# KINETIC MODEL OF THE REDUCTION ZONE OF A DOWNDRAFT BIOMASS GASIFIER

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**ABSTRACT**

The model has been developed by considering two distinct zones in the downdraft gasifier: pyro-oxidation zone and reduction zone. The process in the pyro-oxidation zone has been solved based on the chemical equilibrium consideration considering water gas shift reaction and methanation reaction. The composition of different species ($H_2$, CO, $CO_2$, $CH_4$, $H_2O$, $N_2$ and Char) and the temperature of the gas which flows from the pyro-oxidation to the reduction zone are obtained. Reduction zone has been modeled based on chemical kinetics of reduction reactions by char considering a large number of elemental control volumes along the length of the zone to predict final gas composition. The species and energy balances have been performed across each control volume considering the finite rate of chemical reactions. The contributions of ash in the fuel and heat loss from the downdraft gasifier have been considered in the energy balance equation. In the present modified model pressure drop across the reduction zone has been calculated considering a packed bed of char particles of varying particle diameter due to the char reduction through the zone. Effect of equivalence ratio and moisture content of the biomass have been studied based on the modified model.

**Keywords:** Downdraft gasifer, gasifier model, model validation

## 1. INTRODUCTION

Biomass gasifier is too often thought of as simple device that can generate a combustible gas from any biomass feedstock. A hundred years of research has clearly shown that a successful gasification system can be designed for a particular type of fuel. Although the technology is somewhere inconvenient, it is economical at many places and may lead to self-reliance in fuel crisis [1].

Gasification is a complex and sensitive process dependent on a number of factors. There always exists a high level of disagreement about gasification system among engineers, researchers and manufacturers regarding the reliability of the process [2]. It is quite obvious that performance of biomass gasification system will vary with the physical and chemical properties of the biomass feedstock.

Getting the producer gas is not much difficult, but obtaining in the proper quality and quantity for long run is a challenging task. All the gasifiers have certain requirements of fuel size, moisture, ash content as well as energy content [3]. The physical and chemical properties of producer gas such as energy content, gas composition and impurities may vary from time to time. In this circumstances, built and test method is not at all suitable in regard to time and cost to find out optimal operating parameters and performance. Modeling of

gasification system for engine applications based on thermodynamics and heat transfer principle can provide adequate guide lines to design the system in efficient and economic manner. Models can predict almost desirable operating parameters for available biomasses which can be utilized for power generation.

Modeling of gasification process is a complex task which requires knowledge of thermodynamics, fluid dynamics and chemistry. Developing numerical models for biomass gasification is still more complicated because a large theoretical and experimental background is missing [4].

The thermo-chemical processes that occur inside a downdraft gasifier are very complex involving pyrolysis, partial oxidation and successive gasification at elevated temperatures. The processes are largely dependent on the parent biomass composition, moisture content, ash content, energy content, size, reactivity of biomass, local stoichiometry and the gasifier design. A suitable model of the downdraft gasifier can predict the optimum performance parameters for its operation. Thermo-chemical behaviour of downdraft gasifier has been reported by many researchers based on thermodynamic equilibrium model, considering very high residence time and fast reaction rates, within the gasifier. Ruggiero and Manfrida [5] described a simulation of the biomass gasification process using

