

## PARAMETRIC SENSITIVITY OF DOWNDRAFT GASIFIER AS PREDICTED BY THREE ZONE KF MODEL

Ratnadhariya J. K.<sup>1</sup> and Channiwala S. A.<sup>2</sup>

<sup>1</sup>Lecturer in Mechanical Engg., Sarvajanic College of Engg. & Tech., Athwalines,  
Surat – 395 001, Gujarat State, India.

<sup>2</sup>Professor, Mechanical Engg. Deptt., S. V. National Institute of Technology,  
Surat-395 007, Gujarat State, India.

### ABSTRACT

The gasifier is a device in which gasification process is taking place. This gasification process is a thermo chemical conversion of biomass into gaseous fuel (producer gas). This process in the down draft gasifier passes through four stages i.e., drying, pyrolysis, oxidation or combustion & reduction or gasification. For getting optimal operating parameters of down draft gasifier to obtain good quality gas and safe, non – slagging operation it is necessary to study parametric sensitivity of the down draft gasifier. The present paper is an attempt towards the study of parametric sensitivity of down draft gasifier with the help of three zone KF (Kinetic Free) model. KF model computes gas composition, temperature levels in each zone and performance parameters of the gasifier without involving any reaction kinetics. The drying and pyrolysis zones are clubbed together and form the first zone of the gasifier. The oxidation and reduction zone make the other two zones of gasifier. Each zone has been modeled through use of Stoichiometry of reaction, mass balance, chemical equilibrium and energy balance.

This KF model has been validated with published experimental results and thereafter it is used for the study of sensitivity of gas compositions, temperature profile in each zone and gasifier performance parameters as a function of equivalence ratio, moisture content and C/H ratio. This model clearly indicates the equivalence ratio in the vicinity of 0.3 and moisture content in the range of 10 to 20%, as the optimal operating parameters to obtain good quality gas and safe, smooth running of gasifier with woody biomass as its feed. Also, this model is capable to identify the suitability of biomass material for pyrolysis / gasification process. It clearly indicates that biomass material having C/H ratio in the vicinity of 0.719 are the best-feed stock for pyrolysis / gasification.

**Keywords:** Parametric Sensitivity, Down Draft Gasifier, KF Model.

### 1. INTRODUCTION

Kinetic Free model divides the gasifier in different zones i.e., Pyrolysis, Oxidation and Reduction zone. This model predicts Gas composition & Equilibrium temperature in each zone and Gasifier performance parameters. Kinetic free model as the name suggests, does not involve any reaction kinetics and local chemistry in computation of the product profile. It is simply based on stoichiometry of reaction, mass balance, chemical equilibrium and energy balance in each zone.

First attempt was made by Denn et al., [1] to make a KF modeling of gasification process. They proposed a simplified KF model for updraft gasifier.

It consists of three zones i.e., pyrolysis, oxidation & reduction. Drying has been clubbed with pyrolysis. The model computes the final gas composition and the maximum temperature in the reactor. The Global model of counter-current coal gasifiers developed by Kosky & Floess [2] is a two-zone KF model for updraft

gasification reactor. Drying and Pyrolysis processes constitute one zone and the second zone refers to the combustion and gasification processes clubbed together. The gases exiting from the second zone are assumed to be in shift equilibrium, water vapour and pyrolysis products are assumed to join this gas stream.

The computed values of CO, CO<sub>2</sub> & H<sub>2</sub> are reported to be in good agreement with experimental data confirming validity of the assumption of shift equilibrium. This model fails in the methane predictions probably due to the fact that CH<sub>4</sub> is produced from several sources e.g. pyrolysis, hydrogasification etc. Ali [3] has proposed a KF model for downdraft gasifier, combining the oxidation and gasification zones. Ali too, has computed the exit gas composition assuming shift equilibrium.

