of fuel was 12%, and the gasifier operated in atmospheric condition. The temperature of air after preheating was 550°C, and steam that entered the gasifier was 400°C.

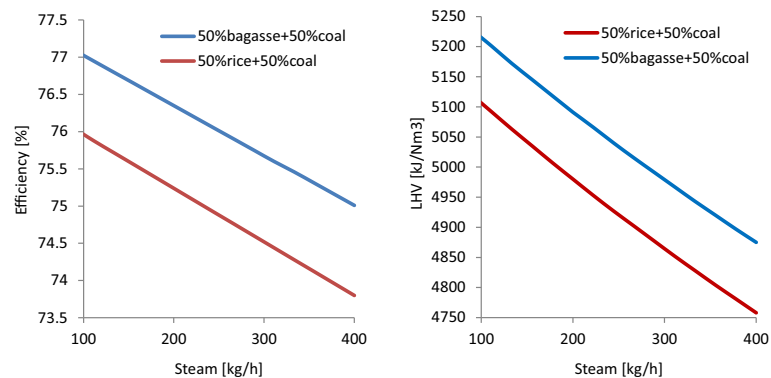


Figure 5 Effect of steam mass flow on gasifier efficiency and LHV of syngas for mixing biomass/coal and rice husk/coal.

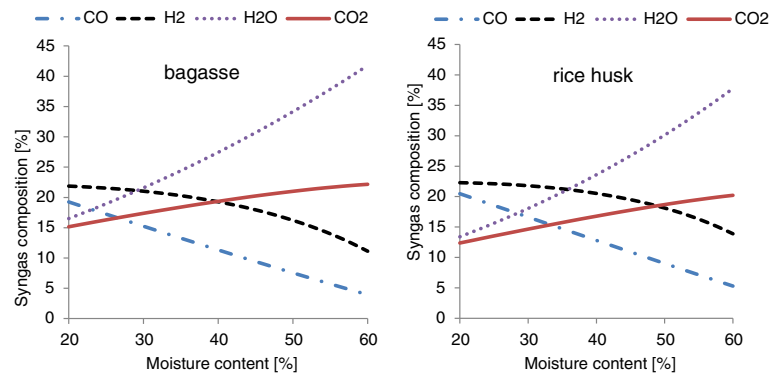


Figure 6 Effect of moisture content on gasifier performance for rice husk and bagasse.

The ultimate analysis of rice husk, coal, and bagasse in Iran, which were considered in this research, is illustrated in Figure 1.

Results and discussion

Effect of steam mass flow

The influence of steam ratio on gasifier performance is shown in Figure 2. The steam mass flow was varied from 100 to 400 kg/h. As a result, the CO, CO₂, and N₂ content of syngas for both bagasse and rice husk would increase, whereas H₂ would decrease.

The effect of steam mass flow on the LHV of syngas and gasifier efficiency is illustrated in Figure 3. It decreases from 4,482 to 4,099 kJ/Nm³ for rice husk and from 4,733 to 4,410 kJ/Nm³ for bagasse.

Figures 4 and 5 compare the results above with mixing fuel which consists of coal and biomass. The ratio of coal to biomass is equal 50:50. In Figure 5, the effect of added coal to biomass has been illustrated on the efficiency and LHV of syngas. The efficiency of mixing coal and bagasse decreases from 77.1% to 75.1%, and for mixing rice husk, the efficiency decreases from 75.9% to 73.8%.

Effect of moisture content

As for the case of Iran, there is the main composition of rice and coal in Mazandaran state; it has a rainy climate in many days of the year. Thus, its fuel mainly consists of moisture. Therefore, the effect of moisture content on the composition of produced gas from biomass and coal gasification is an interesting aspect.

In order to produce syngas from biomass, the moisture content should be less than 20%; otherwise, the biomass should be dried before entering the gasifier. The effect of moisture content on the gas composition of rice and bagasse are revealed in Figure 6. If the fuel moisture content varies from 20% to 60%, the percentage of H₂, CO, CO₂, and H₂O in the syngas of rice husk will be changed from 21.86% to 11.11%, 19.24% to 3.937%, 15.15% to 22.15%, and 16.5% to 41.78%, respectively. These changes for bagasse as feedstock are 22.3% to 13.88% for H₂, 20.48% to 5.304% for CO, and 13.39% to 37.77% for H₂O.

Also, in Figure 7, the effect of moisture content on efficiency and LHV of syngas is illustrated. As can obviously be seen, efficiency decreases from 74.65%

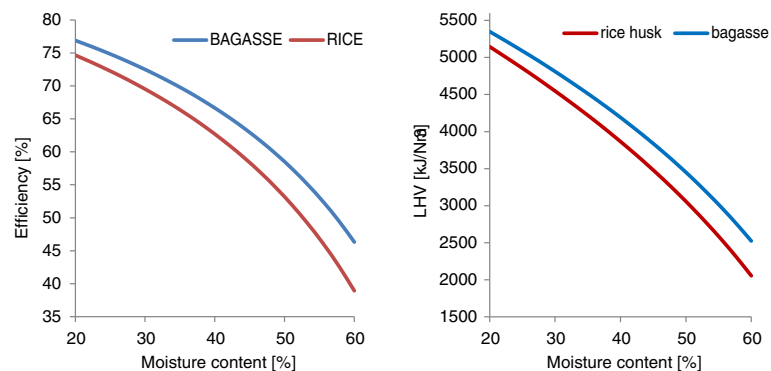


Figure 7 Effect of moisture content on gasifier efficiency and LHV of syngas.

