Parametric Investigation of a Downdraft Gasifier Using Numerical Modelling for Different Biomass Materials in Myanmar

Sithu Han*, Mya Mya Oo, and Thein Min Htike

Abstract— *Myanmar is an agricultural country and biomass materials such as wood, bamboo, rice husk and rice straw are the most abundant biomass resources. Therefore, there is a huge potential of biomass gasification, which can provide the power to the rural population which are still unelectrified. It has also been reported that there have been some applications of downdraft gasifier for this purpose in some parts of the country. However, the widespread application is still limited because of the need to further investigate its performance and environmental concern. In this study, the performance of different biomass species in Myanmar is investigated using the numerical model of downdraft gasifier under different operating conditions. A one-dimensional model of a downdraft gasifier is developed by considering both pyro-oxidation zone and reduction zone. Firstly, species compositions (Char, CO, CO_2, H_2O, H_2, CH_4 and N_2) in pyro-oxidation zone have been solved considering the chemical equilibrium of the species at a given temperature of gas. Next, compositions obtained from the chemical equilibrium model were fed to the kinetic model as initial inputs. Then, the reduction zone has been solved based on the chemical kinetic of reduction reactions by the char considering along the length of the zone to predict the final gas compositions. The results are verified with the values from the literature. Finally, the model was applied to investigate the potential of four different biomass materials (wood, bamboo, rice husk and rice straw) available in Myanmar under different operating conditions such as equivalence ratios and biomass moisture contents. It was found that all the four biomass fuels in Myanmar can be used in downdraft gasifier to produce the combustible gas which has a potential application in internal combustion engines.*

***Keywords*— Biomass, downdraft gasifier, producer gas, reduction zone, numerical modelling.**

1. INTRODUCTION

As Myanmar is planning proper energy mix to fulfil growing demand, more investigation on the potential of different energy resources should be done inclusively to find possible alternatives. Among available renewable resources [1], biomass is particularly abundant waste materials except its application as animal feed in the rural areas. Most of biomass materials are found as by-product in Myanmar since main sources of revenue in Myanmar is agriculture, timber logging and animal rearing. Therefore, biomass would be the most viable form of energy in Myanmar and there have been some applications of biomass gasifiers for rural electrification and SME sectors [2]. Although other renewable energy resources such as solar and wind energy are being planned in Myanmar and studied [3], investigation of potential of biomass gasification for electrification is still needed especially focusing on better understanding of biomass gasification inside the reactor.

Biomass gasification is a process of conversion of solid carbonaceous fuel into combustible gases (known as producer gas with calorific value) by partial combustion. This producer gas can be used to run small reciprocating engines, boiler, processes heaters. Inside a gasification unit, four processes can be identified: drying, devolatilization (pyrolysis), combustion and reduction. In the drying process the feedstock is heated and its temperature increases, thus water undergoes vaporization. Devolatilization occurs as the temperature of feedstock rises, and pyrolysis take places converting feedstock into char and hydrocarbon gases. Reduction or gasification is the results of several chemical reactions involving carbon, steam, hydrogen and carbon dioxide among others. The combustion process provides the thermal energy required for the gasification process, by consuming some of the char or dry feedstock and in some cases the volatiles within the gasifier [4].

Modelling of gasification system is of great importance in order to predict optimum operating conditions and process parameters to obtain acceptable producer gas quality. Different simulation models used for this purpose may be classified into thermodynamic equilibrium model, kinetic model, computational fluid dynamic model and artificial neural network.

Giltrap et al. have investigated kinetic-based reaction model for the reduction zone of a downdraft gasifier to predict the composition of the producer gas under steady-state condition [5]. A constant char reactivity factor was used in his study. Assuming cracking of pyrolysis products into equivalent amount of CO, CH_4 and H_2O limited the accuracy of this model and resulted in an over prediction of methane fraction at the gasifier outlet. Babu and Sheth modified Giltrap's model by incorporating a variation of the char reactivity factor [6]. Finite difference method was applied to predict the

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temperature and composition profiles along the reduction zone of the downdraft gasifier. It was observed that an exponential varying of the char reactivity factor gave the better result for both temperature and gas composition when compared to the experimental data of Jayah et al. [7].

