

# Modeling and Simulation of Reduction Zone of Downdraft Biomass Gasifier: Effect of Air to Fuel Ratio

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## Abstract

Biomass mainly in the form of wood is the oldest form of energy used by humans. Biomass generally means a relatively dry solid of natural matter that has been specifically grown or has originated as waste or residue from handling such materials. The thermochemical conversion of biomass (pyrolysis, gasification, combustion) is one of the most promising non-nuclear forms of future energy.

In the present study, the model reported in literature is simulated to study the effects of pyrolysis fraction on the outlet gas concentration in a downdraft biomass gasifier. It is found that the air to fuel ratio is one of the key parameters in the reduction zone of downdraft biomass gasifier. It effects the value of pyrolysis fraction in the model, and indirectly proportional to the pyrolysis fraction. Steady state composition and temperature profiles for the reduction zone of the downdraft biomass gasifier are also predicted for various values of air to fuel ratio.

*Keywords:* Char Reactivity Factor; Biomass Gasification; Downdraft Gasifier; Modeling; Simulation; Reaction Kinetics; Pyrolysis Fraction.

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## 1. Introduction

Biomass and waste are recognized to be the major potential sources for energy production. It is a renewable source of energy and has many advantages from an ecological point of view [1]. Thermochemical gasification is a process for converting solid fuels into gaseous form. The chemical energy of the solid fuel is converted into both the thermal and chemical energy of gas. The chemical energy contained within the gas is a function of its chemical composition. Thus the chemical composition of the

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product gas determines its quality as a fuel. High concentrations of combustible gases such as  $H_2$ ,  $CO$  and  $CH_4$  increase the combustion energy of the product gas [2].

The pyrolysis process consists of the thermal degradation of the biomass feedstock, in the absence of oxygen/air, leading to the formation of solid, liquid and gaseous products [3-6]. Gasification enables conversion of this material into combustible gas, mechanical and electrical power and synthetic fuels and chemicals. Gasification is a process of conversion of solid carbonaceous fuel into combustible gas by partial combustion. The understanding of the interaction between chemical and physical mechanisms during gasification is of fundamental importance, for the optimal design of biomass gasifiers [7]. In view of the considerable interest in the gasification process worldwide, it is necessary to model and predict the performance of the gasifier *in priori*. Modeling of biomass gasification implies the representation of chemical and physical phenomena constituting pyrolysis, combustion, reduction, and drying in the mathematical form.

Giltrap et al. [2] developed a model for the reduction zone of downdraft biomass gasifier to predict the composition of producer gas under steady state operation. The accuracy of the model is limited by the availability of data on the initial conditions at the top of the reduction zone. Moreover it is assumed that char reactivity factor (*CRF*) which represents the reactivity of char and the key variable in simulation is taken as constant throughout the reduction zone. Babu and Sheth [7] modified the Giltrap's model by incorporating the variation of char reactivity factor (*CRF*) along the reduction zone of downdraft biomass gasifier. Increasing *CRF* exponentially along the reduction bed length in the model gave

better prediction of temperature and composition profiles when compared with the experimental data and earlier models reported in literature. Dogru et al. [8] performed the gasification of hazelnut shells in a pilot scale (5 kWe) downdraft gasifier with different air to fuel ratio. In the present study, steady state model modified by Babu and Sheth [7] is simulated with finite difference method to predict the temperature and composition profiles in the reduction zone. The model predictions are compared with the experimental data reported by Dogru et al. [8].

### Nomenclature

$A$	Cylindrical bed area ( $m^2$ )
$A_i$	Frequency Factor for reaction $i$ ( $sec^{-1}$ )
$c_x$	Molar heat capacity ( $J/mol K$ )
$CRF$	Char reactivity factor
$E_i$	Activation Energy of reaction $i$ ( $Joules/mol K$ )
$f_p$	Fraction of pyrolysis
$K_i$	Equilibrium constant of reaction $I$
$L_n$	Normalized Length
$L_{in}$	Initial normalized length at which 85 % of the total composition change
$n_x$	Molar density of species $x$ ( $mol/m^3$ )
$n$	Summation of $n_x$ of all species
$P_x$	Partial pressure of gaseous species $x$ ( $Pa$ )
$r_i$	Rate of reaction $i$ ( $mol/m^3sec$ )
$R_x$	Rate of formation of species $x$ ( $mol/m^3sec$ )
$R$	Gas constant ( $J/mol K$ )
$T$	Temperature ( $K$ )
$v$	Superficial gas velocity ( $m/sec$ )
$z$	Axial distance ( $m$ )

