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Performance of Household Rice Husk Downdraft Gasifier in Vietnam: Modeling and Experiment

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***Abstract*— Lack of conventional energy is one of the huge problems that challenge human beings in the next decades. The crude oil might become exhausted in the year 2050 as predicted and harm our environment. Renewable energy development is the effective approach to solve this problem in which biomass has the potential to replace crude oil and fossil fuels. Rice husk is one of the most popular biomass resources in ASEAN countries such as Vietnam, Indonesia, The Philippines, Thailand, Cambodia, and Myanmar, and other Asian countries like India. Gasification of this biomass is the first approach that there have many works conducted. Rice husk can be used to supply heating energy via directly burning or gasification. A study is necessary to see how the effects of some variables on the biomass gasification products and how to predict these products without the experiment. This paper has presented the modeling and investigation of the Vietnamese rice husk downdraft gasifier. An equilibrium modeling was developed to be used to predict the amount of biochar and syngas compositions. The modeling results showed a particularly good agreement with the experimental one. The average root means square error (RMSE) between experimental and modeling results is 1.642; 1.882; 1.445 and 1.345 in reduction temperature are 750oC; 800oC; 850oC and 900oC, respectively. Therefore, the model developed might be useful to predict the syngas composition and the biochar for rice husk gasification.**

***Keywords*— Rice husk; biochar; syngas; equilibrium model; downdraft gasifier.**

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I. INTRODUCTION

Biomass has the potential to displace petroleum and other fossil fuels [1]. Biomass exploitation may perform different ways for biological or thermal conversion [2]. Thermal conversion can be included pyrolysis, gasification, or combustion [3]. Pyrolysis is the thermal conversion of biomass in absolutely oxygen-free conditions to produce a liquid fuel called bio-oil. Biomass gasification is a thermochemical conversion in a low oxygen environment, producing syngas, a mixture mainly made of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and other hydrocarbons [4]. It has attracted the highest interest as it offers higher efficiencies than combustion and pyrolysis [5]. It has also been an energy conversion method with an efficiency from 14 to 25% [6]. In terms of sustainable development for clean energy production, biomass gasification can be a cost-effective and environmentally sustainable technology. For some remote areas like high mountain villages, rural areas, and small islands where they are not connected to the grid but have rich waste from agriculture and forest processing, biomass gasification might be one of the best approaches to the electricity generation system [7].

There have many works during the past time to study biomass gasification [8]–[11]. Combustion uses biomass as a fuel in high volumes of air to produce heat in the products of combustion as a mixture of carbon dioxide (CO_2), water vapor (H_2O), and nitrogen oxides (NO_x) [8], [9]. Gasifiers are principally divided into three types: fixed bed, fluidized bed, and entrained suspension gasifiers. The fixed bed gasifiers are categorized as downdraft, updraft, and cross draft [6]. The operation of biomass gasifiers depends on many complex chemical reactions, including fast pyrolysis, partial oxidation of pyrolysis products, gasification of the resulting char, conversion of tar and lower hydrocarbons, and water-gas shift [13], [14]. A general summary of the various numerical approaches developed up to the present is first presented to focus on thermochemical equilibrium models [15], [16]. More detail about the composition of syngas and biochar produced by gasifier from Viet Nam rice husk [10].

It is clear to be seen from some previous works that the amount and quality of produced gas, tar, and char of the

gasification are influenced significantly by some input technological parameters such as the temperature of reduction zone, the equivalence ratio (ER) of airflow, and some operating conditions of gasification [17]. Moreover, the gasification process should be focused and deeply researched to enable higher process efficiencies, better gas quality and purity, and lower investment costs. Selecting the optimal gasifier and its control strategy is fundamental to achieving efficient and clean energy production [8]. To foster the gasification technology in the future, advanced, cost-effective, and highly efficient, the gasification processes and systems are required and need to be studied furthermore. Discovering the method of biomass gasification for syngas and biochar production might solve both problems of effective use of renewable energy and environmental pollution. Therefore, a study is necessary to see how the effects of some variables on the biomass gasification products and how to predict these products without the experiment. In this study, a model uses to prediction the composition of gasification products has been developed. The experimental investigation has also conducted by the manufactured gasifier to verify the model.