equilibrium reactions in the gaseous phase in a zero-dimensional scheme which approaches the conditions of the ideal, well-stirred chemical reactions, the residence time is supposed to be substantially larger than the time interval needed for complete reaction kinetics. The developed model was very simple. Simulation predictions were not well validated with experimental results reported in the study. On the other hand Zainal *et al.* [6] developed an equilibrium model to predict the gasification process in a downdraft gasifier and determined the producer gas composition and its calorific value. The effect of moisture content in the wood and the temperature in the gasification zone on the calorific value had been investigated. The predicted results were compared with experimental results. The calorific value of the producer gas decreased with increase in moisture content in the biomass material. The calorific value of the gases decreased as the gasification temperature was increased. They had calculated the specific heat of the gases based on the mean temperature of inlet air and gasification temperature. An equilibrium model based on minimization of Gibbs free energy for wood waste (saw dust), has been developed by Altafini *et al.* ([7]. A parametric analysis was carried out to study the influence of F/A ratio, moisture content in biomass and reaction temperature on fuel gas composition and calorific values. In another approach, Jarungthammchote and Dutta [8] have developed the thermodynamic model based on equilibrium constant for predicting the composition of producer gas in a downdraft waste gasifier. To enhance the performance of the model, they modified the equilibrium constants with correction coefficients. The reaction temperature, the calorific value and second law efficiency decrease with the increase in moisture content of the biomass. A full equilibrium model of global reduction reactions using thermodynamic principles based on the stoichiometric approach for a downdraft gasifier in order to predict the accurate distribution of gas species, unconverted char and reaction temperature has been also proposed by Sharma [9]. The condition of complete char conversion shifts toward lower equivalence ratio for the case of feedstock having higher moisture content. It was suggested that for optimal energy conversion of Douglas fir bark, the range of moisture content should be limited to 10 to 20%, 0.3 to 0.45 for equivalence ratio and the initial temperature in the reduction zone should not be less than 1200 K. The role of pressure is found to be quite unfavorable in all conditions. However, thermodynamic equilibrium never occurs in reality in the gasification process and can only be approximated in the high temperature zone of the downdraft gasifier. To overcome the limitations of the equilibrium model, recent works have considered finite rate kinetics for the chemical equations, particularly in the reduction zone of the downdraft gasifier. The kinetic models are based on the chemical reaction path prescribed by Wang and Kinoshita [10] for the reduction of biomass char in the char reduction zone of the gasifier.

Giltrap *et al.* [11] developed a kinetic based reaction model for the reduction zone of a cylindrical downdraft biomass gasifier operating at steady state. The composition of the gas at the inlet to the reduction zone has been assumed considering that all the oxygen supplied to the gasifier is used to form $CO_2$ and pyrolysis of the fuel has produced CO, $CH_4$ and $H_2O$. Solid char is considered to be present in the reduction zone. The mass and energy balance equations had been solved considering the kinetic controlled rate of the chemical reactions. A constant char reactivity factor ($C_{RF}$) is considered in the analysis. The model predicted reasonable composition of the producer gas mixture at the gasifier outlet. However, the methane concentration in the producer gas was significantly over-predicted. A modified model of Giltrap *et al.* has been developed by Babu and Sheth [12] with a variable char reactivity factor along the length of the downdraft gasifier reduction zone. The authors interpreted that an exponential variation of the char reactivity factor worked better for the model. However, the predicted results did not show much deviation in the producer gas composition even when a suitable constant value of char reactivity factor was adopted. Recently, Sharma [13] presented a model for the downdraft biomass gasifier, where the reduction zone was modeled using finite rate of reaction following the chemical kinetics followed by Giltrap *et al.* The pyro-oxidation zone, prior to the reduction zone, has also been modeled considering thermodynamic equilibrium. However, the author did not take into account any char combustion in the pyro-oxidation zone and also neglected formation of methane there. The water gas shift equilibrium has been considered at the outlet of the pyro-oxidation zone. In the reduction zone a linear variation of $C_{RF}$ has been adopted. Geometry of the reduction zone has not been taken care of during the formulation for the model of both Giltrap *et al.* and Sharma [13]. A detailed experiments in a throated down-draft gasifier with rubber wood as the fuel to study the effects of operating parameters like chip size, inlet air temperature, moisture content in the biomass, heat loss from the downdraft gasifier and the throat angle of the gasifier has been performed by Jayah *et al.* [14]. The downdraft gasifier structure consisted of a converging-diverging section, where the gasification occurred in the diverging zone. The variation of temperature along the height of the downdraft gasifier has been measured. Dry gas compositions and gas flow rates are measured at different chip sizes, moisture content and air/fuel ratios. In the same work, Jayah *et al.* also predicted the gas composition using a flaming pyrolysis sub-model for the pyro-oxidation zone and a gasification zone sub-model for the reduction zone. The gasification zone sub-model assumed that a single char particle moves downwards along the vertical axis of the gasifier. The model was limited to considering the effect of packed char particles in the reduction zone. The conversion efficiency of the gasification process was evaluated. It has been reported that the moisture content and the heat

loss have large effects on the gasifier conversion efficiency. It was also observed that performance of gasifier varies with change in the biomass composition.