### Greek Letters

$\rho$	Density ( $kg/m^3$ )
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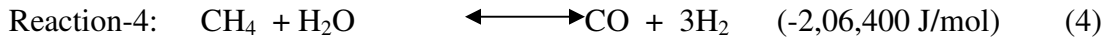
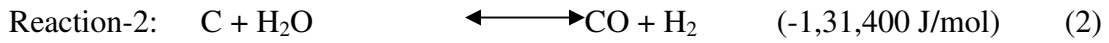
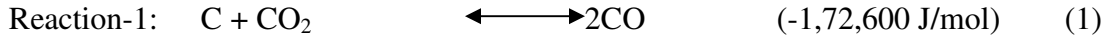
### Subscript

$x$	Species $N_2, CO_2, CO, CH_4, H_2O, H_2$
$i$	Reaction number

## 2. Model

Giltrap et al. [2] proposed a phenomenological model of downdraft gasification under steady state operation for reduction zone of the biomass gasifier. The pyrolysis and

cracking reactions were not considered in this model as the number of possible pyrolysis products along with all the possible reactions and intermediate products would make the model very complex. It is assumed that all the oxygen from the air inlet is being combusted to CO<sub>2</sub> and that the pyrolysis products are completely cracked. Solid carbon in the form of char is assumed to be present throughout the reduction region. Model uses the reaction kinetic parameters developed by Wang and Kinoshita [9] and the adopted reaction scheme is as follows (Eqs. 1-4):



This model assumes a cylindrical gasifier bed of uniform cross-sectional area  $A$  with negligible radial variation in the properties of both the bed and the gas. Molar balance and Energy balance results in a set of following equations (Eqs. 5-7). Species considered here are nitrogen, carbon dioxide, carbon monoxide, methane, steam and hydrogen.

$$\frac{dn_x}{dz} = \frac{1}{v} \left( R_x - n_x \frac{dv}{dz} \right) \quad (5)$$

$$\frac{dT}{dz} = \frac{1}{v \sum_x n_x c_x} \left( - \sum_i r_i \Delta H_i - v \frac{dP}{dz} - P \frac{dv}{dz} - \sum_x R_x c_x T \right) \quad (6)$$

$$\frac{dv}{dz} = \frac{1}{\sum_x n_x c_x + nR} \left( \frac{\sum_x n_x c_x \sum_x R_x}{n} - \frac{\sum_i r_i \Delta H_i}{T} - \frac{dP}{dz} \left( \frac{v}{T} + \frac{v \sum_x n_x c_x}{P} \right) - \sum_x R_x c_x \right) \quad (7)$$

The following empirical formula (Eq. 8) is used to find the pressure gradient of a fluid flowing through a bed of solid char particles, (Supplied by Dr. Donna Giltrap on request which was used, but not reported in their article [2]).

$$\frac{dP}{dz} = 1183 \left( \rho_{\text{gas}} \frac{v^2}{\rho_{\text{air}}} \right) + 388.19 v - 79.896 \quad (8)$$

The reaction rates were all considered to have an Arrhenius-type temperature dependence and to be proportional to the difference between the actual reactant / product ratio and the corresponding equilibrium ratio. The reaction rates for the reactions (Eqs. 1-4) can be written as follows (Eqs. 9-12):

$$r_1 = n \text{ CRF } A_1 \exp\left(\frac{-E_1}{RT}\right) \cdot \left( P_{\text{CO}_2} - \frac{P_{\text{CO}}^2}{K_1} \right) \quad (9)$$

$$r_2 = n \text{ CRF } A_2 \exp\left(\frac{-E_2}{RT}\right) \cdot \left( P_{\text{H}_2\text{O}} - \frac{P_{\text{CO}} \cdot P_{\text{H}_2}}{K_2} \right) \quad (10)$$

$$r_3 = n \text{ CRF } A_3 \exp\left(\frac{-E_3}{RT}\right) \cdot \left( P_{\text{H}_2}^2 - \frac{P_{\text{CH}_4}}{K_3} \right) \quad (11)$$

$$r_4 = n \text{ CRF } A_4 \exp\left(\frac{-E_4}{RT}\right) \cdot \left( P_{\text{CH}_4} \cdot P_{\text{H}_2\text{O}} - \frac{P_{\text{CO}} \cdot P_{\text{H}_2}^3}{K_4} \right) \quad (12)$$

The values of the frequency factor and the Activation energies are taken from the Wang and Kinoshita [9], which are shown in Table 1.