Review of the above mentioned published work in the area of KF model clearly reveals that very little efforts have been made to develop KF model for downdraft gasifier. In case of downdraft gasifier, the

moisture and pyrolysis products enter the oxidation zone and as such it does not mean just joining the equilibrium mixture emerging from the gasification zone. Sensitivity of the composition as well as quantity of the pyrolysis products to the operating conditions e.g. particle size, heating rates etc., adds to the estimation difficulties. Evans and Emmons [4], while studying combustion of wood charcoal observed that when combustion actually proceeds in an oxygen deficient environment, the CO/CO<sub>2</sub> distribution is related to the temperature as:  $n_{CO_{OXD}}/n_{CO_{2OXD}} = 4.3 * e^{-3390/T_{OXD}}$ . This relationship may be used for modeling the oxidation zone. Commensurate with the above-mentioned revelations, Channiwala [5] considered development of a three-zone KF model for the downdraft gasifier. He clubbed drying and pyrolysis zone to form a first zone and treated oxidation and reduction zone separately in second and third zones. He used stoichiometry of reaction, chemical equilibrium of suitable reactions and mass & energy balance to compute product gas quality in each zone of gasifier. The present work is an extension of the work carried out by Channiwala [5] and aims at studying of the parametric sensitivity of downdraft biomass gasifier.

## 2. PHYSICAL DESCRIPTION AND FORMULATION OF MODEL

Fig 1 gives overall view of the physical model of downdraft gasifier along with possible reactions in the different zones i.e., drying & pyrolysis, oxidation and reduction. Drying and pyrolysis zones are clubbed together. Product composition and temperature in this zone is computed assuming equilibrium of water gas, methanation and water gas shift reaction along with condition of mass and energy balance.

These products enter the oxidation zone where incoming air reacts and complete oxidation of hydrogen to H<sub>2</sub>O and partial oxidation of char and methane takes place. The char oxidation yields CO and CO<sub>2</sub>, which are assumed to follow Evans and Emmons relationship [4]. The extent of methane oxidation is assumed to be 60% on molar basis, this proportion being arrived at after several trials towards comparability of model and experimental results. Channiwala [5] in his work assumed this methane carry over as 50%.

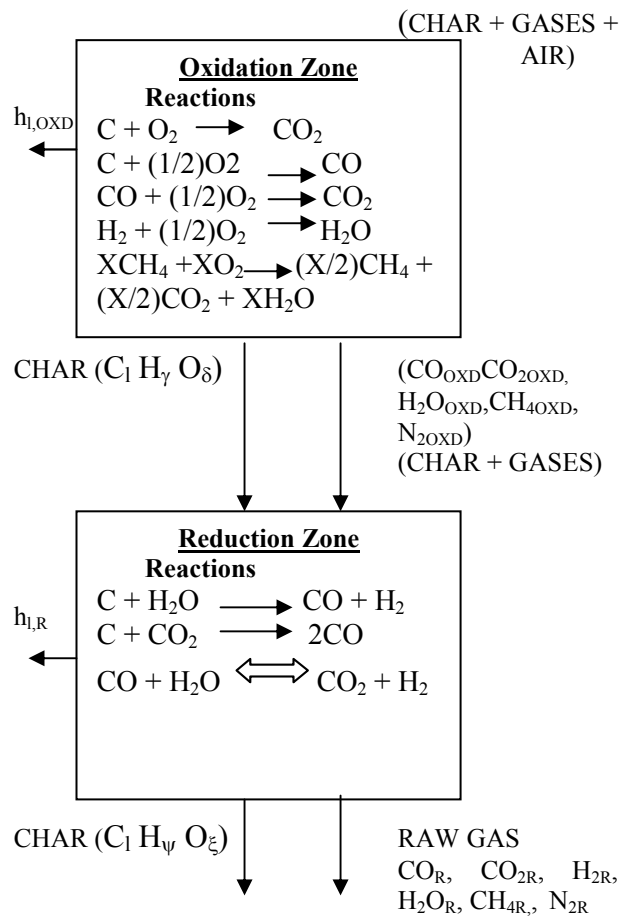
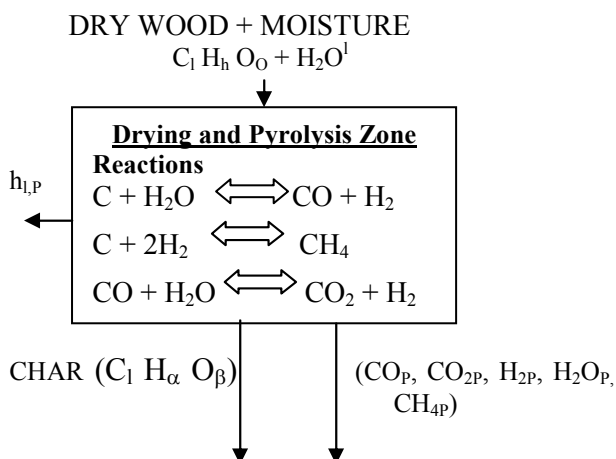