A. K. Sharma has developed the thermodynamic equilibrium and kinetic modelling of char reduction reactions in a downdraft biomass gasifier in order to predict the status of un-converted char in addition to gas composition, calorific values, conversion efficiency, exit gas temperature by comparing these two models [8]. In another study, Roy et al. have built a numerical model of downdraft gasifier based on chemical equilibrium in the pyro-oxidation zone and finite rate kinetic-controlled chemical reactions in the reduction zone [9]. It was reported that the model prediction agreed well with the temperature distribution and gas composition obtained from the experiments at char reactivity factor for 100. It was found that the heating value of the producer gas increased with the increment in equivalence ratio and decreased in the biomass moisture content.

In the present work, the main focus is set on the investigation of potential of four available biomass resources in Myanmar whose compositions have been studied by Min Lwin Swe [1]. For the analysis, two separate sub-models in the downdraft gasifier - one for pyro-oxidation zone and another for reduction zone following the concept by Roy et al. [9]. The sub-model for pyro-oxidation zone is based on proposal by Zianal et al. [10] and the sub-model for reduction zone is studied based on proposals by Giltrap et al. [5] and Babu and Sheth [6]. The models used in this work are discussed in the second part, methodology. A parametric investigation is also performed to study the effects of equivalence ratio and biomass moisture content on the gas composition and lower heating value. Results are reported and discussed on the third part of the paper and concluded in the last part.

2. METHODOLOGY

2.1 Model Formulation

The present model consists of two distinct zones: pyro-oxidation zone where the drying, pyrolysis and oxidation reactions occur, and reduction zone where the gasification or reduction reactions take place in the downdraft gasifier. The sub-model for the pyro-oxidation of the downdraft gasifier has been solved based on the chemical equilibrium approach considering water gas reaction and methanation reaction, as the reactions occur at a reasonably high temperature there. The composition of different species (C, CO, CO_2, H_2O, H_2, CH_4 and N_2) and the temperature of the gas which flows from the pyro-oxidation zone to the reduction zone are obtained. The sub-model for the reduction zone is established based on chemical kinetics of reduction reactions by char considering along the length of zone to predict final gas composition.

2.2 Sub-model for pyro-oxidation zone

In the present study, this pyro-oxidation step is modelled using a single step global reaction as follows;

$$\begin{aligned} CH_\alpha O_\beta + wH_2O + mO_2 + 3.76mN_2 &= x_1C + x_2CO + x_3CO_2 \\ &+ x_4H_2O + x_5H_2 + x_6CH_4 + x_7N_2 \end{aligned} \qquad (1)$$

where, α and β are the number of atoms of hydrogen and oxygen per number of atom of carbon in the biomass obtained by ultimate analysis using empirical data studied by Min Lwin Swe for Myanmar biomass as shown in Table 1 [1]; *m* is the moles of oxygen in air and *w* is the amount of moisture content in biomass; x_1, x_2, x_3, x_4, x_5, x_6 and x_7 are the number of mole of product species: C, CO, CO_2, H_2O, H_2, CH_4 and N_2 respectively. Since the number of mole for N_2 is known, there are six unknown species in the product. Moreover, number of mole of O_2, *m* is unknown in the reactant. Hence, altogether, there are seven unknown species representing the six unknown species of the producer gas and one unknown for oxygen content for the reaction. Necessary equations for solving these unknowns were generated by using mass balance, equilibrium constants relationships and energy balance. Balancing each chemical species in Eq. (1) results in;

$$C: \quad x_1 + x_2 + x_3 + x_6 = 1 \qquad (2)$$

$$H: \quad 2x_4 + 2x_5 + 4x_6 = \alpha + 2w \qquad (3)$$

$$O: \quad x_2 + 2x_3 + x_4 = 2m + \beta + w \qquad (4)$$

$$N: \quad x_7 = 3.76m \qquad (5)$$

In this model, the thermodynamic equilibrium was assumed for all chemical reactions in the gasification reaction. All gases were assumed to behave ideally and all reactions form at 1 atm pressure. Nitrogen is considered to be inert, but it dilutes the final energy of density of gas. The equilibrium modelling is developed based on equilibrium constants for each reaction in equations, (6) and (8).