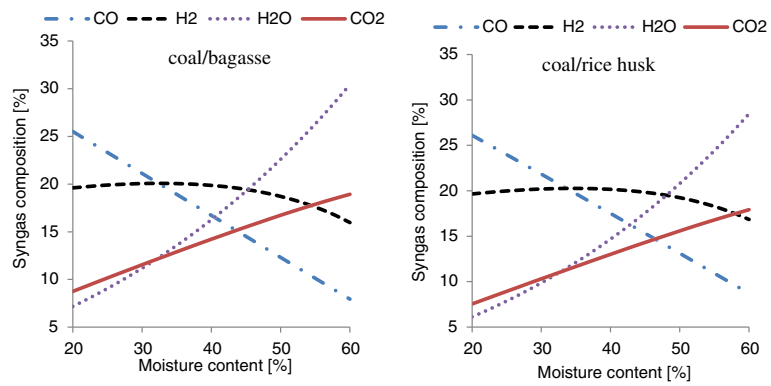


Figure 8 Effect of moisture content on gasifier performance for mixing coal/rice husk and coal/bagasse.

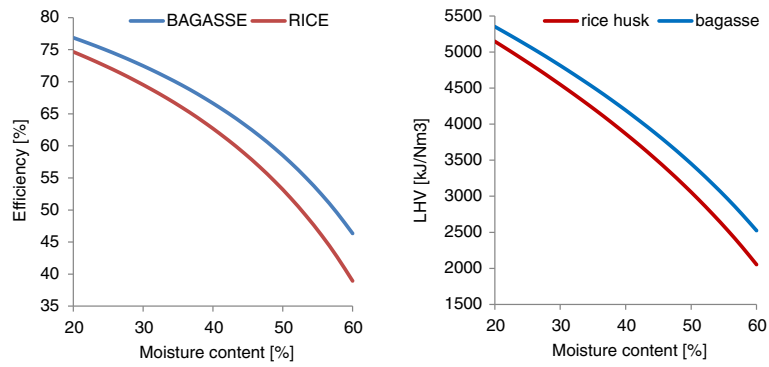


Figure 9 Effect of moisture content on gasifier efficiency and LHV of syngas.

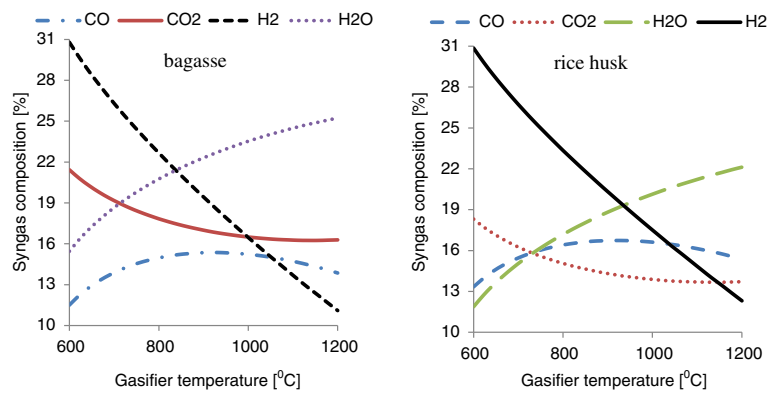


Figure 10 Effect of gasifier temperature on syngas composition from rice husk and bagasse.

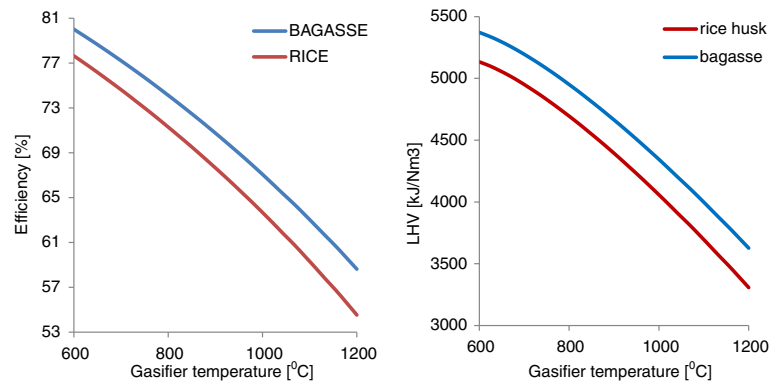


Figure 11 Effect of gasifier temperature on gasifier efficiency and LHV of syngas.