## 2. MODEL DESCRIPTION

The model has been developed by considering two distinct zones in the downdraft gasifier: pyro-oxidation zone (lumped with drying, pyrolysis and oxidation zone) and reduction zone. The process in the pyro-oxidation zone has been solved based on the chemical equilibrium consideration considering water gas shift reaction and methanation reaction, as the reactions occur at a reasonably high temperature there. The composition of different species ($H_2$, CO, $CO_2$, $CH_4$, $H_2O$, $N_2$ and Char) and the temperature of the gas which flows from the pyro-oxidation to the reduction zone are obtained. Reduction zone has been modeled based on chemical kinetics of reduction reactions by char considering a large number of elemental control volumes along the length of the zone to predict final gas composition. The species and energy balances have been performed across each control volume considering the finite rate of chemical reactions. The contributions of ash in the fuel and heat loss from the downdraft gasifier have been considered in the energy balance equation. As geometry of the zone has significant influence on the species formation rate, an optimization of the geometry has been considered during the analysis.

Figure 1 shows the two distinct zones in the gasifier: zone-1 (pyro-oxidation zone), where the drying, pyrolysis and oxidation reactions occur, and zone-2 (reduction zone), where the gasification or reduction reactions take place. The modeling of zone-1 has been performed considering chemical equilibrium of the species in the zone and that of zone-2 considers finite rate chemical reactions following the reaction kinetics. Input data of the zone-2 comes as the output from the zone-1. The following assumptions are made for the development of the model:

a) The air used in the gasifier is assumed to be dry.
b) Chemical equilibrium exists among the gaseous species at the exit of the pyro-oxidation zone.
c) The gasifier reduction zone has been considered to be one-dimensional.
d) The concentration of tar or unburned hydrocarbon in the exhaust of the downdraft gasifier is negligible.
e) The fixed carbon present in the fuel has the molecular weight same as carbon.
f) The specific heats of the gaseous species and char vary with the local temperature, while the specific heat of ash is constant.
g) Energy transport in the porous fixed bed of the reduction zone takes place primarily through advection of gas and conduction through the bed solid is of less consequence.
h) The heat loss from the downdraft gasifier takes

place from the oxidation zone, where the temperature is high. The heat loss from the reduction zone is negligible as it is surrounded by the high temperature producer gas flowing up towards its exhaust.
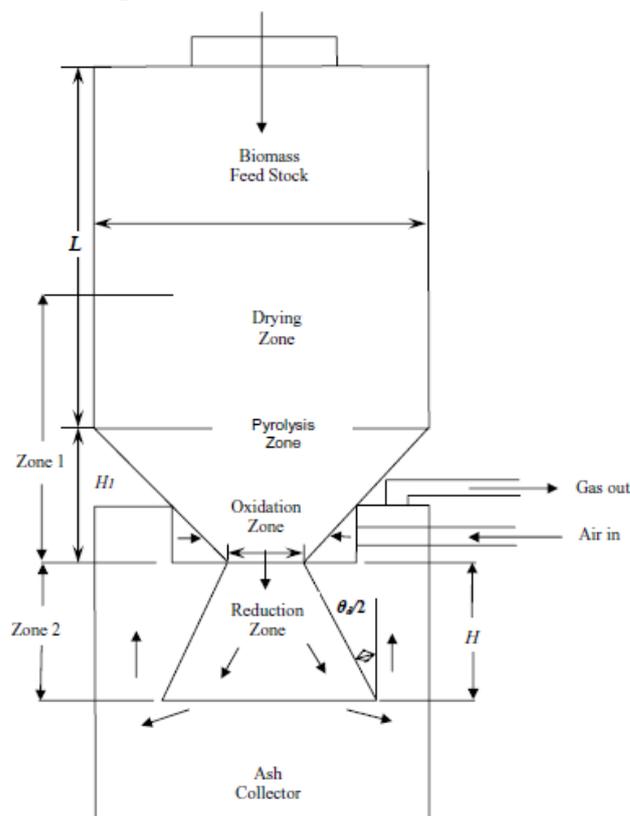


Fig. 1. Schematic of the downdraft draft gasifier [14].