Water gas shift reaction

$$CO_{(g)} + H_2O_{(g)} \leftrightarrow CO_{2(g)} + H_{2(g)}; \Delta H_R^\circ = -41 \tfrac{KJ}{mol} \qquad (6)$$

$$K_1 = \tfrac{x_3 . x_5}{x_2 . x_4} \qquad (7)$$

Methanation reaction

$$C_{(s)} + 2H_{2(g)} \leftrightarrow CH_{4(g)}; \Delta H_R^\circ = -75 \tfrac{KJ}{mol} \qquad (8)$$

$$K_2 = \tfrac{x_6}{x_5^2} \qquad (9)$$

Two equilibrium equations are required to determine the equilibrium constants K_1 and K_2 in equations, (7) and (9). The equilibrium constant is a function of temperature only for each reaction considered and their expressions are derived using data reported in Zainal et al. [10].

The energy balance for gasification process was then incorporated into the equilibrium model. The kinetic and potential energy changes in the stream were neglected and the steady state energy flow equation was applied. Therefore, the heat balance for this process, assumed to be adiabatic was in Eq. (10);

$$H_{reactants} = H_{products} \tag{10}$$

$$H^{\circ}_{f_{biomass}} + w\left[H^{\circ}_{fH_2O(l)} + H^{\circ}_{fH_2O(g)}\right] = x_2 H^{\circ}_{fCO} + x_3 H^{\circ}_{fCO_2} + x_4 H^{\circ}_{fH_2O(g)} + x_6 H^{\circ}_{fCH_4} + \Delta T \begin{pmatrix} x_2 C_{pCO} + x_3 C_{pCO_2} + x_4 C_{pH_2O} \\ + x_5 C_{pH_2} + x_6 C_{pCH_4} + 3.76 m C_{pN_2} \end{pmatrix} \tag{11}$$

where, H_f° is the enthapy of formation in kJ/kmol and its value is zero for all chemical elements at standard temperature and pressure. ΔT represents the temperature difference between any given state and at reference state. C_p is the specific heat at constant pressure in kJ/kmol K and is a function of temperature. The system of the equations (2-5), (7), (9) and (11) has been performed to evaluate the gas fractions and the temperature at the end of the pyro-oxidation zone. System of equations were solved by using Newton's Jacobi iteration in MATLAB. The results of this sub-model were then transferred to the kinetic model of the reduction zone as input boundary conditions.

Table 1. Ultimate Analysis for Different Biomasses Available in Myanmar (Dry Basis, Weight Percentage) [1]

Biomasses	C	H	O	N	S
Rice Husk	35.145	3.706	60.438	0.211	0.1215
Bamboo	45.66	4.32	48.329	0.243	0.064
Wood	44.925	4.935	49.616	0.188	0.079
Rice Straw	39.875	5.1165	53.829	0.594	0.216

2.3 Sub-model for reduction zone

The model for reduction zone is based on the kinetically control chemical reactions within the downdraft gasifier operating under steady-state conditions. It was originally presented by Giltrap et al. [4]. During the reduction process, the five simultaneous reactions R1 to R5 take place. These reactions are selected from the previous research work of Sharma [8]. Reaction 5 (water gas shift) can be neglected as it does not affect the rate for that particular moisture to biomass ratio, however, here in this study the shift reaction is included as one part of gasification reactions. Table 2 shows the values of the frequency factors and activation energy for each reaction [11]. The char reactivity factor was introduced by Babu and Sheth [6] to the model by Giltrap et al. [5]. The value of the char reactivity factor may vary between 1 and 1000 and sometimes exponentially and linearly, for the present model it is taken as 1000.

