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Downdraft gasifier identification via neural networks

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Abstract

This research presents the identification of producer gas resulting from the conversion of a given type of biomass in a downdraft gasifier, the use of a neural network (NN) to predict the identity for a given biomass type and the comparison of the NN prediction to measured results of biomass fuel conversions. Each type of biomass has different characteristics which affect the composition of the producer gas and thus its effective energy content. This research predicts the composition of the producer gas from the characteristics of the biomass by creating a mathematical model using a neural network. The model is then used to run simulations which are compared to actual measured values from experiments and then the accuracy of the simulations are verified with Simulink/MATLAB. The results show that the simulation predicts the CO content of producer gas with an average error of 1.73%, 7.01% for H_2, and 1.58% for CH_4. The simulation predicts the higher heating value with an average error of 0.73% and a lower heating value with an average error of 0.81%.

Keywords: *downdraft gasifier, identification, neural network, producer gas*

1. Introduction

Energy consumption in Thailand is increasing for both household and industrial uses, which leads to increased demand for fossil fuels such as fuel oil, natural gas, coal, etc. Renewable energy is an alternative source of energy which decreases the import of fossil fuels and reduces global warming. Biomass can be a source of renewable energy. It is a cheap fuel source and plentiful in Thailand. The use of biomass can help to reduce the demand on fuel imports. Moreover, the energy produced from biomass by using proper technology will reduce pollution and global warming. One clean technology, which can be used to produce energy from biomass is a gasifier. Gasifiers can change solid biomass into a gas which is called a producer gas. It has a higher heating value than just burning the original biomass and it is easier to control the rate of combustion. Producer gas can be used to reduce the use of fossil fuels.

The amount of biomass available in Thailand is high. Each type is different in physical and chemical properties. These properties affect the composition and heat value of producer gas that is produced from each type of fuel. Being able to accurately estimate the heat values of producer gases that are generated from each biomass, can be used for classifying biomass for its most suitable application.

2. Objective

To study the composition of producer gas resulting from biomass conversion by a downdraft gasifier and create a model of the conversion using a neural network. The accuracy of the model is then verified against producer gas composition measurements obtained from experiments are then used to verify the accuracy of the model using Simulink/MATLAB.

3. Theory

3.1 Downdraft gasifier

Downdraft gasifier as shown in Figure 1 has special characteristics where the combustion zone at the center of reactor has smaller diameter (throat) than the main reactor. This condition causes the gasification process to be more complicated. The gas production is influenced by the diameter of the throat and the continuity of fuel flow down inside of the reactor, especially when it passed through the throat (Sivakumar, Ragunathan, & Elango, 2014; Montuori, Vargas, & Alcázar-Ortega, 2015). Fuel continuity will travel down depending on the proportionality of fuel size to the throat diameter. The suitable design will help the production of combustible gas in gasification process.

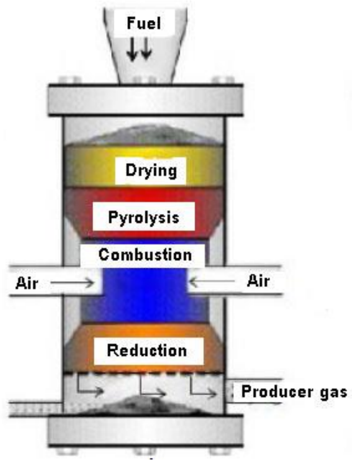


Figure 1 Downdraft gasifier furnace. (Chenxi, Ruthut, & Sukanya, 2011)

The various zones in the downdraft gasifier as shown in Figure 1 are as follows:

3.1.1. Combustion zone (Ingle & Lakade, 2015)

In the combustion zone, the oxygen in the air-stream reacts with the carbon and hydrogen in the fuel to reduce carbon and hydrogen to form carbon dioxide and water. Carbon dioxide is obtained from carbon and water is obtained from the hydrogen in the biomass fuel. Also, exothermic reaction takes place here and the temperatures is normally 1100 - 1500˚C. The main reactions are:

$$C + O_2 \rightarrow CO_2 + Heat \quad (1)$$

$$2H_2 + O_2 \rightarrow 2H_2O + Heat \quad (2)$$

3.1.2. Reduction zone (Ingle & Lakade, 2015)

The partial combustion products, carbon dioxide (CO_2) and water (H_2O) that are obtained from the combustion zone are now passed through the reduction zone. Here, CO_2 and H_2O are reduced to form carbon monoxide (CO) and hydrogen (H_2) by absorbing heat from the combustion zone. The combustion zone raises the temperature of the reduction zone to promote the carbon/steam gasification reaction which has higher activation energy. This reaction requires temperature of 900˚C or above. Over 90% of CO_2 is reduced to CO at temperatures above 900 ˚C. The main reactions are:

Boudouard Reaction:

$$C + CO_2 \rightarrow 2CO - Heat \quad (3)$$

Water Gas Reaction:

$$C + H_2O \rightarrow CO + H_2 - Heat \quad (4)$$

Water Gas Reaction:

$$C + 2H_2O \rightarrow CO_2 + 2H_2 - Heat \quad (5)$$

Water Shift Reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 + Heat \quad (6)$$