Fig 1. Three Zone KF Model of Downdraft Gasifier

The composition of oxidation zone is computed using mass and energy balance equations along with Evans & Emmon's relationships [4].

The products from oxidation zone enter reduction zone. The balance 40% methane is assumed to be carried forward through this zone while char carry over is assumed to be 3% on molar basis based on the work of Channiwala [5]. The other gas constituents in reduction zone are assumed to be at shift equilibrium. The product distribution and temperature level in this zone is obtained using mass and energy balance equations along with the condition of shift equilibrium.

This model predicts the gas composition, temperature and gasifier performance parameter in all the three zones, using respective thermodynamic equilibrium and mass and energy balance equations. Three zone product distribution and temperature profiles in the downdraft gasifier are thus obtainable.

For the solution of the model versatile computer programming in Turbo-C has been developed. Independent solution of model is obtained for each zone and coupled to yield an overall solution of the model. This program computes product gas composition, equilibrium temperature and gasifier performance parameters at each zone. In formulation and solution of the model the biomass is represented as dry, ash, S & N free biomass plus liquid moisture, the char composition in each zone is taken from experimental data of

Channiwala [5]. The overall heat loss is assumed to be 10% of product of ER & HHV, the pyrolysis, oxidation and reduction zone sharing 25%, 40% & 35% of this loss, respectively.

## 5. RESULTS AND DISCUSSIONS

### 5.1 Model Validation

The validation of three-zone KF model has been carried out through comparison of final gas composition with published literature. In all cases char composition is kept same due to unavailability of this data in literature. The data of wood and char compositions are taken from the Channiwala [5]. The heat loss in all calculation is assumed to be 10% of product of ER & HHV of the material. Table 1 shows the materials and input operating parameters of published experimental results while Table 2 shows the comparison of model prediction with published experimental results. Also Table 3 shows the zone wise prediction of Temperature level.

It can be seen from comparisons of results presented in Table 2 & 3 that the model predictions are in good agreements with published experimental results.

The predictions of CO, CO<sub>2</sub>, H<sub>2</sub>, N<sub>2</sub> & the hydrocarbon in the form of CH<sub>4</sub> are in good agreement with the published experimental results as is reflected from their error levels. The better agreement even for CH<sub>4</sub> prediction certainly justifies the assumption of 60% methane oxidation and 40% methane carry over along with 3% char carry over in reduction zone. Predictions of Pyrolysis zone temperature compares well with experimental results while over prediction of oxidation and reduction zone temperatures may be due to use of Evans and Emmons relationship. The similar observation was also made by Channiwala [5].

It can therefore be stated that the model developed is fairly versatile and inspite of being a KF model, which is rather simplistic approach, can be used to generate biomass specific performance data generally needed for reactor design. The model thus stands validated over the wide range of biomass material and operating conditions.

### 5.2 Model Predictions

The basic purpose of any mathematical model lies in its utility as a tool for design, scale-up and performance predictions.