### 2.1 Modeling of zone-1 (Pyro-oxidation zone)

From the ultimate analysis data of the parent biomass, a representative chemical formula ($CH_xO_yN_z$) can be derived for the dry, combustible part of the fuel, assuming that the fuel contains C, H, O and N only. The values of *x, y* and *z* in the chemical formula can be

obtained as $x = \dfrac{(\%H)MW_C}{(\%C)MW_H}$ , $y = \dfrac{(\%O)MW_C}{(\%C)MW_O}$ and

$z = \dfrac{(\%N)MW_C}{(\%C)MW_N}$ , where $(\%C)$, $(\%H)$ , $(\%O)$ and $(\%N)$

are the percentage of carbon, hydrogen, oxygen and nitrogen in the biomass and $MW_C$, $MW_H$ $MW_O$ and $MW_N$ are the molecular weights of the four species, respectively [15]. Most of the biomass fuels contain high percentage of moisture. The moisture content in the biomass has been separately accounted in the chemical reaction equation of this zone. In the pyro-oxidation zone, the fuel is pyrolyzed and oxidized in a sub-stoichiometric environment of air supplied from the atmosphere. The quantity of air is determined from the equivalence ratio, at which the gasifier is operated.

The conversion of biomass to the product mixture in zone-1 follows a global reaction equation:

$$CH_xO_yN_z + wH_2O + aO_2 + 3.76aN_2 = x_1H_2 + x_2CO$$
$$+ x_3CO_2 + x_4H_2O + x_5CH_4 + x_6N_2 + x_7C$$

(1)
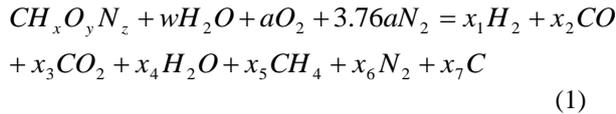
The number of moles of moisture in the fuel ($w$) and the number of moles of oxygen from air ($a$) per mole of the combustible biomass are obtained as follows:

$$w = \frac{FM}{(100 - FM) \times (100 - ASH)} \times \frac{MW_F}{MW_W} \qquad (2)$$

$$a = \frac{(1 + x/4 - y/2)}{\phi} \qquad (3)$$

*FM* and *ASH*, in Eq. (2), are the percentage moisture content in the biomass as received and percentage ash from the ultimate analysis performed on dry fuel. $MW_F$ and $MW_W$ are the molecular weights of dried biomass fuel ($CH_xO_yN_z$) and water respectively. In Eq. (3), $\phi$ denotes the equivalence ratio of the air-fuel mixture supplied to the gasifier (i.e., stoichiometric air/actual air per unit quantity of fuel ($CH_xO_yN_z$)).

The values of $x_1$ through $x_7$, on the right hand side of Eq. (1), denote the number of moles of the respective species formed in the zone from one mole of $CH_xO_yN_z$. The solution of the seven unknowns ($x_1$ through $x_7$) requires seven equations. The mole fractions of the individual gas species are evaluated from the total number of moles that has been elaborately discuss in details [16]

**2.2 Modeling of zone-2 (Reduction zone)**

In the zone-2, reductions of the products formed in zone-1 take place to form the final producer gas based on the kinetically controlled chemical reactions. The reduction reactions considered in this zone are (Giltrap *et al.*). The geometry of the reduction zone has been considered as diverging in nature, similar to that conceived by Jayah *et al*. The entire reduction zone has been divided into a number of elemental control volumes [16], having uniform temperature and concentrations. The species mass and energy balance have been performed across each of the control volume considering the rate of formation/consumption of the species following the different reaction equations. The species concentrations and temperature at the outlet of the last elemental control volume of the reduction zone determine the values in the producer gas leaving the gasifier. [16].