II. Materials and Methods

A. Materials

The present study used the rice husk from the variety IR 50404 as fuel sourced from a rice mill located in Dong Thap province in the Mekong Delta. IR 50404 rice husk proximate and ultimate analysis for use in the downdraft gasifier model and experiment (Table. 1).

TABLE I
PROXIMATE AND ULTIMATE ANALYSIS FOR RICE HUSK

Characteristics	**IR 50404**
Proximate analysis (%)	
Volatile matter	58,28 ± 0,34
Fixed carbon	13,98 ± 0,32
Moisture	9,99 ± 0,76
Ash	17,71 ± 0,37
Ultimate analysis (%)	
C	41,26 ± 0,46
H	4,75 ± 0,16
O	35,46 ± 0,68
N	0,48 ± 0,05
S	0,01 ± 0,01
Heating value (MJ/kg)	15,55 ± 0,46
Density (kg/m^3)	100,42 ± 1,49

B. Model Development

In the model, the gasifier has been considered a black box, where some known streams flow in and the syngas flows out of the gasifier. The model predicts the syngas chemical compositions and biochar, while the equivalence ratio of airflow and the reduction temperature of the process are parameters of the problem.

The equilibrium model has been developed based on the following assumptions:

- The gasifier is in thermodynamic equilibrium.
- The rice husk consists of carbon, hydrogen, and oxygen. So, the chemical formula of rice husk is defined as CH_aO_b.
- The agent is air at a temperature of 25°C, moisture of 75%, and the system is at a pressure of 101.13 kPa.
- The products include CO, CO_2, H_2, CH_4, H_2O, N_2 and Biochar.
- Nitrogen is not involved in any chemical reaction inside the system.
- The gasifier is completely adiabatic and there is no heat loss from the gasifier.
- Gasification reaction rates are fast enough, and residence time is sufficiently long to reach the equilibrium state.

In real conditions, not all gasification products are gases. In particular, the presence of some solid output can be seen at the end of the process, which is known as biochar. The biochar is mainly made up of carbon and is formed by the biomass that has not reached the reaction zone [10]. To consider that not all the carbon participates in the equilibrium reactions, the n_1 factor has been introduced. This factor represents the carbon fraction that does not take part in the equilibrium reactions, while the remaining carbon bypasses the reaction zone.

Therefore, the global gasification reaction can be written as follows:

$$\begin{aligned} CH_{1.38}O_{0.64} + 0.146H_2O_{(l)} + qH_2O_{(g)} + mO_2 \\ + 3{,}76mN_2 \\ = n_1C + n_2H_2 + n_3CO + n_4CO_2 \\ + n_5H_2O + n_6CH_4 + 3{,}76mN_2 \end{aligned} \quad (1)$$

Where q is the amount of moisture air; m is the amount of oxygen per Kmole of rice husk. All inputs on the left-hand side of Eq. (1) are defined at 25°C. On the right-hand side n_1, n_2, n_3, n_4, n_5 and n_6 are the numbers of mole of the carbon, hydrogen, carbon monoxide, carbon dioxide and methane that are also unknown.

To find the six unknown species of the gasification product, six equations were required. Those equations were generated using mass balance, equilibrium constant relationships, and energy balance.

1) Mass balance:

Considering the global gasification reaction in Eq. (1), the first three equations were formulated by balancing each chemical element as shown in Eqs. (2) – (4).

Carbon balance:

$$n_1 + n_3 + n_4 + n_6 = 1 \quad (2)$$

Hydrogen balance:

$$2n_2 + 2n_5 + 4n_6 = 1.672 + 2q \quad (3)$$

Oxygen balance:

$$n_3 + 2n_4 + n_5 = 0.786 + q + 2m \quad (4)$$

Where $q = \frac{4{,}76}{45{,}5}m$; $m = \frac{4.1}{4}ER$

2) Thermodynamic equilibrium

Chemical equilibrium is usually explained either by minimization of Gibbs free energy or by using an equilibrium constant. To minimize the Gibbs free energy, constrained optimization methods are generally used, which requires understanding complex mathematical theories. For that reason, the present thermodynamic equilibrium model is developed based on the equilibrium constant and not on the

Gibbs free energy. The remaining two equations were obtained from the equilibrium constant of the reactions occurring in the gasification zone as shown below:

Methane reaction: C + 2H2 = CH4 (5)

Boudouard reaction: C + CO2 = 2CO (6)

Water-gas reaction: C + H2O = CO + H2 (7)

Eq. (6) and Eq. (7) can be combined to give the water–gas shift reaction by subtracting Eq. (6) from Eq. (7).