R1: Boudouard reaction

$$C_{(s)} + CO_{2(g)} \leftrightarrow 2CO_{(g)}; \Delta H^{\circ}_R = +173 \tfrac{KJ}{mol}$$
$$r_1 = c_{RF} k_1 \left(x_{CO_2} - \tfrac{x_{CO}^2}{K_{eq,1}} \right) \tag{12}$$

R2: Water gas reaction

$$C_{(s)} + H_2O_{(g)} \leftrightarrow CO_{(g)} + H_{2(g)}; \Delta H^{\circ}_R = +131 \tfrac{KJ}{mol}$$
$$r_2 = c_{RF} k_2 \left(x_{H_2O} - \frac{x_{CO} . x_{H_2}}{K_{eq,2}} \right) \tag{13}$$

R3: Methanation reaction

$$C_{(s)} + 2H_{2(g)} \leftrightarrow CH_{4(g)}; \Delta H^{\circ}_R = -75 \tfrac{KJ}{mol}$$
$$r_3 = c_{RF} k_3 \left(x_{H_2}^2 - \tfrac{x_{CH_4}}{K_{eq,3}} \right) \tag{14}$$

R4: Steam reforming reaction

$$CH_{4(g)} + H_2O_{(g)} \leftrightarrow CO_{(g)} + 3H_{2(g)}; \Delta H^{\circ}_R = +206 \tfrac{KJ}{mol}$$
$$r_4 = c_{RF} k_4 \left(x_{CH_4} . x_{H_2O} - \tfrac{x_{CO} . x_{H_2}^3}{K_{eq,4}} \right) \tag{15}$$

R5: Water gas shift reaction

$$CO_{(g)} + H_2O_{(g)} \leftrightarrow CO_{2(g)} + H_{2(g)}; \Delta H^{\circ}_R = -41 \tfrac{KJ}{mol}$$
$$r_5 = c_{RF} k_5 \left(x_{CO} . x_{H_2O} - \tfrac{x_{CO_2} . x_{H_2}}{K_{eq,5}} \right) \tag{16}$$

Table 2. Frequency Factors and Activation Energy [11]

Reactions	*A_i (1/s)*	*E_i (kJ/mol)*
1	3.616×10^{1}	77.39
2	1.5170×10^{4}	121.62
3	4.189×10^{-3}	19.21
4	7.301×10^{-2}	36.15
5	2.842×10^{-2}	32.84

The sub-model for the reduction zone assumes a cylindrical form of reduction zone with a uniform cross-section in the axial direction and neglects variations of gas properties in the radial direction. The molar (for six gas species) and energy balances result in the following set of nine differential equations with the corresponding number of unknown parameters [7].

$$\tfrac{dn_x}{dz} = \tfrac{1}{V} \left[R_x - n_x \tfrac{dV}{dz} \right] \tag{17}$$

$$\tfrac{dT}{dz} = \frac{1}{V \sum_x n_x c_x} \begin{bmatrix} -\sum\limits_i r_i \Delta H_i - V \tfrac{dP}{dz} - P \tfrac{dV}{dz} \\ -\sum\limits_x R_x c_x T \end{bmatrix} \tag{18}$$

$$\frac{dV}{dz} = \frac{1}{\sum_x n_x c_x + nR}\left[\begin{array}{l} \frac{\left(\sum_x n_x c_x\right)\left(\sum_x R_x\right)}{n} - \frac{\sum_i r_i \Delta H_i}{T} \\ - \frac{dP}{dz}\left(\frac{V}{T} + \frac{V\sum_x n_x c_x}{P}\right) - \sum_x R_x c_x \end{array}\right] \quad (19)$$

$$\frac{dP}{dz} = 1183\left(\rho_{gas}\frac{V^2}{\rho_{air}}\right) + 388.19V - 79.896 \quad (20)$$

The set of nine differential equations was integrated using MATLAB program based on the fourth-order Runge-Kutta method to obtain concentrations of six gas species, the temperature, the velocity and pressure along the length of the reduction zone.