Methanation Reaction:

$$C + 2H_2 \rightarrow CH_4 + Heat \quad (7)$$

3.1.3. Pyrolysis zone (Sanjay Gupta, 2006)

Biomass pyrolysis is an intricate process. Products depend on temperature, pressure and heat losses. Up to 200 ˚C, only water is driven off. In range 200-280 ˚C, CO_2, acetic acid, and water are given off. In range 280-500 ˚C, real pyrolysis occurs and produces large quantities of tar and gases containing CO_2. In the range of 500-700 ˚C, gas production is small and contains hydrogen. The main reactions are:

$$\text{Dry biomass} + \text{Heat} \rightarrow \text{Charcoal} + CO + CO_2 + H_2O + CH_4 + C_2H_6 + \text{Pyroligneous Acid} + \text{Tar} \quad (8)$$

3.1.4. Drying zone (Sanjay Gupta, 2006)

Biomass is being dried in the drying zone. Usually the moisture content of biomass is 10-30%. Some organic acids come out during drying process which may cause corrosion of gasifiers. The main reactions are:

$$\text{Biomass} + \text{Heat} \rightarrow \text{Dry biomass} + \text{steam} \quad (9)$$

3.2 Heat energy of producer gas

For higher heating value (HHV) and lower heating value (LHV) of producer gas can be found in equations (10) and (11), which are in kJ/m^3 units (Kowkasikum, 1994).

$$LHV = HHV - 2016(H_2) + 2(CH_4) + \frac{n}{2}(C_mH_n) \quad (10)$$

$$HHV = 12684(CO) + 12810(H_2) + 39984(CH_4) + 70770(C_2H_6) + 64218(C_2H_4) + 101472(C_2H_8) + 133518(C_2H_{10}) \quad (11)$$

3.3 Biomass fuels

Biomass gasifier can be designed for a wide range of biomass fuels such as corn cob, coconut shell, Eucalyptus, and bamboo. Biomass fuels from different sources will have different qualities, but the important factor that affects the quality of biomass fuels is the amount of carbon that is in the fuels. For biomass fuels with high carbon content, the producer gas will have a high heating value. For the analysis and testing of solid biomass fuels, it needs to be complied with ASTM standards, including proximate analysis in accordance with ASTMD3172, ultimate analysis by ASTMD3176, and heating value according to ASTM D2105 (Jittabut et al., 2010). The properties of some biomass fuels are shown in Table 1 and Table 2.

Table 1 The properties of some biomass fuels (Proximate analysis)*

Biomass fuel	Moisture, %	Fixed Carbon, %	Volatile Matter, %	Ash, %
Coconut shell	4.23	18.22	76	1.43
Eucalyptus	1.14	17.90	79.70	2.64
Bamboo	5.89	20.73	70.48	2.90
Corncob	10.6	5.54	80.8	3.09
Wood chip	8.28	12.82	73.12	5.81

*(Jareansuk & Patarakeadvit, 2015; Homduang, Dudsade, & Sasujit, 2015; Narongthong & Sottigulanun, 2013)

Table 2 The properties of some biomass fuels (Ultimate Analysis)*

Biomass fuel	C,%	H,%	O, %	N, %	S, %	Cl, %	HHV, kJ/kg	LHV, kJ/kg
Coconut shell	46.20	5.42	47.46	0.87	0.05	0.10	20202	20188
Eucalyptus	48.93	8.05	42.28	0.58	0.09	1.67	18557	18392
Bamboo	44.76	5.98	16.21	0.11	0.04	ND	17418	16162
Corncob	42.28	6.34	40.26	1.20	ND	ND	24092	22,472
Wood chip	43.73	6.09	40.41	0.16	ND	ND	23897	22,386

*(Jareansuk & Patarakeadvit, 2015; Homduang et at., 2015; Narongthong & Sottigulanun, 2013)

3.4 Neural network (NN) learning and training

NN has outstanding features in terms of fast and accurate calculations (Widrow & Lehr, 1990; Janpong, Areerak, & Areerak, 2011). Therefore NN is suitable for applying as a mathematical model to identify the downdraft gasifier. This paper uses a backpropagation neural network (BPNN) for this identification. A feed-forward backpropagation network toolbox in MATLAB is used for learning and training (Beale, Hagan, & Demuth, 1992-2013 a); (Beale, Hagan, & Demuth, 1992-2013 b) as shown in equations (12) - (14). The learning and training structure of BPNN for this research is 4 layers called 1x8x8x6 BPNN; the first layer or the input layer has 1 node, the second and the third layer has 8 nodes and the fourth layer or the output layer has 6 nodes. The transfer functions for layers 1, 2, 3 and 4 are logsig, logsig, logsig, purelin, respectively. The BPNN structure is shown in Figure 2 and the equation of the output for each layer is shown in equation (15) - (18). The BPNN learning and training uses 11 inputs that consist of a number of elements that are the biomass components and various parameters that effect the burns on a downdraft gasifier. The six target values are the producer gases as shown in the article (Jareansuk & Patarakeadvit, 2015; Homduang et at., 2015; (Narongthong & Sottigulanun, 2013). For learning and training, the weight and bias are adjusted, which the output value of NN is close to the target value.