Water-gas shift reaction: CO + H2O = CO2 + H2 (8)

For the model in this study, the thermodynamic equilibrium was assumed for all chemical reactions in the gasification zone. All gases were assumed to be ideal and all reactions form at pressure 1 atm. Therefore, the equilibrium constants, which are functions of temperature for the water–gas shift reaction and the methane reaction are:

The equilibrium constant for methane reaction

$$K_1 = \exp\left[-\frac{\overline{\Delta G_T^0}}{RT}\right] = \frac{n_6}{(n_2)^2} \quad (9)$$

$\overline{\Delta G_T^0}$ is the standard Gibbs function.

R = 8,314 kJ/kmol K is the universal gas constant.

T is the reaction temperature.

The equilibrium constant for water–gas shift reaction

$$K_2 = \exp\left[-\frac{\overline{\Delta G_T^0}}{RT}\right] = \frac{n_2 n_4}{n_3 n_5} \quad (10)$$

3) Energy balance:

The equation for the energy balance for the gasification process, assumed to be adiabatic, is:

$$\begin{aligned} &H^0_{fricehusk} + 0.146\left(H^0_{fH_2O(l)} + H_{(g)}\right) \\ &\quad + q\left(H^0_{fH_2O(g)} + H_{(g)}\right) + mH^0_{fO_2} \\ &\quad + 3{,}76mH^0_{fN_2} \\ &\quad = n_1H^0_{fC} + n_2H^0_{fH_2} + n_3H^0_{fCO} \\ &\quad + n_4H^0_{fCO_2} + n_5H^0_{fH_2O(g)} \\ &\quad + n_6H^0_{fCH_4} + \Delta T(n_1C_{PC} \\ &\quad + n_2C_{PH_2} + n_3C_{PCO} + n_4C_{PCO_2} \\ &\quad + n_5C_{PH_2O} + n_6C_{PCH_4} \\ &\quad + 3{,}76mC_{PN_2}) \end{aligned} \quad (11)$$

At ambient temperature: $H^0_{fC}, H^0_{fH_2}, H^0_{fN_2}, H^0_{fO_2} = 0$

Eq. (10) reduces to:

$$\begin{aligned} &H^0_{fricehusk} + 0.146\left(H^0_{fH_2O(l)} + H_{(g)}\right) \\ &\quad + q\left(H^0_{fH_2O(g)} + H_{(g)}\right) \\ &\quad = n_3H^0_{fCO} + n_4H^0_{fCO_2} \\ &\quad + n_5H^0_{fH_2O(g)} + n_6H^0_{fCH_4} \\ &\quad + \Delta T(n_1C_{PC} + n_2C_{PH_2} + n_3C_{PCO} \\ &\quad + n_4C_{PCO_2} + n_5C_{PH_2O} \\ &\quad + n_6C_{PCH_4} + 3{,}76mC_{PN_2}) \end{aligned} \quad (12)$$

Where:

$H^0_{fricehusk}$ is the heat of formation of rice husk;

$H^0_{fH_2O(l)}$ is the heat of formation of liquid water;

$H_{(g)}$ is the heat of vaporization of water;

$H^0_{fH_2O(g)}$ is the heat of formation of vapor water;

$H^0_{fCO}, H^0_{fCO_2}$ and $H^0_{fCH_4}$ are heats of formation of CO, CO_2 and CH_4;

$C_{PC}, C_{PH_2}, C_{PCO}, C_{PCO_2}, C_{PH_2O}, C_{PCH_4}$ and C_{PN_2} are spicific heats of the carbon and gaseous products.