Table 1: Materials and Input Parameters of Published Experimental Results

Table 2: Model Validation with Published Experimental Results

Table 3: Model Validation for Temperature level in Each Zone with Published Experimental Results (Material: Subabul Wood, heat loss =10%, C<sub>1</sub>H<sub>1.451</sub>O<sub>0.697</sub>, HHV =19.777MJ/kg) [5]

Material/ Input Parameters
Birch Wood [9] ER = 0.3268, MC = 10%, HHV = 18.900 MJ/kg
Wood chips R.No.910 [10] ER = 0.2978, MC = 16.52%, HHV = 19.826 MJ/kg
Wood chipsR.No.1119 [10] ER = 0.2643, MC = 15.32%, HHV = 19.826 MJ/kg
Pine [11] ER = 0.2039, MC = 6.4%, HHV = 22.596 MJ/kg
Cubed bean straw [2] ER = 0.3191, MC = 13%, HHV = 18.752 MJ/kg
Rice hall pallets [2] ER = 0.4837, MC = 8.6%, HHV = 19.277 MJ/kg

$\phi$	MC, %	T <sub>p</sub> , K	T <sub>OXD</sub> , K	T <sub>R</sub> , K
0.360 (Exp.)	11.4	837	1303	936
0.360 (Model)	11.4	800.6	1658.6	1400.3

#### Dry Gas Composition [% by Volume]

CO <sub>2</sub>	CO	H <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub>	C <sub>2</sub> H <sub>6</sub>	
11.00	21.50	19.00	1.40	47.10	-	Exp.
10.91	23.54	15.38	2.08	48.09	-	Model
16.25	18.05	15.00	2.63	47.89	0.5	Exp.
11.96	22.38	17.79	2.73	45.12	-	Model
15.51	19.62	15.56	2.49	45.96	0.86	Exp.
11.52	23.89	21.22	2.46	40.91	-	Model
9.51	26.64	18.28	2.82	40.95	1.80	Exp.
7.22	28.24	26.90	2.85	34.79	-	Model
12.60	20.30	15.45	2.74	48.71	0.14	Exp.
10.88	24.26	16.29	1.77	46.80	-	Model
10.50	16.10	9.60	0.95	62.80	0.05	Exp.
10.96	19.28	9.06	0.35	60.34	-	Model
0.329 (Exp.)	10.9	888	1351	1112		
0.329 (Model)	10.9	805.5	1633.21	1323.5		
0.291 (Exp.)	11.1	855	1266	989		
0.291 (Model)	11.1	806.2	1590.2	1209.8		

Accordingly, the present three-zone KF model, which has been validated experimentally to a sufficient degree of accuracy has been used typically to study the sensitivity analysis with respect to input parameters i.e., effect of equivalence ratio on final gas composition (reduction zone) & temperature profile of each zone. However, it must be emphasized over here that the model is capable to predict gas quality in pyrolysis and oxidation zones. The salient features of this results and observations are presented in the following paragraphs.

**5.2.1 Influence of Equivalence Ratio**

Fig. 2 presents the variation of gas composition as a function of equivalence ratio in reduction zone. Increasing N<sub>2</sub> concentration and reducing CH<sub>4</sub> concentration with increasing equivalence ratio is simply attributed to increasing moles of air intake. The profile of CO, CO<sub>2</sub>, H<sub>2</sub> & H<sub>2</sub>O concentration are coupled to the equilibrium constant of shift reaction and hence the variations are governed by the variation of K<sub>pS</sub> which results through changes in equilibrium temperature occurring due to increasing equivalence ratio [1,2,5]. The H<sub>2</sub> concentration continuously decreases with increasing equivalence ratio because