In the present modified kinetic model, pressure drop across the reduction zone has been calculated considering a packed bed of char particles of varying particle diameter due to the char reduction through the zone. Pressure drop across one cell of the reduction zone is given by Ergun's equation as follows: [17]

$$-\Delta p = h \left[ 150 \frac{(1-\varepsilon)^2}{\varepsilon^3} \frac{\mu_g U_g}{(\phi_s d_p)^2} + 1.75 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho_g U_g^2}{\phi_s d_p} \right]$$

where, $h$ is the cell height, $\mu_g$ the viscosity of gases,

$\rho_g$ the density of producer gases, $U_g$ the superficial velocity, $d_p$ the particle diameter, $\phi_s$ the sphericity of particle and $\varepsilon$ the void fraction

The diameter of the char particle ($d_p$) changes continually in the gasifier. A certain amount of char is consumed in the pyro-oxidation zone to form methane. Considering no change in char density, the mean diameter of the char particles entering zone-2 is obtained as Sharma [18]

$$d_p^r = d_p^o \left[ \frac{X_c^o}{X_c^i} \right]^{\frac{1}{3}}$$

where, $d_p^r$ is the mean diameter of char particle entering the reduction zone and $d_p^o$ is the mean diameter of the particle coming to the oxidation zone. The molar flow rates of char at the inlet and outlet of the oxidation zone are $X_c^i$ and $X_c^o$ respectively.

In the reduction zone particle size reduces in each cell due to char conversion through reduction reactions. The mean particle diameter in different cells can be evaluated as

$$d_p^{r(k+1)} = d_p^{r(k)} \left[ \frac{X_c^{r(k+1)}}{X_c^{r(k)}} \right]^{\frac{1}{3}}$$

where, $d_p^{r(k+1)}$ is the mean diameter of particles entering the (k+1)[th] cell, $d_p^{r(k)}$ is the mean diameter entering the kth cell and $X_c^{r(k)}$ and $X_c^{r(k+1)}$ are the molar flow rates of char at the kth cell and (k+1)[th] cell, respectively.

The void fraction ($\varepsilon$) varies with the change in particle diameter and is evaluated using a correlation suggested by Chen and Gunkel [19] as

$$\varepsilon(T) = 0.5 - 0.2 \left( 1 - \frac{d_p^{r(k+1)}}{d_p^{rk}} \right)$$

The viscosity of gases (in Ns/m²) is obtained from the correlation of Hagge and Bryden [20] as
$$\mu_g(T) = 4.847 X 10^{-7} T^{0.64487}$$

Superficial velocity, $U_g$, is calculated using the volume flow rate of product gases across the mean cross section area of each cell.

**2.3 Grid Independence Test**

A grid independence test has been performed considering different numbers of control volume in the reduction zone under study and comparing a parameter at the gasifier exit, e.g. the exit gas temperature. It has been observed that beyond 100 numbers of control volumes only a negligible variation is observed in the exit gas temperature shown in Figure 2. Therefore, the length of the reduction zone has been divided into 100

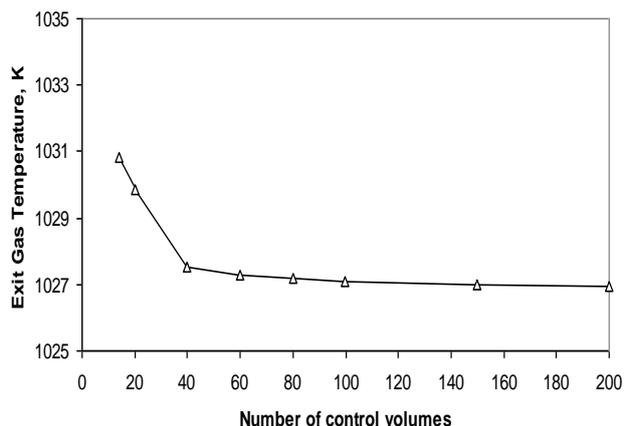control volumes for the analysis of the reduction zone.



Fig. 2. Variation of exit gas temperature with number of control volume considered.

### 2.4 Model Validation

The present model has been validated as a test case against the experimental results of Jayah *et al.* at the corresponding gasifier dimensions, biomass properties and operating conditions. A good agreement has been found between the experimental and predicted data. Even the $CH_4$ concentration has been predicted fairly accurately from the model, showing improvement over the previous models with similar approach [12,13,16].