$\Delta T = T_2 - T_1$, T_2 is the gasification temperature at the reduction zone; T_1 is the ambient temperature.

$$\begin{aligned} &dH_{ricehusk} + 0.146dH_{H_2O(l)} + qdH_{H_2O(g)} \\ &\quad = n_1dH_C + n_2dH_{H_2} + n_3dH_{CO} \\ &\quad + n_4dH_{CO_2} + n_5dH_{H_2O(g)} \\ &\quad + n_6dH_{CH_4} + 3{,}76mdH_{N_2} \end{aligned} \quad (13)$$

Where:

$$dH_{(gas)} = H^0_f + \Delta H,\ \Delta H = \Delta T(C_{p(g)}) \quad (14)$$

$$dH_{H_2O(l)} = H^0_{fH_2O(l)} + H_{(vap)} \quad (15)$$

$$dH_{ricehusk} = H^0_{fricehusk} \quad (16)$$

Eqs. (2), (3), (4), (9), (10) and (13) represent six equations with six unknowns. Two of the eqs (9) and (10) are nonlinear equations while the rest are linear equations.

The set of equations is:

$$\left\{\begin{array}{c} n_1 + n_3 + n_4 + n_6 = 1 \\ 2n_2 + 2n_5 + 4n_6 = 1.672 + 2q \\ n_3 + 2n_4 + n_5 = 0.786 + q + 2m \\ K_1 = \frac{n_6}{(n_2)^2} \\ K_2 = \frac{n_2n_4}{n_3n_5} \\ dH_{ricehusk} + 0.146dH_{H_2O(l)} + qdH_{H_2O(g)} = \\ n_1dH_C + n_2dH_{H_2} + n_3dH_{CO} + n_4dH_{CO_2} + \\ n_5dH_{H_2O(g)} + n_6dH_{CH_4} + 3{,}76mdH_{N_2} \end{array}\right\} \quad (17)$$

4) Calculation procedure

$dH_{ricehusk}, dH_{H_2O(l)}, dH_{H_2O(k)}$ are the contants. $q, m, K_1, K_2, dH_C, dH_{H_2}, dH_{CO}, dH_{CO_2}, dH_{H_2O}, dH_{CO_2}, dH_{CH_4}, dH_{N_2}$ are the parameters that are determined when ER = 0.2 ÷ 0.4 and T_2= 750 ÷ 900. The set of equations was solved using the Newton-Raphson method.

C. Experimental Investigation

In order to study the gasification of rice husk in a downdraft, a household scale downdraft gasifier is designed and developed. The downdraft gasifier used in the present work is shown in Fig. 1.

Fig. 1 The manufactured downdraft gasifier [11]

Notes: 1) Rice husk feeder; 2) Reactor; 3) Biochar remover; 4. Cyclone; 5). Syngas cooling; 6) Syngas filter; 7) Fan; 8) Swirl bunner.

The gasification temperature is set in the reduction zone through a temperature controller from 750°C to 900°C. The agent is supplied in the combustion zone by a fan speed

controller. The airflow was calculated by equivalence ratio (ER) from 0.2 to 0.4 at a pressure of 101.13 kPa.

A portable infra-red syngas analyzer (Gasboard 3100P, Wuhan Cubic Optoelectronics Co, Ltd) was used to simultaneously measure CO, CO_2, CH_4, H_2, and O_2 in the syngas and for calculation of the heating value. The resolution and the precision of the compositions for all gas testing are below 0,01% and 2%, respectively.

D. Model Validation Method

The equilibrium model developed in this study was tested by comparing the calculation results with data from the experiment. The error in this comparison is estimated by the root mean square error (RMSE), defined as

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(y_e - y_m)^2}{n}} \qquad (18)$$

Where y_e is the value from the experimental results, y_m is the model's predicted value, and n is the amount of data.

III. Results and Discussion

A. Analyzation of the model

The model is used to predict the syngas compositions and biochar performance from different equivalence ratio and temperature values.