net = newff(PR,[S1 S2...SNl],{TF1 TF2...TFNl},BTF,BLF,PF) (12)

[net,tr] = train(net,input,taget,Xi,Ai,EW) (13)

[Y,Xf,Af,E,perf] = sim(net,input) (14)

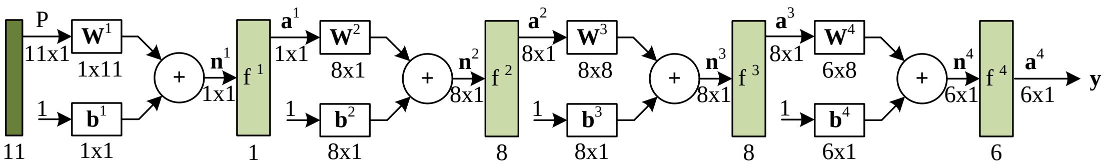


Figure 2 Learning and training structure of BPNN

$$\mathbf{a}^1_{1x1} = \text{logsig}\left(\mathbf{W}^1_{1x11}\mathbf{P}_{11x1} + \mathbf{b}^1_{1x1}\right) \quad (15)$$

$$\mathbf{a}^2_{8x1} = \text{logsig}\left(\mathbf{W}^2_{8x1}\mathbf{a}^1_{1x1} + \mathbf{b}^1_{8x1}\right) \quad (16)$$

$$\mathbf{a}^3_{8x1} = \text{logsig}\left(\mathbf{W}^3_{8x8}\mathbf{a}^2_{8x1} + \mathbf{b}^3_{8x1}\right) \quad (17)$$

$$\mathbf{y}_{6x1} = \mathbf{a}^4_{6x1} = \text{purelin}\left(\mathbf{W}^4_{6x8}\mathbf{a}^3_{8x1} + \mathbf{b}^4_{6x1}\right) \quad (18)$$

where $\mathbf{W}^{\text{l}}_{\text{nxi}}$ is the weight value of the layer l with n nodes and the I inputs. $\mathbf{b}^{\text{l}}_{\text{nx1}}$ is the bias value of the layer l with n nodes. $\mathbf{a}^{\text{l}}_{\text{nx1}}$ is the output value of the layer l with n nodes.

The parameters from the BPNN design are used in learning and training. The results are shown in Figure 3. The weight and bias values updating is the process of learning and training of BPNN. The difference between the BPNN's output and the target value is called the mean square error (MSE), which must less than the set value 1×10^{-10}. The NN adjusts the weight and bias value by 575 iterations. This process results in getting a proper weight and bias value for the mathematical modeling to identify the operation of the downdraft gasifier using the neural network as show in Equations (19) - (26).

4. Methodology

4.1 Simulation setup

This step is to create a mathematical model to identify the type of downdraft gasifier. The data is from the learning and training of BPNN based on the past research on the production of producer gas from biomass (Jareansuk & Patarakeadvit, 2015; Homduang et at., 2015; Narongthong & Sottigulanun, 2013). The proper weight and bias values are used as parameters for mathematical modeling in Simulink/MATLAB as shown in Figure 4. After creating the model, Identification tests will be performed by entering the 11 input values for the biomass properties and the output of the model will be the producer gasses, which its calculation can be shown in Figure 4.

4.2. Experimental setup

4.2.1 Designing and building a downdraft gasifier furnace

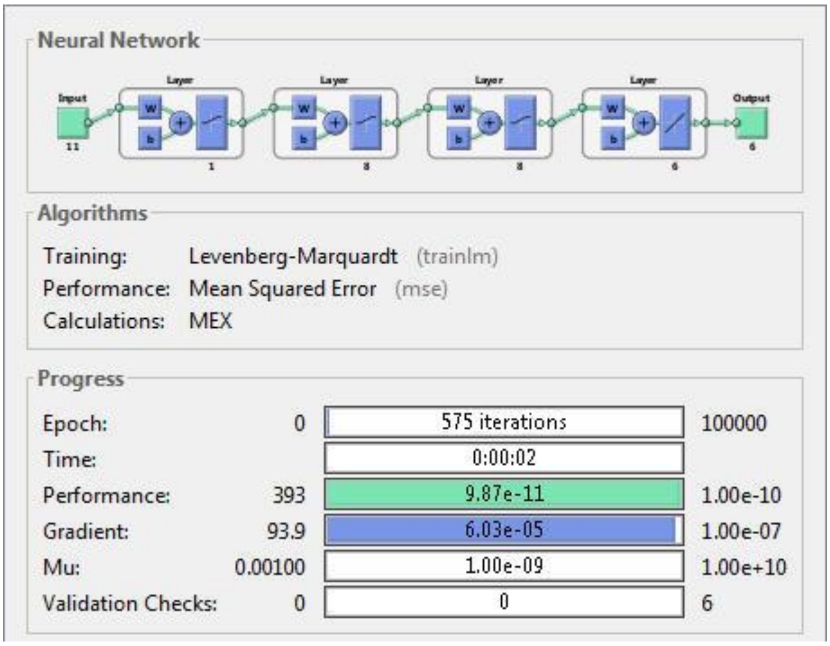
This step is designing and building a downdraft gasifier furnace. The furnace is cylindrical, 1.43 m in length, with 4 layers, inside diameter 0.36 m, and outside diameter 0.46 m. The inner wall is fireproof brick, sealed with fireproof mortar, covered with insulation, and the outer layer is sheet steel. The downdraft gasifier furnace is shown in Figure 5.