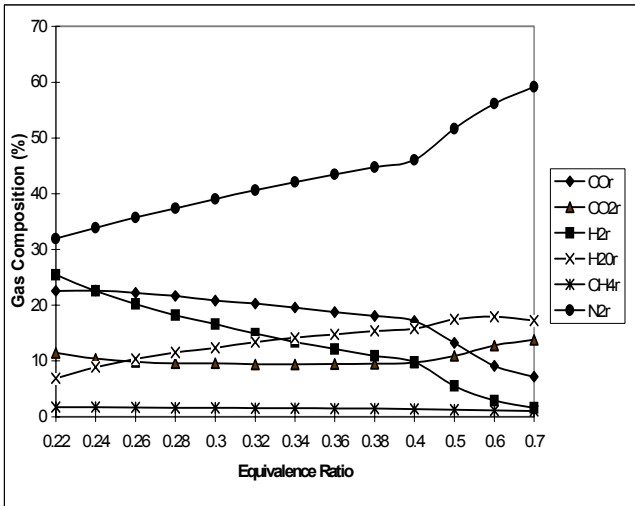


Fig 2. Influence of Equivalence Ratio on Gas Composition of Reduction Zone (Material: subabul wood, MC = 15%, heat loss=10%)

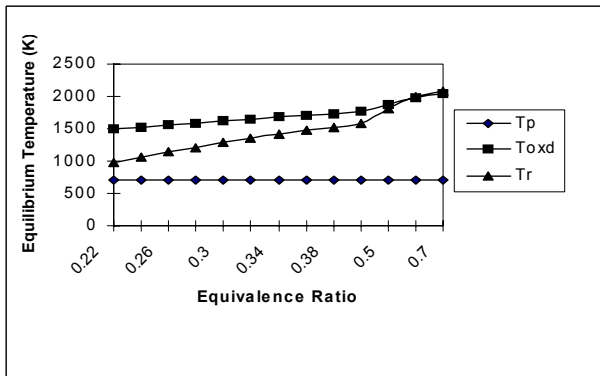


Fig 3. Influence of Equivalence Ratio on Equilibrium Temperature (Material: subabul wood, MC = 15%, heat loss = 10%)

higher availability of O<sub>2</sub> first consumes H<sub>2</sub>, which is also reflected in increasing concentration of H<sub>2</sub>O. The CO concentration is observed to be reducing with peak at equivalence ratio equal to 0.24.

Reducing CO concentration is obviously due to oxidation of CO at higher equivalence ratio, which is further, substantiated by the increasing trend of CO<sub>2</sub> concentration with equivalence ratio. This signifies that prominent gasification region lies in the equivalence

ratio range of 0.28 to 0.34 for the subabul wood as a biomass material.

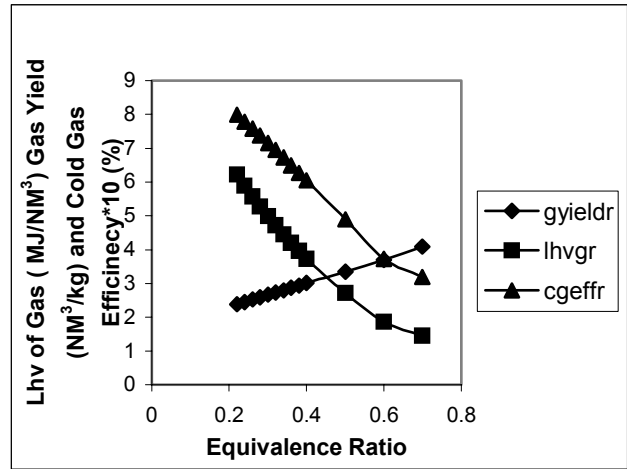


Fig 4. Influence of Equivalence Ratio on Gas Quality, Gas Yield & Cold Gas Efficiency (Material: subabul wood, MC = 15%, heat loss = 10%)

Fig. 3 presents the variations of equilibrium temperature as a function of equivalence ratio in each zone. It is obvious that pyrolysis zone temperature remains constant because the pyrolysis occurs in the absence of air and further that the present model does not take into account the kinetic of chemical reaction, as it is a KF model. The increasing trends of T<sub>OXD</sub> & T<sub>R</sub> are quite obvious because with increasing equivalence ratio reactions enter the combustion regions and hence the amount of heat energy liberated in each zone continuously increases which in turn offers higher temperature levels. However, it is worth mentioning here that at an equivalence ratio of 0.6 and above the oxidation zone temperature is observed to be less than that in reduction zone. This seeming disparity may be attributed to the use of Evan and Emmons relationship [4] for CO/CO<sub>2</sub> distributions. It is believed that this relation does not hold good at higher equivalence ratio.