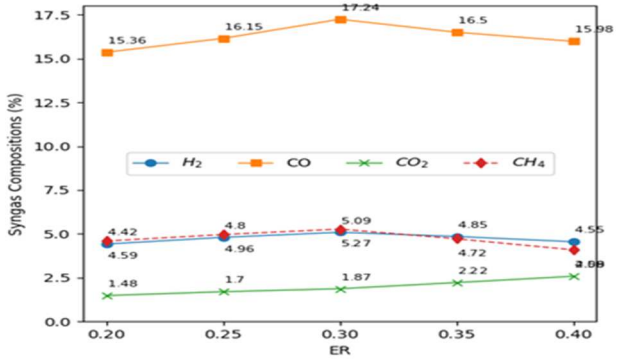

Fig. 2 Syngas compositions at T_2 = 750°C

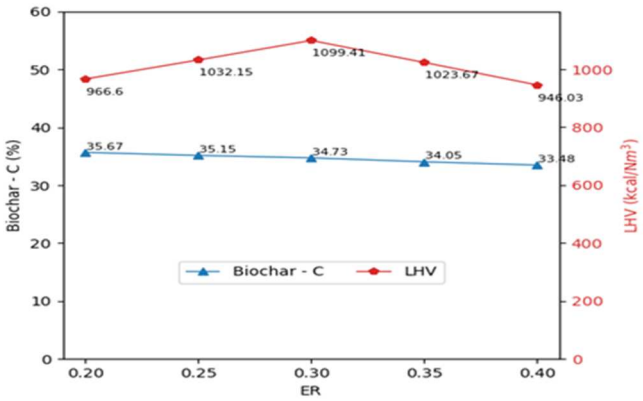

Fig. 3 Biochar and LHV at T_2 = 750°C

The syngas components and biochar are shown in Fig. 2-5 by fixing the reduction temperature at T_2 = 750°C – 900°C. It is observed that the ER increased from 0.2 to 0.4 the amount of biochar decreased, while the syngas increased when ER from 0.2 to 0.3 and the syngas decreased when ER from 0.3 to 0.4.

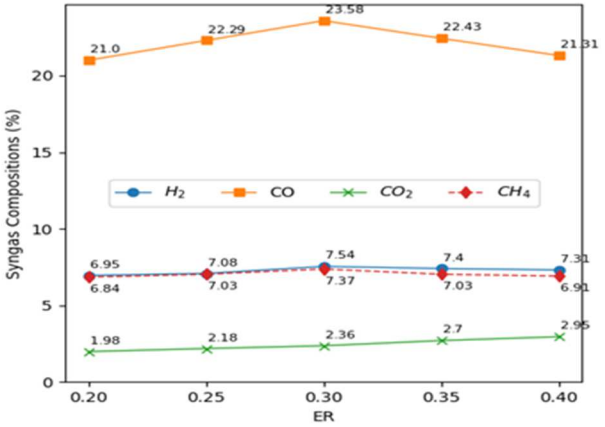

Fig. 4 Syngas compositions at T_2 = 900°C

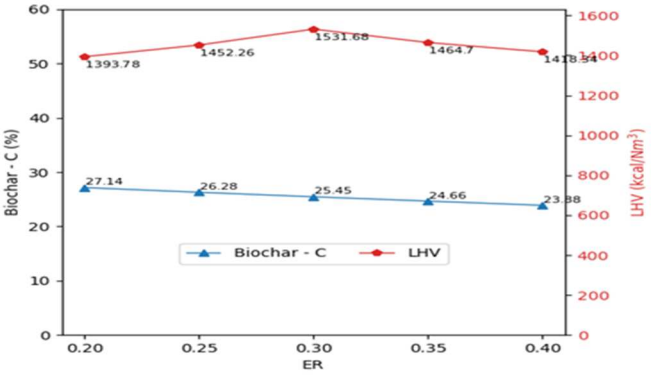

Fig. 5 Biochar and LHV at T_2 = 900oC

B. Validation of the model

Proper validation of the results from any model is an important part of numerical calculation. We have validated the mathematical model comparing the calculation results with the experimental data of Ma *et al.* [18] and Gai *et al.* [19], which are referred to as a process of gasification in a downdraft gasifier.

Ma *et al.* [18] have investigated the effect of equivalence ratio on the temperature inside the downdraft gasifier, the composition and heating values of the producer gas, the gas production rate, cold gas efficiency, and the carbon conversion rate using rice husk biomass.