4.2.2 Bamboo fuel analysis

Bamboo fuel was analyzed by proximate analysis according to ASTMD3172 and ultimate analysis by ASTMD3176 and the heating value according to ASTM D2105. The bamboo fuel used in the experiment has a scientific name “Dendrocalamus sericeus”.

4.2.3 Downdraft gasifier furnace testing

Test the downdraft gasifier furnace and collect the sample of producer gas produced to analyze the gas components and the heating value.



(a) Neural network training

(b) Performance

Figure 3 BPNN learning and training result

$$\mathbf{W}^{1}_{1\times 11} = [0.000449 \quad 0.005367 \quad 0.001579 \quad 0.000221 \quad 0.003408 \quad 0.000455 \quad \ldots$$
$$\ldots \quad 0.001234 \quad 8.38\times 10^{-6} \quad 3.05\times 10^{-6} \quad 0 \quad 23829.79\,] \tag{19}$$

$$\mathbf{W}^{2}_{8\times 1} = [-44.4865 \quad -44.2753 \quad -45.0255 \quad -45.3042 \quad -43.655 \quad 45.5109 \quad 44.3854 \quad -44.9862\,]^{T} \tag{20}$$

$$\mathbf{W}^{3}_{8\times 8} = \begin{bmatrix} 1.4365 & 1.5595 & 3.9919 & 1.6327 & 2.8110 & -0.7035 & 3.6087 & -3.3271 \\ -1.0060 & -2.5424 & 0.9323 & 3.0714 & 5.8813 & -6.6126 & -0.3098 & -1.3744 \\ -2.8387 & -6.6967 & 1.7720 & 0.9009 & -3.5380 & -0.2301 & -2.4072 & -1.5252 \\ 3.4896 & 6.0620 & 8.2498 & 6.5616 & 4.4159 & -2.0509 & 2.3953 & -0.8050 \\ 4.3534 & 1.5332 & 3.3182 & -1.5105 & 2.7643 & 3.8238 & 3.5560 & -2.0583 \\ -1.5847 & 0.7787 & -4.3891 & -2.1859 & 0.7673 & 0.9051 & -4.1670 & -2.2297 \\ -1.9421 & -5.9503 & -4.4143 & -2.2679 & -2.8980 & -0.3017 & -1.1190 & 1.7027 \\ -1.3954 & 1.2357 & -1.9900 & 1.3251 & -0.8424 & -4.9807 & 4.1403 & 2.3412 \end{bmatrix} \tag{21}$$

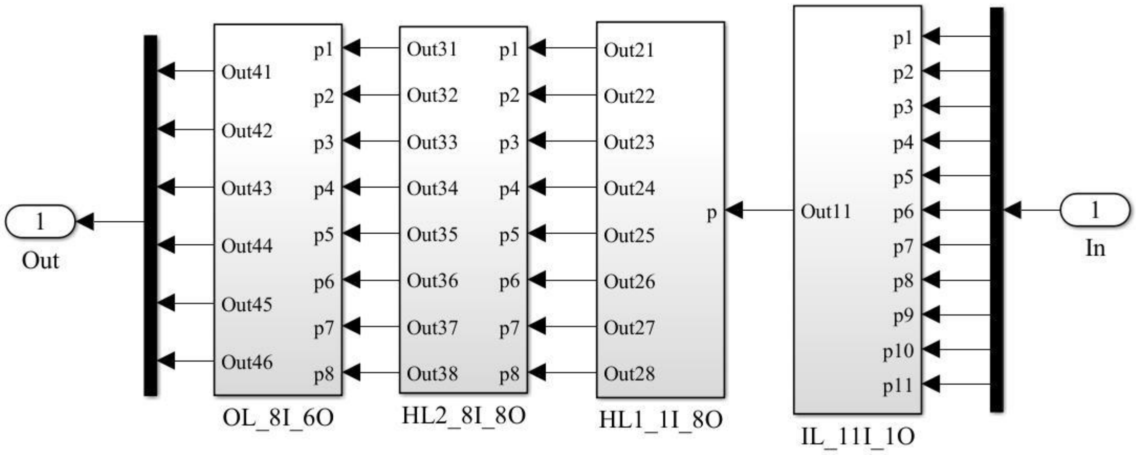
$$\mathbf{W}^{4}_{6\times 8} = \begin{bmatrix} 3.2685 & 3.1353 & 6.6308 & 1.8125 & 2.6293 & 4.1126 & 2.2695 & 5.9632 \\ 1.6432 & 1.4590 & 1.9014 & 0.6761 & -0.5459 & -2.0629 & -0.0707 & 1.4189 \\ 2.9659 & 3.1353 & 4.7210 & 1.3897 & 2.9548 & -2.5151 & -1.2676 & -15.9913 \\ 3.9723 & -3.6309 & 6.4445 & -1.5351 & 4.9411 & 4.0870 & 3.8203 & 12.2711 \\ 5.8555 & -46665 & 8.7556 & -2.3104 & 12.7966 & 2.8178 & 4.2596 & -4.1729 \\ 0.2564 & 0.4792 & 2.1078 & 0.0134 & 1.2903 & -6.1085 & 1.1102 & 0.4791 \end{bmatrix} \tag{22}$$