Fig. 4 presents the variation of gasifier performance parameters i.e., cold gas efficiency, gas yield & LHV of gas with equivalence ratio. The increasing gas yield is obviously due to higher air intake with increasing equivalence ratio. The decreasing cold gas efficiency and LHV of gas may be attributed to the consumption of combustible gas due to more availability of air with increasing equivalence ratio. A sharp reduction observed in LHV of gas and cold gas efficiency after equivalence ratio of 0.4 signifies the gasification reactions entering combustion region. Thus, it may be treated as a limiting value of equivalence ratio for gasification with subabul wood as a biomass material. These results clearly indicate that the present model can be used to define the useful range of equivalence ratio for gasification for any biomass material.

**5.2.2 Influence of Moisture Content**

Fig 5 represents the variation in composition in reduction zone with moisture content for a constant

equivalence ratio as 0.3 and subabul wood as biomass material. The decreasing  $N_2$  concentration is essentially due to increased availability of the moles of moisture. Higher moisture level also seem to reduce CO concentration level and increase  $CO_2$  and  $H_2$  level due to equilibrium of water gas shift reaction. The variation of  $CH_4$  concentration are quite interesting, it has a direct bearing with the pyrolysis zone results.

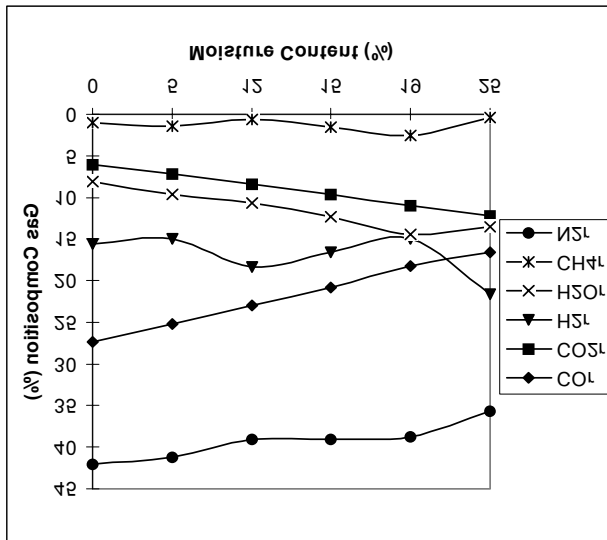


Fig 5. Influence of Moisture Content on Gas Composition (Reduction Zone) (Material: subabul wood, ER = 0.3, heat loss = 10%)

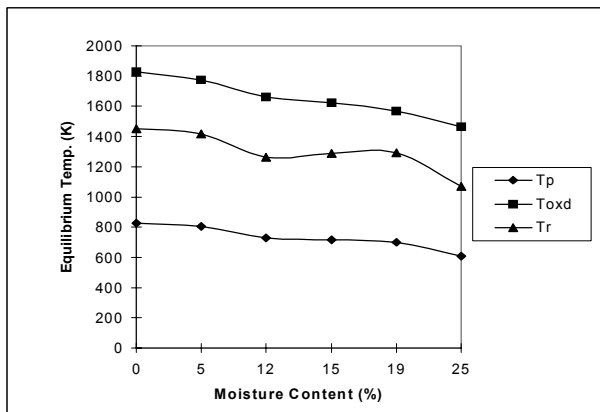


Fig 6. Influence of Moisture Content on Equilibrium Temperature (Material: subabul wood, ER = 0.3, heat loss = 10%)

Fig. 6 represents the influence of moisture content on equilibrium temperatures of pyrolysis, oxidation and reduction zones. Very obviously the temperatures at each zone decreases with increasing moisture content because higher moisture content consumes more amount of heat energy as a latent heat and thereby reduces the temperature levels.

### 5.2.3 Influence of C/H Ratio

Five different biomass materials have been selected (Lignite char (C/H = 6.798), Long leaf pine barks

(C/H = 0.8613), Ground nut shell (C/H = 0.719), Saw dust (C/H = 0.7023), Subabul wood (C/H = 0.689)) to study the sensitivity based on C/H ratio.