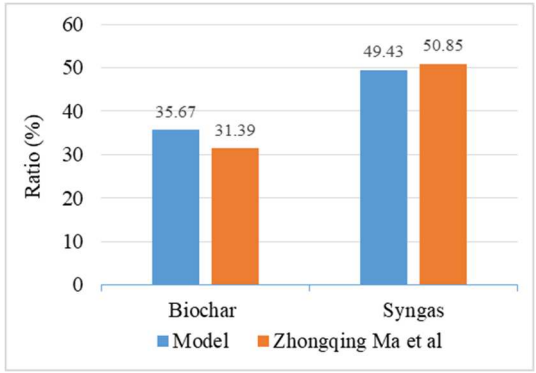

Fig. 6 Comparison biochar and syngas percentage between the model and Ma et al [18].

Gai *et al.* [19] have studied the influence of the operating conditions as equivalence ratio and reactor temperature on gas composition and gasification characteristics in terms of LHV, gas yield, gasification efficiency, and tar concentration in the raw gas during the gasification of non-woody biomass on downdraft gasifier.

The comparisons between the model and the experimental results consider the biochar and the syngas percentages. Fig. 6 shows that the percentage of biochar is over 11.8% and the percentage of syngas is lower than 2.8% estimated by the model. Moreover, the model syngas LHV is 4.04 MJ/Nm^3, compared with Ma et al. [18], which is 4.44 MJ/Nm3, and Gai *et al.* [19] is 4.43 MJ/Nm^3 (Fig. 7).

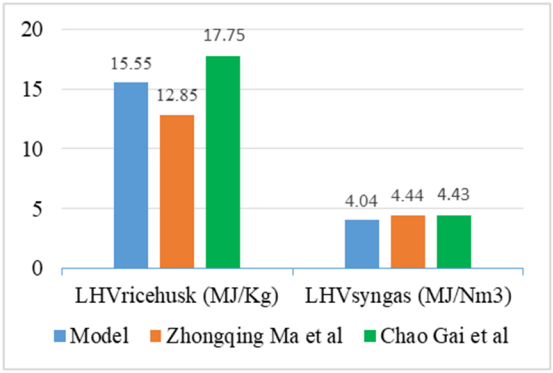

Fig. 7 Comparison syngas heating value between the model and Ma *et al.* [18] and Gai *et al.* [19].

Regarding the percentages of biochar and syngas predicted by the model, there is a very good correspondence with Alhinai *et al.* [20] reported the experiments have conducted at different temperatures, ranging within 400, 500, and 600°C to produce and characterize biochar from rice husk sample mixtures by pyrolysis in a fixed bed reactor. (Fig. 8).

Moreover, the model is validated by comparing its results with measured data in experimental—four sets of data from an experimental investigation. The results of this validation are summarized in Table. 2 – 5. The average RMSE between experimental and modeling data is 1.642; 1.882; 1.445 and 1.345 in reduction temperature is 750°C; 800°C; 850°C and 900°C, respectively.

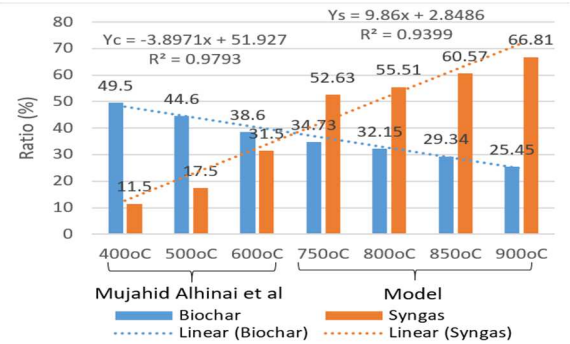

Fig. 8. The biochar and syngas in a variation of temperature

So, the model predicts the gas composition and biochar much closer to the experimental value.