$$\mathbf{b}^{1}_{1\times 1} = [-64.9957\,] \tag{23}$$

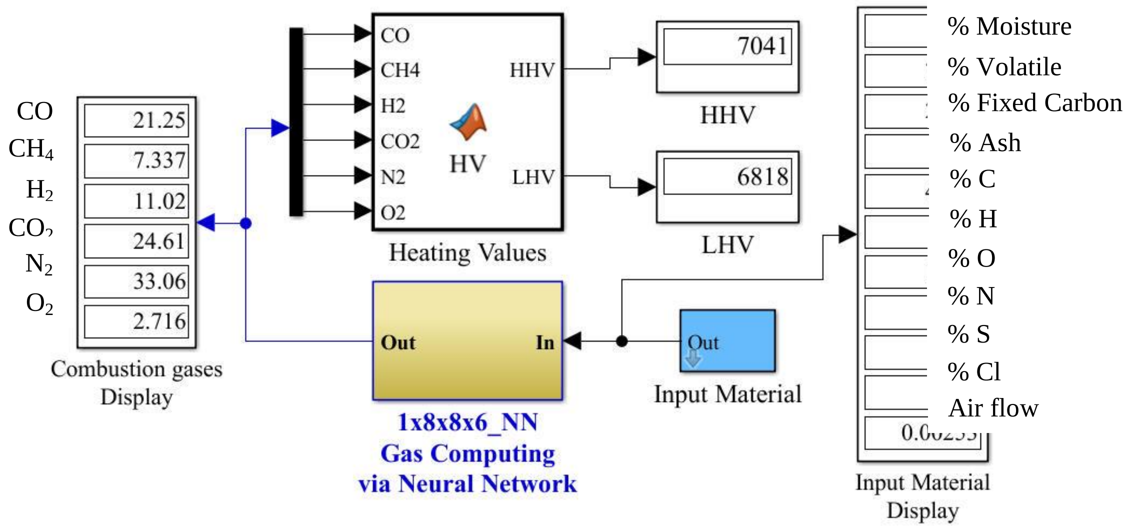
$$\mathbf{b}^{2}_{8\times 1} = [45.0437 \quad 39.0904 \quad 31.6066 \quad 24.6870 \quad 21.6887 \quad -9.6927 \quad -9.1410 \quad -2.3942\,]^{T} \tag{24}$$

$$\mathbf{b}^{3}_{8\times 1} = [4.2139 \quad -8.0921 \quad -2.4820 \quad -2.6281 \quad -2.6908 \quad 1.0673 \quad -5.6811 \quad 0.9692\,]^{T} \tag{25}$$

$$\mathbf{b}^{4}_{6\times 1} = [10.9711 \quad 4.8633 \quad 8.9286 \quad 13.3798 \quad 18.8483 \quad 0.9413\,]^{T} \tag{26}$$



(a) 1x8x8x6_NN Gas Computing via Neural Network block



(b) Simulation test block

Figure 4 The gasifier identification via neural network on Simulink/MATLAB

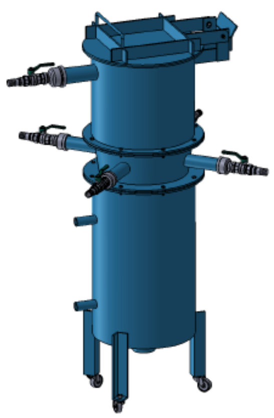


Figure 5 Downdraft Gasifier furnace

5. Results and discussion

5.1 Simulation results

The simulation of the downdraft gasifier furnace, choosing bamboo fuel can be resulted as in Table 3 and Figure 6

Table 3 and Figure 6 show the best simulated result is 0.00253 kg/s flow rate of air into the downdraft gasifier furnace. The producer gas is composed of 21.25% carbon monoxide (CO), 7.38 % methane (CH_4), 11.02% hydrogen (H_2), 24.61% carbon dioxide (CO_2), 33.06% nitrogen (N_2), and 2.72% oxygen (O_2). Compositions of producer gas can be seen that only 3 types are gas fuels; these are carbon monoxide, hydrogen, and methane. In addition to this flow rate of air, the higher heating value was 7040.64 kJ / kg and the lower heating value was 6818.18 kJ / kg. This is the highest among other flow rates.