## 3. RESULTS AND DISCUSSION
### 3.1 Effect of Equivalence Ratio

In a gasifier, sub-stoichiometric air is supplied and the equivalence ratio ($\phi$) remains above unity. The range of equivalence ratio over which a gasifier may operate is limited by the quality of the producer gas generated from the gasifier and the stable operation of it. In the present work, the equivalence ratio has been considered in the range of 2 to 3.4 [8,13,15].
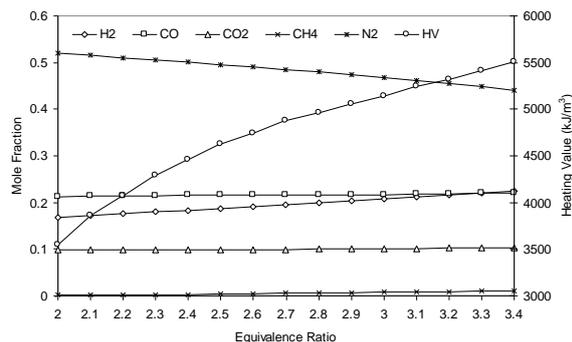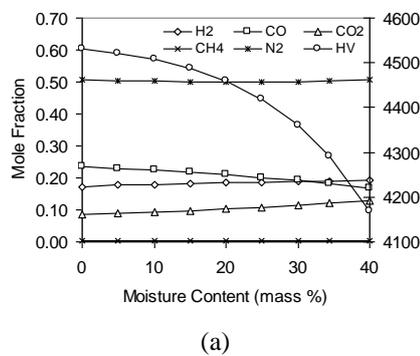


Fig. 5. Variation of producer gas composition and heating value at different equivalence ratio (Moisture content in biomass = 16%)

Figure 5 shows the gas composition and heating value of the producer gas, predicted by the present model, when the equivalence ratio is varied in a range of 2 to 3.4. The moisture content in the fuel for the study of this parametric variation has been considered as 16%. It is observed that the increase in equivalence ratio (i.e.

decrease in the actual supply of air) increases the $H_2$ and $CH_4$ content in the producer gas. On the other hand, the CO and $CO_2$ content increases slightly, when the equivalence ratio is increased. This observation contradicts the apparent fact that operating the gasifier in a richer atmosphere (i.e. with higher $\phi$) should produce less $CO_2$. However, **Melgar *et al.* [15]** reported a variation in the gas composition with the change in equivalence ratio similar to that obtained in the present case, both experimentally and from an equilibrium model of the gasifier, with pine wood fuel containing 18% moisture. They argued that the equilibrium of the water shift reaction in the model inclines to the formation of $CO_2$ and $H_2$, when the fuel contains high moisture. It is clear from the present analysis that the present model also reach to the same conclusion regarding the composition of the producer gas.

### 3.2 Effect of Moisture Content

Almost all the biomass fuels contain high percentage of moisture. The moisture may be inherent to the biomass (intrinsic moisture) and may also be due to the prevailing weather condition (extrinsic moisture). The moisture content in the biomass is one of the important parameter that affects the performance of the gasifier through the variation in the producer gas composition and conversion efficiency. When the moisture content in the fuel is high, a lot of heat generated in the gasifier is expended in vaporizing the moisture and superheating the vapour. As a result, the operating temperature of the gasifier decreases.



(a)
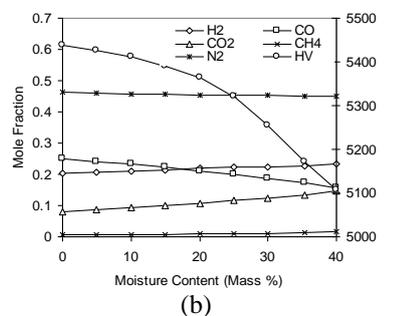


(b)

Fig. 6. Variation of producer gas composition and heating value at different moisture content in the biomass and with (a) $\phi = 2.4$ and (b) $\phi = 3.2$

Figures 6(a) and 6(b) show the effect of moisture in the biomass feed stock on the composition of the producer