TABLE II
COMPARISON BETWEEN EXPERIMENTAL AND MODEL RESULTS AT T_2 = 750°C

ER	Experimental					Model					RMSE
	Biochar (%)	CO (%)	CO_2 (%)	H_2 (%)	CH_4 (%)	Biochar (%)	CO (%)	CO_2 (%)	H_2 (%)	CH_4 (%)	
0.2	37.80	17.08	1.32	4.90	4.96	35.67	15.36	1.48	4.42	4.59	1.256
0.25	37.50	18.56	1.42	5.30	5.87	35.15	16.15	1.70	4.80	4.96	1.580
0.3	37.30	20.16	1.51	5.80	6.65	34.73	17.24	1.87	5.09	5.27	1.880
0.35	36.90	19.08	1.61	5.40	5.23	34.05	16.50	2.22	4.85	4.72	1.773
0.4	36.60	17.97	1.68	5.10	4.15	33.48	15.98	2.58	4.55	4.09	1.721
										Average	1.642

TABLE III
COMPARISON BETWEEN EXPERIMENTAL AND MODEL RESULTS AT T_2 = 800°C

ER	Experimental					Model					RMSE
	Biochar (%)	CO (%)	CO_2 (%)	H_2 (%)	CH_4 (%)	Biochar (%)	CO (%)	CO_2 (%)	H_2 (%)	CH_4 (%)	
0.2	36.40	18.12	1.42	5.40	5.44	33.02	16.97	1.63	4.82	5.02	1.631
0.25	36.10	19.16	1.54	6.10	6.49	32.59	17.72	1.79	5.37	5.55	1.782
0.3	35.80	21.17	1.59	6.50	7.10	32.15	18.43	1.91	5.65	5.87	2.153
0.35	35.20	20.74	1.62	6.20	5.89	31.86	17.98	2.14	5.43	5.46	1.991
0.4	34.90	19.18	1.74	5.80	4.30	31.34	17.34	2.34	5.17	4.91	1.854
										Average	1.882

TABLE IV
COMPARISON BETWEEN EXPERIMENTAL AND MODEL RESULTS AT T_2 = 850°C

ER	Experimental					Model					RMSE
	Biochar (%)	CO (%)	CO_2 (%)	H_2 (%)	CH_4 (%)	Biochar (%)	CO (%)	CO_2 (%)	H_2 (%)	CH_4 (%)	
0.2	34.70	19.12	1.44	5.60	5.45	30.78	18.96	1.80	5.58	5.50	1.762
0.25	33.80	19.16	1.47	6.30	6.50	30.11	19.88	1.91	6.12	5.86	1.719
0.3	32.50	21.11	1.59	7.10	7.30	29.34	20.86	2.11	6.34	6.22	1.553
0.35	30.30	20.74	1.67	6.20	5.90	28.53	19.11	2.45	6.42	6.05	1.137
0.4	29.40	18.87	1.75	5.50	4.32	27.74	18.58	2.82	5.66	5.56	1.053
										Average	1.445

TABLE V
COMPARISON BETWEEN EXPERIMENTAL AND MODEL RESULTS AT T_2 = 900°C

ER	Experimental					Model					RMSE
	Biochar (%)	CO (%)	CO_2 (%)	H_2 (%)	CH_4 (%)	Biochar (%)	CO (%)	CO_2 (%)	H_2 (%)	CH_4 (%)	
0.2	29.10	20.15	1.63	6.92	6.53	27.14	21.00	1.98	6.95	6.84	0.978
0.25	28.60	21.16	1.69	7.10	7.02	26.28	22.29	2.18	7.08	7.03	1.175
0.3	28.20	24.02	1.70	7.69	7.62	25.45	23.58	2.36	7.54	7.37	1.287
0.35	27.50	22.45	1.88	6.74	6.08	24.66	22.43	2.70	7.40	7.03	1.420
0.4	27.10	21.18	1.98	6.30	4.66	23.88	21.31	2.95	7.31	6.91	1.866
										Average	1.345

IV. CONCLUSION

This study has developed an equilibrium model to simulate the gasification process in a downdraft gasifier. The model has been verified by comparing it with the experimental investigation results. The percentage of biochar and syngas components predicted from the developed model and the experimental investigation is in good agreement. The results indicated that the average RMSE value of the model is the criterion of the agreement between experimental data and model, when ER from 0.2 to 0.4, the average RMSE value was 1.642; 1.882; 1.445 and 1.345 in T_2 was 750°C; 800°C; 850°C and 900°C, respectively. Therefore, the model is reliable for predicting the biochar and syngas compositions by varying the gasification temperature and equivalence ratio. It can be acceptable for further prediction.

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