Table 3 The producer gas from simulation (Bamboo Fuel)

Air flow rate, kg/s	Producer gas, % by volume						HHV kJ/kg	LHV kJ/kg
	CO	CH_4	H_2	CO_2	N_2	O_2		
0.00253	21.25	7.38	11.02	24.61	33.06	2.72	7040.64	6818.18
0.00269	19.76	6.89	13.34	22.98	34.43	2.59	6971.71	6702.50
0.00273	19.54	6.84	13.93	22.53	34.59	2.56	6997.39	6716.29
0.00296	19.83	6.68	10.45	25.52	35.11	2.42	6523.21	6312.28

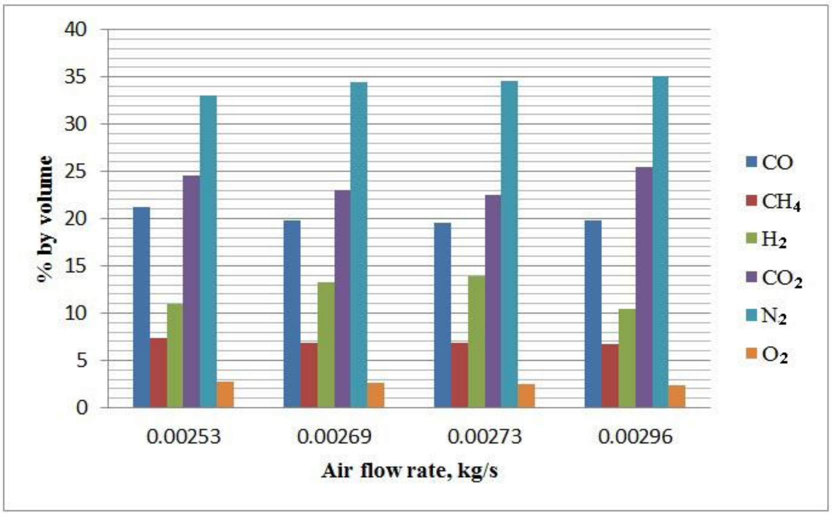


Figure 6 The producer gas from simulation

5.2 Experimental results

The analysis of the properties of bamboo fuel by Proximate analysis and Ultimate Analysis found that the Moisture 5.89% Fixed Carbon 20.73 % , Volatile Matter 70.48 % Ash 2.90 % carbon 44.76 % , hydrogen 5.98 %, oxygen 16.21 %, nitrogen 0.11% ,sulfur 0.04 % ,higher heating value (HHV) 17418kJ/kg and lower heating value (LHV) 16162 kJ/kg . The results of the producer gas analysis are shown in Table 4 and Figure 7.

From the results of the downdraft gasifier furnace test as shown in Table 4 and Figure 7, it was found that the flow rate of air was 0.00253 kg/s providing the best amount of producer gas. The producer gas produced consists of carbon monoxide (CO) 22.37%, methane (CH_4) 7.67%, hydrogen (H_2) 9.29%, carbon dioxide (CO_2) 25.83%, nitrogen (N_2) 32.02%, and oxygen (O_2) 2.82%. In addition, the higher heating value was 7096.06 kJ/kg and lower heating value was 6908.48 kJ/kg, which is higher than the other air flow rate.

Table 4 The producer gas from experimental (Bamboo Fuel)

Air flow rate, kg/s	Producer gas, % by volume						HHV kJ/kg	LHV kJ/kg
	CO	CH_4	H_2	CO_2	N_2	O_2		
0.00253	22.37	7.67	9.29	25.83	32.02	2.82	7096.06	6908.48
0.00269	19.90	6.95	13.41	22.89	34.25	2.60	7020.83	6750.20
0.00273	19.77	6.87	12.88	23.38	34.52	2.58	6905.25	6645.34
0.00296	19.84	6.63	10.53	25.49	35.20	2.32	6516.23	6303.74

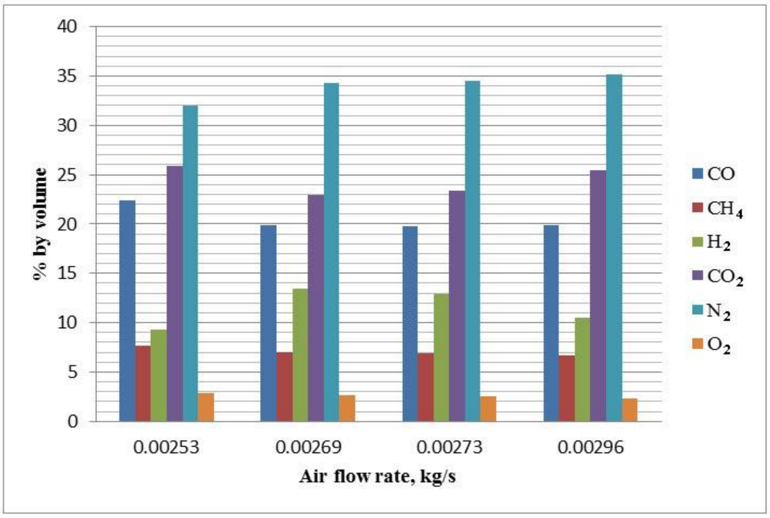


Figure 7 The producer gas from experimental

5.3 Comparison of simulation results and experimental results.

The test results are similar to the simulation model. Table 5 and Figure 8 show the quantity and composition of the producer gas in comparison between the actual test and the simulation model.