**Table 1. Frequency factor and Activation Energies values [9]**

Reaction <i>i</i>	$A_i$ (1/s)	$E_i$ (kJ/mol)
1	$3.616 \times 10^1$	77.39
2	$1.517 \times 10^4$	121.62
3	$4.189 \times 10^{-3}$	19.21
4	$7.301 \times 10^{-2}$	36.15

In the reduction zone, endothermic reactions are carried out and the degree of temperature drop depends upon the extent of reactions. The extent of reaction depends upon the reactivity of char, which is represented by Char Reactivity Factor (*CRF*) value. *CRF* in turn depends upon thermal history, degree of burn-off, and number of active sites on char and its particle size. As char moves downwards in the reduction zone, the degree of burn-off increases. Due to char-gas reactions and shrinking of particles, char size decreases and porosity increases so gases would come across more active sites and extent of reaction increases. For higher *CRF* value, reduction zone temperature drops faster and reaction completion occurs rapidly. Due to this, the gas compositions predicted by the model are changed in the initial length of reduction zone only. Above understanding leads to the fact that *CRF* value must be increased along the length of the reduction zone. Quantitative increment in *CRF* value depends upon the type of biomass and its physical characteristics. Giltrap et al. [2] simulated for constant *CRF* value for the entire reduction zone. In their work, they varied the *CRF* value of 1 to 10000 and the results of simulation are compared with the final composition of the producer gas with the data reported in literature. But temperature and composition profiles are not compared.

Babu and Sheth [7] varied the *CRF* value of 1 to 10000 linearly and exponentially and their effects on composition and temperature profiles are observed. When exponential increment in *CRF* value is used in the simulation, it predicted the temperature and composition profiles better when compared with the experimental data reported by Jayah et al. [10]. The results of exponentially varying *CRF* are quite satisfactory and realistic.

In addition, the composition profile changes over the entire length of the bed of reduction zone [7].

### **3. Method of solution and simulation of model equations**

Eq. (5) to (8) gives a set of nine first order differential equations in the system variables  $n_x$  (where  $x$  denotes the six different gas species considered),  $P$ ,  $v$ , and  $T$  that is solved by explicit finite difference method [11, 12].

#### *3.1 Initial Conditions*

The initial position in this model is the top of reduction region and the end of oxidation zone. Gases coming from the oxidation zone are a mixture of pyrolysed gas, incombustible CO<sub>2</sub> and inert N<sub>2</sub>. The exact proportion of each of these components depends upon the rate of air flowing into the gasifier relative to the rates of combustion, pyrolysis and cracking reactions. Instead of calculating this directly, Giltrap et al. [2] introduced a variable ‘pyrolysis fraction’ ( $f_p$ ), which can vary from 0 (no pyrolysis products) to 1 (pyrolysis products only). The air flowing into the gasifier is a mixture of N<sub>2</sub> and O<sub>2</sub>. It is assumed that all O<sub>2</sub> from air inlet had been consumed by combustion reactions with the char while N<sub>2</sub> remains inert. The pyrolysis products are assumed to crack into an equivalent amount of CO, CH<sub>4</sub> and H<sub>2</sub>O for a typical biomass.

Initial velocity, pressure and temperature for the model would be of gas coming out of the oxidation zone. The velocity has been approximated from the airflow rate and the throat dimensions reported by Dogru et al. [8]. The operating pressure does not affect the

gasification efficiency significantly. Increase of the pressure is limited on two counts: (1) due to the amount of entrained dust (the gas, being denser, exerts a higher thrust on the dust particles), and (2) by the increased cost of manufacturing [13]. Due to these limitations and to overcome the pressure drop offered by the bed, operating pressure should be above the atmospheric pressure. The value has to be found out by approximating the pressure drop in the bed. The value of 1.005 atm is used in simulations and check has been made that pressure at the outlet remains above atmospheric [7].