3. RESULTS AND DISCUSSION

3.1 Model Validation

The present model was validated with Jayah's experimental data from the literature [7] at the same parameters as shown in Table 3. Table 4 shows comparison between the present model and experimental results by dry basis for producer gas. The compositions of the producer gas predicted by present model were in good agreement with that of the producer gas adopted by Jayah's experimental data, except that for hydrogen content. The hydrogen content predicted is more than experimental value, while maximum discrepancy for the other species content is less than 20%.

Table 3. Parameters used for Model Validation with Jayah's Experimental Data [7]

Parameters	*Values*
Bed length (z)	0.275 m
Superficial Velocity (V)	1.175 m/s
Initial Temperature (T)	1400 K
Pressure (P)	1atm
Moisture Content (MC)	16 % (Dry Basis)
Char Reactivity Factor (CRF)	1000

Table 4. Comparison of the Present Model Results with Jayah's Experimental Data [7]

Species	***Jayah (Experiment)***	***Present Model***	***Percentage discrepancy***
CO	18.4	21.7	-17.93
CO_2	10.60	8.8	-16.98
H_2	17.00	10.9	35.88
CH_4	1.3	1.4	- 7.69
N_2	52.70	57.14	- 8.43

Fig. 1 presents the temperature variation along the length of the reduction zone of the gasifier, predicted from the present model. It can be seen obviously that temperature declines along the length of the reduction zone as the reduction reactions are endothermic reactions in nature. In addition, temperature decays very fast over a short distance from the inlet of the reduction zone. However, after the temperature reaches 925 K, at a distance of 0.4 m from the inlet, it hardly drops any further in the remaining length of the gasifier because of the fact that all almost all the char entering the reduction zone gets consumed within the initial length of 0.4 m, leading to almost no further reduction reaction in downstream.

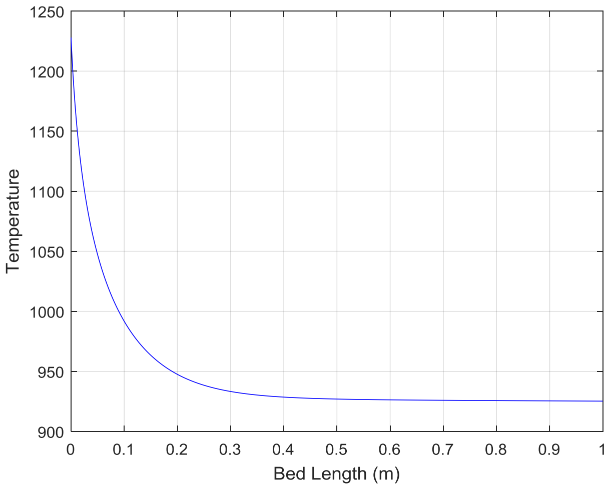

Fig. 1. Variation of temperature along the length of the reduction zone.

3.2 Influence of moisture content (MC) on producer gas

Fig. 2 shows the effects of moisture content in the biomass feedstock (rice husk) on the composition of producer gas predicted by the present model at ER=0.3. The moisture content is varied from 0% to 40% and the gas composition is presented on dry basis. It was observed that the content of hydrogen and carbon dioxide in the producer gas increase with the increase in moisture content, while the carbon monoxide decrease significantly. The trend in the variation of H_2, CO_2 and CO concentration in the producer gas at different moisture content of the biomass was attributed to the fact that reaction R2 contributed more than reaction R1 with higher moisture content in converting the char in the reduction zone. Reaction R2 increases the formation of hydrogen and produces one mole of CO instead of two moles of CO as in case of reaction R1. Therefore, the CO concentration is reduced as the reaction R2 prevailed over the reaction R1. The concentration of CO_2 in the producer gas increases because of the water-gas homogeneous reaction which completed the combustion of some carbon monoxide and produced hydrogen and carbon dioxide. The concentration of CH_4 varies with moisture content according to reaction R3 and reaction R4. Although nitrogen is an inert gas, the fraction of its concentration is decreasing because the concentrations of the other gases are changing in the producer gas.