Table 5 and Figure 8 show that the amount of gas, obtained from the simulation results and the results from the actual tests are very similar, for example at 0.00253 kg/s air flow rate; the results from the simulation for carbon monoxide were 21.25%, 7.38% for methane and 11.02 % for hydrogen. While the results from the actual test were 22.37%, 7.67% and 9.29%, respectively.

5.4 Accuracy of simulations

In general, the accuracy of the model can be obtained by comparing the results between the simulation and the experimental results. These are generally expressed in error percentages. As shown in Table 6 and Figures 9 to11.

Table 5 The producer gas and the heating value from experiment and simulation

Producer Gas	Air flow rate kg/s							
	0.00253		0.00269		0.00273		0.00296	
	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.	Exp.	Sim.
CO	22.37	21.25	19.90	19.76	19.77	19.54	19.84	19.83
CH_4	7.67	7.34	6.95	6.89	6.87	6.84	6.63	6.68
H_2	9.29	11.02	13.41	13.34	12.88	13.93	10.53	10.45
CO_2	25.83	24.61	22.89	22.98	23.38	22.53	25.49	25.52
N_2	32.02	33.06	34.25	34.43	34.52	34.59	35.20	35.11
O_2	2.81	2.72	2.60	2.59	2.58	2.56	2.32	2.42
HHV	7096.06	7040.64	7020.83	6971.71	6905.25	6997.39	6516.23	6523.21
LHV	6908.48	6818.18	6750.20	6702.50	6645.34	6716.29	6303.74	6312.28

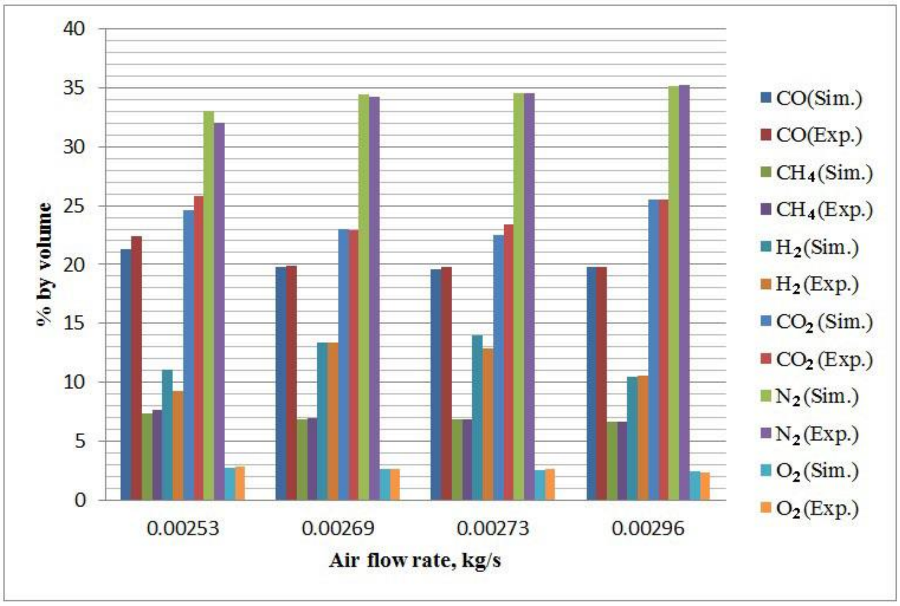


Figure 8 The producer gas from the simulation and the experimental

Table 6 The percentage error of producer gas and heating value

Producer Gas, % by volume	Air flow rate, kg/s				Average %
	0.00253	0.00269	0.00273	0.00296	
CO	5.03	0.70	1.17	0.03	1.73
CH_4	4.38	0.81	0.48	0.66	1.58
H_2	18.63	0.52	8.16	0.73	7.01
CO_2	4.73	0.39	3.62	0.13	2.22
N_2	3.25	0.53	0.21	0.24	1.06
O_2	3.41	0.54	0.80	3.96	2.18
HHV, kJ/kg	0.78	0.70	1.33	0.11	0.73
LHV, kJ/kg	1.31	0.71	1.07	0.14	0.81