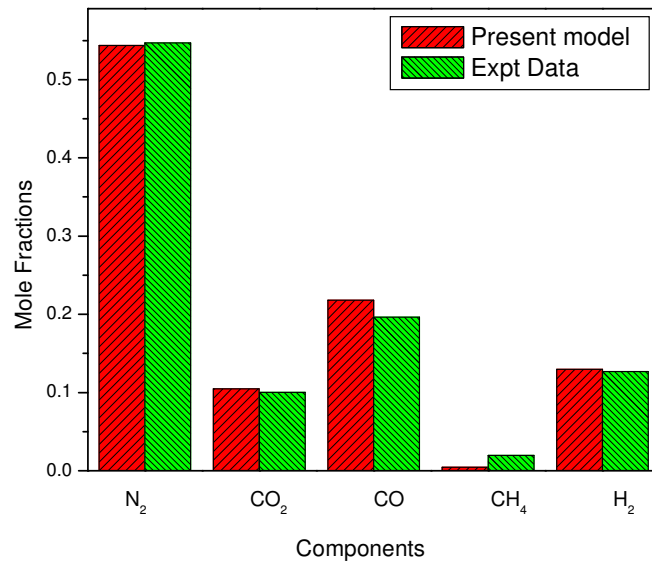
Table 2 shows the values of the parameters used in two different model simulations. In Table 2, bed length, velocity, temperature, moisture content, and air-to-fuel ratio (S.Nos. 1-5) are taken to be the same as reported by Dogru et al. [8]. Other parameters ( $CRF$  and  $f_p$ ) are new ones that are incorporated in the present proposed model.

**Table 2. Parameters used in the model simulation [8]**

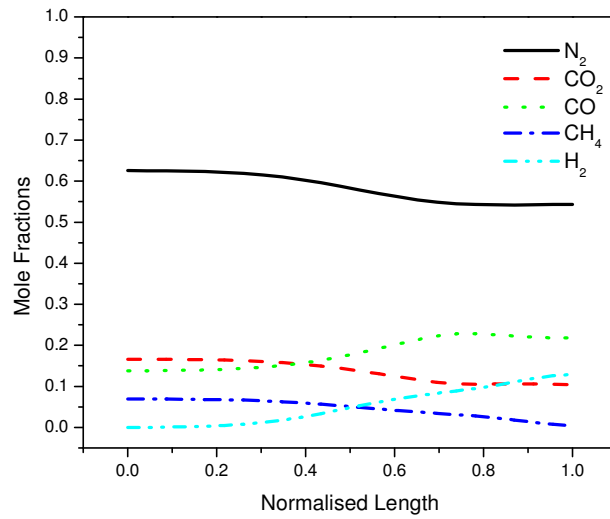
S No	Parameters	Values (Run 7)	Values (Run 11)
1	Bed Length	11.5 cm	11.5 cm
2	$v$ initial	0.426963 m/sec	0.579471 m/sec
3	$T$ initial	1293 K	1293 K
4	Moisture Content	12 % (wet basis)	12 % (wet basis)
5	Air-to-Fuel ratio	1.47	1.5
6	$CRF$	Exponentially varying	Exponentially varying
7	$f_p$	0.25	0.2 & 0.25

#### 4. Results and Discussion

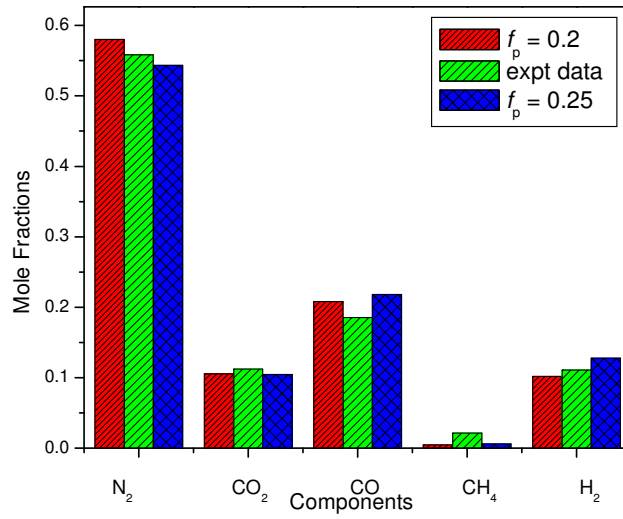
Fig. 1 shows the comparison of the model predictions of gas compositions with the experimental data for air to fuel ratio of 1.47 [8]. The value of pyrolysis fraction variable used is 0.25. The model predictions are good with an average deviation of 5%. Fig. 2 shows the composition profile of all the components for the experimental run 7 [8].