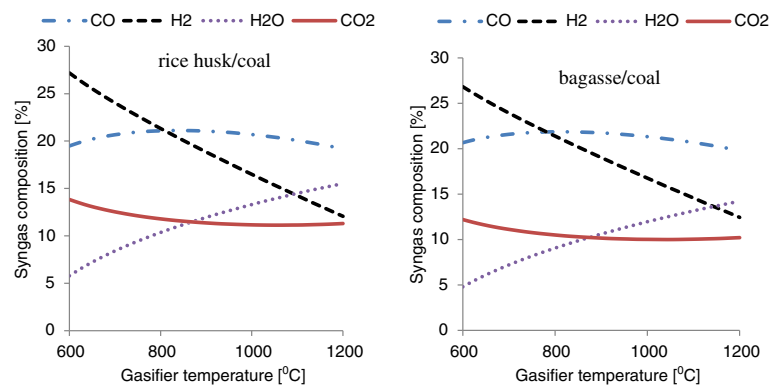


Figure 12 Effect of gasifier temperature on syngas composition of mixing coal/rice husk and coal/bagasse.

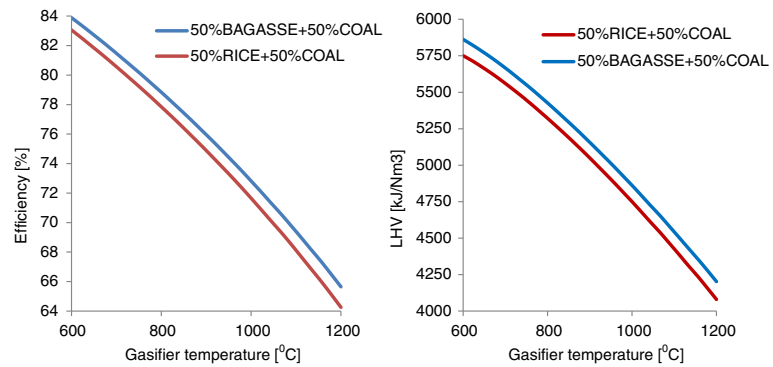


Figure 13 Effect of gasifier temperature on gasifier efficiency and LHV of syngas.

to 38.93% for rice husk and from 76.88% to 46.33% for bagasse. The LHV of syngas for rice husk and bagasse is changed from 5,146 to 2,054 kJ/Nm³ and 5,350 to 2,525 kJ/Nm³, respectively.

In Figures 8 and 9, the effect of increasing moisture content on mixing coal and biomass composition, efficiency, and LHV of syngas are presented.

Effect of gasifier temperature

The influence of gasifier temperature on syngas composition, gasifier efficiency, and LHV of syngas is illustrated in Figures 10 and 11. The temperature was varied from 600°C to 1,200°C. As a result, the gasifier efficiency for rice husk and bagasse would decrease from 77.64% to 45.53% and from 80.02% to 58.63%, respectively. Also the LHV of syngas would decrease from 5,133 to 3,307 kJ/Nm³ for rice husk and from 5,171 to 3,627 kJ/Nm³ for bagasse. The amount of H₂, CO, CO₂, and N₂ changes from 30.78% to 11.11%, 11.51% to 13.86%, 21.43% to 16.28%, and 35.27% to 57.75% for rice husk, respectively. For bagasse, component changes (H₂, CO, CO₂, and N₂) from 30.85% to 12.31%, 13.34% to 15.37%, 18.3% to 13.72%, and 36.51% to 57.6% respectively.

The effect of gasifier temperature on syngas production, gasifier efficiency, and LHV of syngas which are produced from the mixture of coal with bagasse and coal with rice husk were depicted in Figures 12 and 13.

Conclusions

Recent decades have seen an increasing attitude towards developing biomass power plants responding to worldwide energy crisis and global warming. The use of agricultural waste to produce electricity has several advantages. First, biomass is a renewable energy with near-zero net CO₂ emissions. Second, it is a local resource that reduces energetic dependence and creates green jobs. Finally, biomass power plants can be easily integrated with the public grid because their load does not depend on conditions (unlike wind farms or solar stations). As biomass is a dispersed resource, local small-scale power plants (less than 25 MWe) are best options to use agricultural waste considering transportation expenses.

In this article, two types of agricultural waste were considered as the feedstock to run a co-gasification system. It was observed that, by increasing steam mass flow, the LHV of syngas would decrease from 4,607 to 4,099 kJ/Nm³ for rice husk and from 4,867 to 4,387 kJ/Nm³ for bagasse. By increasing the moisture content-to-fuel ratio, the LHV of syngas would decrease from 5,146 to 2,054 kJ/Nm³ for rice husk and from 5,350 to 2,525 kJ/Nm³ for bagasse. By increasing gasifier temperature, the LHV of syngas would decrease

from 5,133 to 3,307 kJ/Nm³ for rice husk and from 5,171 to 3,627 kJ/Nm³ for bagasse.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

A. Ataei was supervisor of the project, participated in the model development and drafted the manuscript. S. B. Kalhori and A. Azimi collected the lab/experimental data and developed the model and wrote the thesis. M. F. Abari and H. Radnezhad helped in the data analysis and revised the paper. All authors read and approved the final manuscript.

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