Fig 7 represents the influence of C/H ratio on final gas quality. It is observed that the maximum methane concentration is observed at C/H ratio 0.719. At this C/H ratio good levels of CO and  $H_2$  are also observed indicating that probably, this biomass is best suited for gasification.

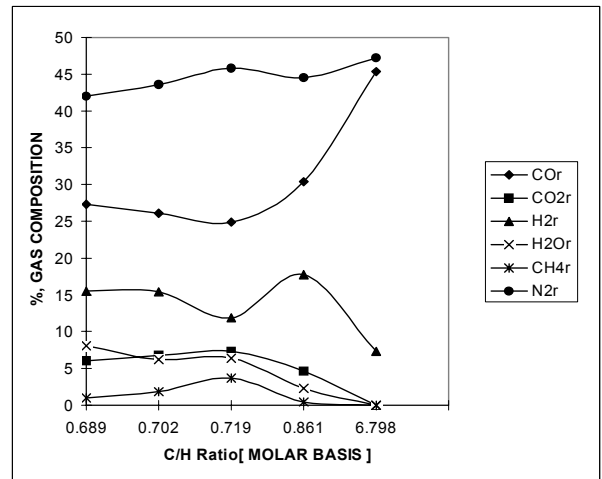


Fig 7. Influence of C/H Ratio on Gas Composition (Reduction Zone). (ER = 0.3, MC = 0%, heat loss = 10%)

The highest CO level observed at C/H ratio of 6.798 once again signifies that the matured form of biomass material probably promotes the CO oxidation reaction rather than methanation reaction due to poor char reactivity.

Fig 8 represents the variation of temperature with C/H ratio of pyrolysis, oxidation & reduction zones. It is interesting to observe that the biomass material having C/H ratio of 0.861 undergoes the decomposition at

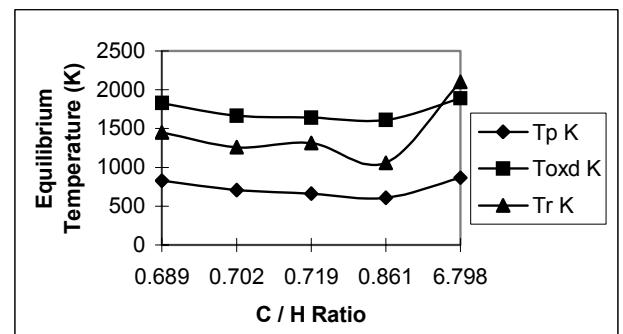


Fig 8. Influence of C/H Ratio on Equilibrium Temperature (ER = 0.3, MC = 0%, heat loss = 10%)

minimum temperature of pyrolysis, oxidation and reduction zones. This means that the biomass material in the form of barks is easily decomposable and can be gasified readily. However, as seen earlier the best gas composition is achieved with the biomass material with C/H ratio in the vicinity of 0.719.

## 6. CONCLUSIONS

Based on the results the following conclusions may be derived.

(1) The comparison of KF model predications with published experimental results and the illustrated closeness between the two proves the quantitative and qualitative validity of the KF model for most parameters of interest. This means that the present model may be accepted for performance prediction of downdraft gasifier.

(2) Inclusion of independent oxidation zone in the model facilitates the predictions of maximum temperature in the gasifier and thereby provides important information needed for design and selections of materials of constructions.

(3) The model predictions to parametric sensitivity study such as the influence of equivalence ratio; moisture content and C/H ratio provide extremely useful information regarding the effect of these parameters on the gas quality and temperature levels in different zones of downdraft gasifier. This results suggested the equivalence ratio in the vicinity of 0.3 and moisture content in the range of 10 to 20% should be the operating parameters to obtain good quality of gas & safe, non slagging operations of gasifier with the woody biomass as its feed.

(4) The most important contribution through this model is to identify the different category of biomass for their suitability as a feedstock for pyrolysis and gasification process for the downdraft gasifier.