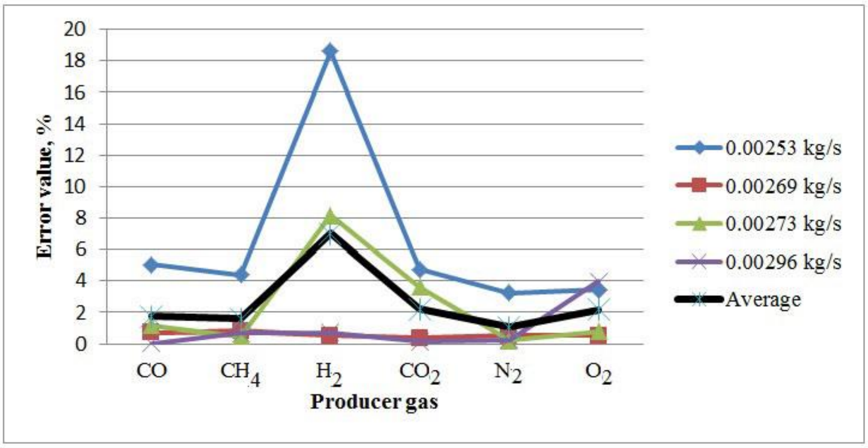


Figure 9 The percentage error of producer gas

Table 6 and Figures 9 to 11 show the percentage error of producer gas and heat energy from the downdraft gasifier furnace. By comparing the results from the model and the actual test, it was found that the air flow rate is ranged from 0.00253 to 0.00296 kg/s, the error for carbon monoxide (CO) is varied from 0.03-5.03%, 0.48-4.38% for methane (CH_4), 0.52-18.63% for hydrogen (H_2), 0.13-4.73% for carbon dioxide (CO_2), 0.25-3.25%, for nitrogen (N_2), and 0.54-3.96% for oxygen (O_2). Therefore, the average errors of producer gas are 1.73% for CO, 1.58% for CH_4, 7.01% for H_2, 2.22% for CO_2, 1.06% for N_2, and 2.18% for O_2. For the error of the heat energy, we found that higher heating values are varied from 0.11-1.33% and the average value is 0.73%. Lower heating values are varied from 0.14-1.31%, giving the average value of 0.81%. These errors are minimal.

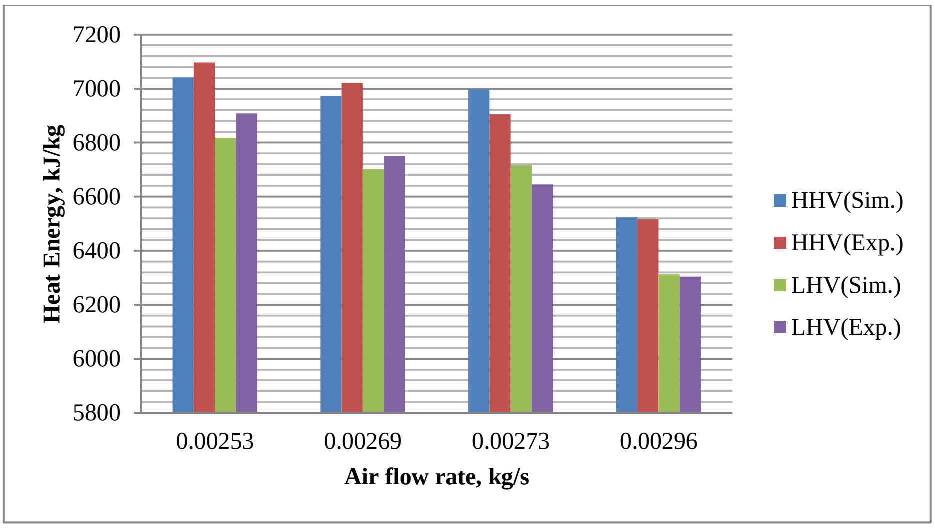


Figure 10 The heat energy form the simulation and the experimental

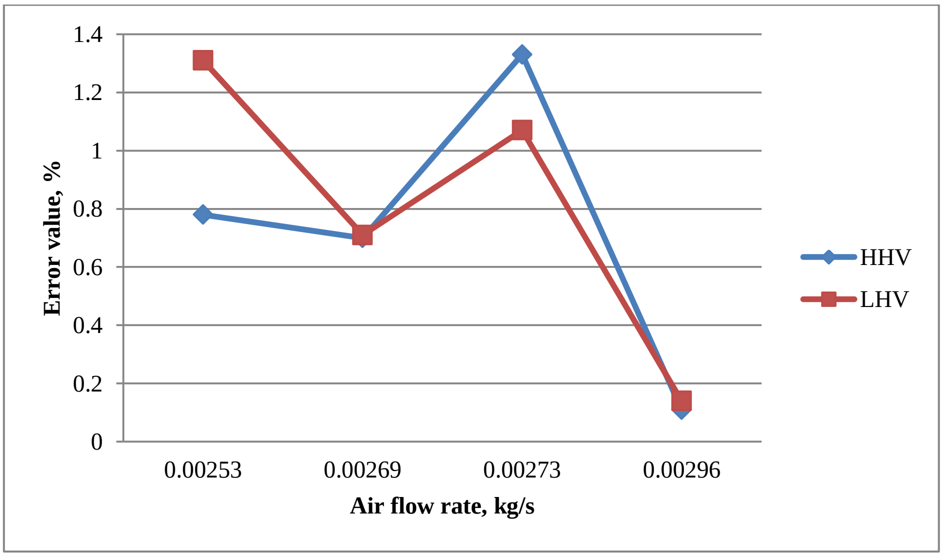


Figure 11 The percentage error of heat energy

6. Conclusions

By comparing the quantity of composition and the heat energy of the producer gas between the results obtained from the simulation model and the actual test, it was found that the average error of gas for CO is 1.73%, CH_4 is 1.58%, H_2 is 7.01%, CO_2 is 2.22%, N_2 is 1.06%, and O_2 is 2.18%, and the average of heat energy are 0.73% HHV and 0.81% LHV.

From the observation, the errors are in minimal so that we can use the results as the primary data for the production of producer gas (for downdraft gasifier furnace). We can select the type of biomass fuel in order to produce the required amount of heat energy for a given application.

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