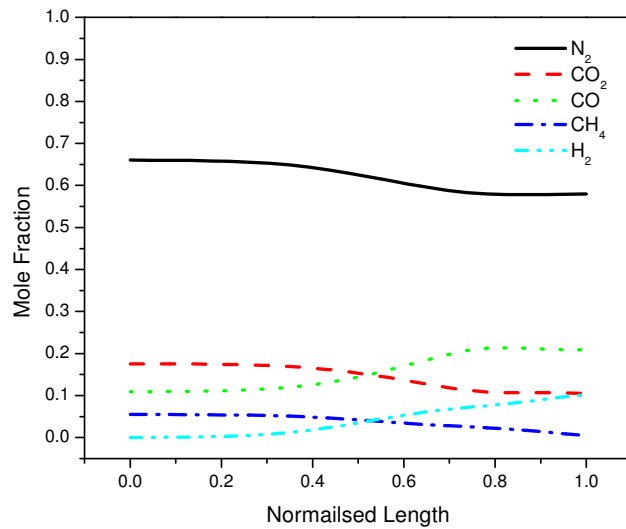
**Fig. 1 Comparison of the Model predictions of Gas Compositions with the Experimental Data for Run7 [8]**



**Fig.2 Composition variation with the normalized length of the reduction zone for Run 7 [8]**



**Fig. 3 Comparison of the Model predictions of Gas Compositions with the Experimental Data for Run 11 [8]**



**Fig.4 Composition variation with the normalized length of the reduction zone for Run 11 [8]**

The amount of CO and H<sub>2</sub> increases, while that of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub> decreases across the length of the reduction zone. N<sub>2</sub> content remains same as it is an inert gas, but its composition decreases as the content of other components change across the length.

Dogru et al. [8] performed the run 11 with an air-to-fuel ratio of 1.5 which is significantly higher than that of run 7. It indicates that the amount of N<sub>2</sub> and CO<sub>2</sub> at the entrance of reduction zone, is higher for run 11 compared to those values of run 7. Pyrolysis fraction variable accounts for the percentage of pyrolysed gas at the entrance of the reduction zone. For run 7 simulations,  $f_p = 0.25$  is used (table-2) and for run 11, simulations are carried out with  $f_p$  of 0.2 and 0.25. Fig. 3 shows the comparison of the model predictions of gas compositions with the pyrolysis fraction values of 0.2 and 0.25 for run 11 [8]. Model simulation with pyrolysis fraction,  $f_p = 0.2$ , predicts better compared to those with  $f_p = 0.25$  for run 11 [8] due to the higher value of air-to-fuel ratio (1.5).

Fig. 4 shows the composition profile of all the components for the experimental run 11 [8]. The qualitative trends of all the profiles are similar to those obtained with run 7 (Fig. 2), though quantitatively they are different.

## **Conclusions**

The steady state model discussed here predicts the composition and temperature profiles across the length of the reduction zone. Char reactivity factor and the pyrolysis fraction variable are the key parameter in modeling of downdraft gasifier and it directly represents

the reactivity of char in the reduction zone. Based on the results obtained and the discussions carried out in the earlier section, the following conclusions are drawn:

- It is found that air to fuel ratio is one of the key parameter in the simulation. And its effect can be incorporated by varying the value of pyrolysis fraction variable.
- For higher value of air to fuel ratio, the lower value of pyrolysis fraction variable has to be used.
- Model simulation with  $f_p = 0.2$  predicts better compared to the simulated results of the  $f_p = 0.25$  for run 11 [8].

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He is the recipient of National Technology Day (11<sup>th</sup> May, 2003) Award given by CSIR, obtained in recognition of the research work done in the area of 'A New Concept in Differential Evolution (DE) – Nested DE'. One of his papers earned the *Kuloor Memorial Award, 2006 awarded for the Best Technical Paper* published in the Institute's Journal "Indian Chemical Engineer" in its issues for 2005.

He is Life member of many professional bodies such as IChE, ISTE, IE (I), IEA, SOM, Fellow of ICCE, Associate Member of ISSMO, IIIS, and IAENG. Nine of his technical papers have been included as successful applications of Differential Evolution (DE: a population based search algorithm for optimization) on their Homepage at <http://www.icsi.berkeley.edu/~storn/code.html#appl>. He has around 120 research publications (International & National Journals & Conference Proceedings) to his credit. He completed three consultancy projects successfully. He has published five books, and wrote several chapters in various books and lecture notes of different intensive courses.

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He is Editorial Board Member of three International Journals 'Energy Education Science & Technology', 'Research Journal of Chemistry and Environment', and 'International Journal of Computer, Mathematical Sciences and Applications'. He is the referee & expert reviewer of 24 International Journals. He reviewed three books of McGraw Hill, Oxford University Press, and Tata McGraw Hill publishers. He is PhD Examiner for one candidate and PhD Thesis Reviewer for 3 Candidates. He is the Organizing Secretary for "National Conference on Environmental Conservation (NCEC-2006)" held at BITS-Pilani during September 1-3, 2006.

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