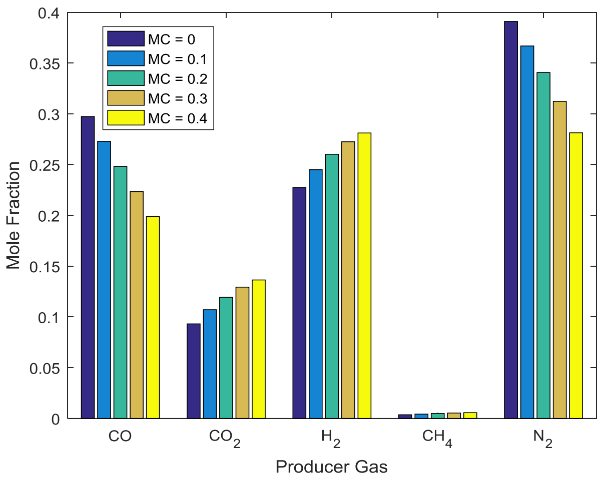

Fig. 2. Effects of moisture content on producer gas for rice husk at ER = 0.3.

3.3 Influence of equivalence ratio (ER) on producer gas

Fig. 3 depicts the effect of equivalence ratio on the gas composition, predicted by the present model at MC = 0.2. The equivalence ratio has been considered in the range of 0.1 to 0.5. It was seen that the content of hydrogen, carbon dioxide and methane slightly decline with the increment in equivalence ratio, while the carbon monoxide and nitrogen increase apparently. A higher value of ER represents a higher amount of air which leads to more amount of CO_2 production in pyro-oxidation zone and more amount of N_2 entry with the air flow. With an increase in ER from 0.1 to 0.5, increased amount of CO_2 in pryo-oxidation zone was converted into CO according to reaction R1 in the reduction zone.

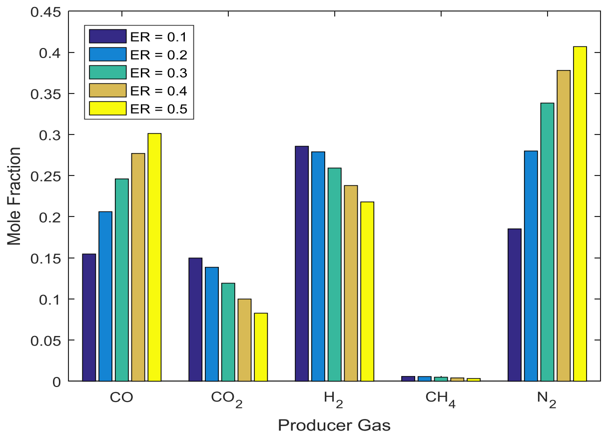

Fig. 3. Effects of equivalence ratio on producer gas for rice husk at MC = 0.2.

3.4 Influence of moisture content (MC) on LHV of producer gas

The variation of lower heating value (LHV) for the four different biomasses against moisture content is shown in Fig. 4. The heating value is calculated using the composition of the producer gas. Carbon monoxide, methane and hydrogen are the main components of the producer gas and are responsible for lower heating value. It was observed that the effect of increasing moisture content was the decrease in LHV of the producer gas. This trend can be explained that reduction in carbon monoxide content was more than the increase in hydrogen content as the increase of moisture content. For the moisture content higher than 0.2, Lower heating values of wood, bamboo and rice straw are higher than that of rice husk. The heating values of producer gas for wood, bamboo, rice husk and rice straw are between 6.3MJ/Nm^3 and 7.2MJ/Nm^3 which are heating values for product gas based on gasifying agent, air as the increase in the range of moisture content studied. The nature of the variation of LHV shows that the reduction in LHV with the increase in moisture is more significant at the higher moisture level. Therefore, the quality of the producer gas is progressively poorer in lower heating value as the moisture content increases. However, heating values for all four types of biomass fuel are in the range of 4 to 7MJ/Nm^3 which is typical heating value of producer gas necessary for using it as a fuel in internal combustion engine.