gas and its heating value predicted by the present model at two different equivalence ratios, i.e. $\phi$ =2.4 and 3.2 respectively. The moisture content is varied between 0 to 40% and the gas composition is presented on dry basis. It is observed from the results that with the increase in the moisture content, the $H_2$ and $CO_2$ content in the producer gas increases, while the CO content in the gas decreases. The variation of $CH_4$ content in the producer gas with moisture strongly depends on the operating stoichiometry of the gasifier, while $N_2$ concentration of the gas remains almost constant. At $\phi$ =2.4, the $H_2$ concentration in the producer gas increases about 11.4% for the increase in moisture from 0% to 40% in the fuel. The corresponding increase of $H_2$ concentration at $\phi$ = 3.2 is about 16.0%. On the other hand, for the same increase in the moisture content in fuel, the CO mole fractions decreases by 27.8% at $\phi$ = 2.4 and by 37.5% at $\phi$ = 3.2. The $CH_4$ content in the producer gas shows different nature of variation with the moisture content at the two different equivalence ratios. While methane mole fraction remains almost unchanged with the variation of moisture at $\phi$ = 2.4, it continually increases with the increase in moisture content at $\phi$ = 3.2. The mole fraction of methane in the producer gas at $\phi$ = 2.4 is found to be increased only by 8.65% from 0% moisture to 40% moisture. However, at $\phi$ = 3.2, the methane mole fraction in the producer gas is 0.0064 at 0% moisture and 0.017 at 40% moisture (almost 165% increase). Zainal *et al.* [6] and Jarungthammachote and Dutta [8] show the effect of biomass moisture on the composition of the producer gas from the equilibrium model. They also obtained a similar qualitative variation in the composition of different gaseous species with the variation in moisture.

Figures 6(a) and 6(b) also present the variation in the heating value of the producer gas with the variation in the moisture content. The heating value depends on the concentration of the combustible components (like $H_2$, CO and $CH_4$) in the producer gas. At both the equivalence ratios (i.e. $\phi$ = 2.4 and 3.2), the heating value of the producer gas reduces with the increase in moisture. The nature of the variation further shows that the reduction in heating value of the gas with the increase in moisture is more at the higher moisture level. Therefore, the gas quality becomes progressively poorer in heating value as the moisture content increases. However, the effect of moisture in reducing the heating value is less when the gasifier operates at a higher equivalence ratio. At $\phi$ = 2.4, the heating value has decreased by almost 8% when the moisture content increases from 0 to 40%. For the same increase in the moisture content at $\phi$ = 3.2, the heating value decreases by almost 6%. It is further noted that at 20% moisture content in the fuel, the decrease in the heating value is only 1.6% at $\phi$ = 2.4 and 1.3% at $\phi$ = 3.2 from the corresponding heating values at 0% moisture. It shows that up to 20% moisture content is possibly acceptable for getting good quality producer gas from the gasifier.

## 4. CONCLUSION

A model has been developed for the simulation of the performance of a throated downdraft biomass gasifier considering two distinct zone: pyro-oxidation zone and reduction zone. The process of the pyro-oxidation zone of the gasifier has been solved considering chemical equilibrium of the species and the composition of different species ($H_2$, CO, $CO_2$, $CH_4$, $H_2O$, $N_2$ and Char) and the temperature of the gas which flows from the pyro-oxidation to the reduction zone are obtained. Reduction zone has been solved based on chemical kinetics of reduction reactions by char considering a large number of elemental control volumes along the length of the zone to predict final gas composition. The temperature and species concentration distributions in the gasifier have been predicted in the model. A specific char reactivity factor of the combination of constant, linear and exponential variation with the distance of the reduction zone has been considered after validating the predictions with the experimental results from the literature. A parametric study has been performed with the model at different equivalence ratio and biomass moisture content to predict the gas composition and heating value. The $H_2$ and $CH_4$ contents in the producer gas at the exit of the gasifier are found to increase while the concentration of CO and $CO_2$ increases slightly with the increase in equivalence ratio. The heating value of the producer gas increases with the increase in the equivalence ratio. Increase in biomass moisture content deteriorates the quality of the producer gas and its heating value decreases. The relative decrease in the heating value with the increase in moisture content increases with the increased wetness of the feedstock. Moreover, the operating equivalence ratio also influences the change in the heating value with the change in moisture in biomass. At lower equivalence ratio the percentage decrease in the heating value with the increase in moisture increases. The increase in moisture reduces the CO content in the producer gas and increases $H_2$ and $CO_2$. The change in $CH_4$ content depends on the equivalence ratio at which the gasifier is operating. At low equivalence ratio (e.g. $\phi$ =2.4), the $CH_4$ mole fraction remains almost constant with the change in moisture content, while at $\phi$ = 3.2, the $CH_4$ mole fraction increases as the moisture content in the fuel increases.

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