The model clearly identified the biomass material having C/H ratio in the vicinity of 0.719(Shell) as the best-feed stock for pyrolysis. It also identifies that the biomass material having C/H ratio in the range of 0.7 to 0.861 is the better-feed stock for the gasification rather than the material having C/H ratio above unity.

## 7. REFERENCES

1. Denn, M. M. and Wen, C.Y., 1979, "Parameter Sensitivity and Kinetic -Free Modeling of Moving Bed Coal Gasifiers", Ind. Engg. Chem. Fundam., 18,3, pp. 286-288.
2. Kosky P.G. and Floess J.K., 1980, "Global Model of Counter Current Coal Gasifier" Ind. Engg. Chem. Process Des. Dev. 19, pp. 586-592.
3. Ali T.R., 1982, "Studies of Biomass Gasification" Ph.D. Thesis, Univ. of California, Berkeley,
4. Evans D. and Emmons H., 1977, "Combustion of wood Charcoal" Fire Research, 1, pp. 51-56.
5. Channiwala S. A., 1992, "On Biomass Gasification Process and Technological Development Some Analytical and Experimental Investigations" Ph.D. Thesis, IIT Bombay.
6. Gumz W., 1950, "Gas Producers and Blast Furnaces" Theory and method of Calculation, John wiley, New York, pp. 109-167
7. Stull D. R. and Prophet H., 1971, "JANAF Thermo chemical Tables" NSRDS - NBS - 37, Washington, 2<sup>nd</sup> edition.
8. Jenkins B.M., 1980, "Downdraft Gasification Characteristics of Major California Residue

Derived Fuels", Ph.D. Thesis, Univ. of California, Davis.

9. Liinanki L., Svenningsson, P. and Thessen G., 1985, "Gasification of Agricultural Residues in a Down Draft Gasifier" in 3<sup>rd</sup> E.C. Conference on Energy From Biomass, Eds. Coombs, P.W. and Hall, D.O., Elsevier, Essex, England, pp. 832-836.
10. Walawender W.P., Chern S.M. and Fan L.T., 1985, "Wood Chip Gasification in a Commercial Downdraft gasifier in Fundamentals of Thermo chemical Biomass Conversion" Eds. Overend R.P., Milne T.A. and Mudge L.K., Elsevier N.Y. pp. 911-921.
11. Graham R.G. and Huffman D.R,1981, "Gasification of wood in a Commercial Scale Downdraft Gasifier in Symposium On Energy From Biomass and Wastes" V. IGT. Pp. 633-650
12. Hodam R.H. and Williams R.O., 1978, "Small Scale gasification of Biomass to Produce a Low Btu Gas, in Symposium on Energy From Biomass and Wastes, IGT, Washington D.C., pp. 729-748.

## 8. NOMENCLATURE

Symbol	Meaning	Unit
ER	Equivalence Ratio	-
HHV	High Heating Value of Fuel on Dry Basis	kJ/kg
$h_1$	Heat Losses From the Reactor	kJ/Mole
$l, h, o$	Molecular Coefficient for Carbon, hydrogen and oxygen respectively.	Mole
MC	Moisture Content	-
T	Temperature	K
$T_e$	Equilibrium Temperature	K
$T_r$	Reaction Temperature	K
$\alpha, \gamma, \psi$	Molecular Hydrogen char Coefficient in Pyrolysis, oxidation and reduction Zone respectively.	Mole
$\beta, \delta, \xi$	Molecular Oxygen char Coefficient in Pyrolysis, oxidation and reduction Zone respectively.	Mole
$\phi$	Equivalence ratio	
e	Equilibrium Condition.	
OXD	Oxidation Zone	
P	Pyrolysis Zone	
R	Reduction Zone.	
r	Reaction.	
l	Liquid form.	
gyield	Gas Yield	NM <sup>3</sup> /kg
LHVg	Low Heating Value of Gas	MJ / NM <sup>3</sup>
Cgeff	Cold Gas Efficiency	%