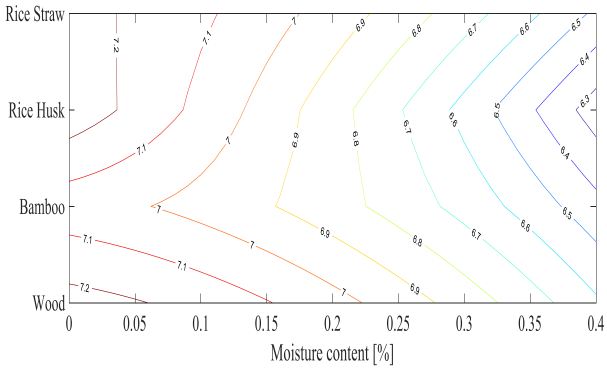

Fig. 4. Effects of moisture content on LHV of producer gas for different biomasses.

3.5 Influence of equivalence ratio (ER) on LHV of producer gas

Fig. 5 represents the lower heating values for all biomasses are function of the variation of equivalence ratio with moisture content of 20%. As seen in the figure, the predicted heating values for all biomasses increase with the equivalence ratio. The fraction of CO content and N_2 content significantly rise up with the rise in equivalence ratio, while the content of H_2, CO_2 and CH_4 were dropped. This behaviour can be clarified that the increase in carbon monoxide content is more than the reduction in hydrogen content as increase in equivalence ratio. At any given equivalence ratio, the wood, rice straw and bamboo have the highest heating value and the amount of heating values of producer gas for rice husk is the lowest. This is because of the fact that the content of carbon percent in feedstock of wood, bamboo and rice straw is higher than that of rice husk. However, lower heating value of these biomass materials are lying within typical range of heating value (4 to 7MJ/Nm^3) for producer gas based on gasifying agent, air.

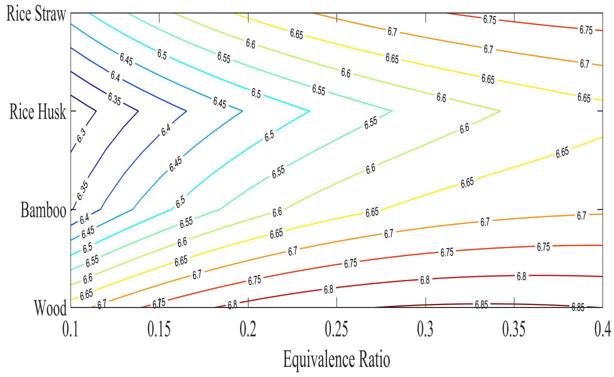

Fig. 5. Effects of equivalence ratio on LHV of producer gas for different biomasses.

4. CONCLUSION

The numerical model has been developed for the simulation of the performance of a downdraft gasifier considering two separate zones: pyro-oxidation zone and reduction zone to predict the final gas compositions and lower heating values.

A parametric study has been performed with one dimensional model at different equivalence ratio and moisture content. The compositions and lower heating values of the producer gas were determined for four different biomasses available in Myanmar; wood, bamboo, rice straw and rice husk. From the analysis, it was concluded that the increase in moisture reduced the CO fraction in the producer gas and increase the H_2 and CO_2.The CH_4 content remained nearly constant with the change in moisture content. The increase in moisture content for all raw materials deteriorated the quality of the producer gas and its lower heating value reduced. The predicted lower heating value for all raw materials was increasing with the equivalence ratio. The heating values of biomass materials with air as a gasifying agent in this study are 4 to 7MJ/Nm^3, which is in agreement with the values reported in [12]. Moreover, the study by Kaupp and Goss [13] also reported that producer gas with such lower heating value can be used as fuels in reciprocating internal combustion engines. Therefore, it can be implied that producer gas that can be generated using four biomass fuels in Myanmar proposed by this study can be used in reciprocating internal combustion engines.

Based on the results in this study, it can be concluded that all biomasses available in Myanmar has high potential to be used as fuel in biomass gasification and some other biomass resources should be studied in future works. More experimental investigations should also be done to fully verify its performance in internal combustion engines.

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