DOWNDRAFT GASIFICATION MODELING: THERMODYNAMIC EQUILIBRIUM APPROACH

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Abstract

Biomass is a renewable potential energy source which can reduces dependency on fossil fuels. Gasification of biomass is a chemical process that converts carbonaceous material such as biomass and coal into gaseous fuel or chemical feedstock. This gaseous fuel is known as producer gas or syngas which contains CO_2, H_2, CO, H_2O, CH_4 and N_2 compounds. The mathematical model is formulated on the similarities between real and abstract system in which mathematical equations are applied to abstract system to study the real system. The object of the present work is to develop mathematical model for the downdraft gasifier based on non stoichiometric equilibrium approach to measure producer gas composition and to study the influence of moisture content, equivalence ratio on the producer gas composition (H_2, CO, CO_2, CH_4, N_2), final temperature, lower heating value, cold gas efficiency. The results show that H_2, CO_2 increases, while CO, CH_4, lower heating value and cold gas efficiency decreases with increasing moisture content. Increasing equivalence ratio, N_2 and final temperature increases, while lower heating value and cold gas efficiency decreases.

Index Terms — Biomass Gasification, Downdraft Gasifier, Gibbs free energy Minimization, Thermodynamic Equilibrium Model.

INTRODUCTION

BIOMASS

The World is facing crucial time for energy due to consumption of fossil fuels (natural gas, coal, and oil), rise in fuel price, and unacceptable environmental effect in recent years. Biomass is a renewable potential energy source which can reduces dependency on fossil fuels. Biomass is available in various forms throughout year in India. It accumulates solar energy by photosynthesis method from sunlight. It is available in the form of farm products (corn, wheat, sugarcane, jatropha, etc.), ligno cellulosic materials (straw, husk, wood, slash etc.) and municipal solid waste [26] .

Biological or thermo chemical method is used in the production of producer gas from biomass. Anaerobic digestion is a biological method in which chemical reaction is occurred in the absence of air and organic waste, convert biomass into the form of biogas and bio fertilizer. Drying, pyrolysis, oxidation and reduction are the most important process for thermo chemical method.

During drying process moisture content is reduced with the help of waste heat or solar energy and temperature ranges between 100°C-150°C. Pyrolysis is the breaking down process by heat in the absence of air and temperature is up to 150°C-700°C. During pyrolysis process charcoal, gases, tar vapors are formed. In the oxidation process limited amount of oxygen is supplied with large amount heat released and temperature ranges from 700°C to 1500°C. In reduction process, temperature ranges from 800°C to 1100°C and reduction reaction occurred which are mostly endothermic process. It depends upon gasification temperature, pressure, gasification agent, gasifier types, heating [18] .

GASIFIER

Gasifier is a reactor that transform wood, or other biomass substances, into a combustible gas which can be burned for heating, cooking, running an internal combustion engine [15] .

TYPES OF GASIFIER

Based on movement of feedstock or gasification agent, fixed bed and fluidized bed are the main two type of gasifier.

Fixed bed gasifier

In this type of gasifier, bed remains fixed. Design of reactor is simple in the comparison with fluidize bed. This kind of gasifier is usually applicable for power generation up to 10 mw. Main disadvantage of fixed bed gasifier is its unsteady temperature. Updrafts, downdraft, cross draft are the main types of gasifiers.

Updraft gasifier

Feedstock is supplied from top side and air is supplied from bottom side (also known as counter current gasifier). Producer gas is available from top side. It has higher thermal efficiency. Lower heating value is 5-6 Mj/Nm3. It can handle 5-100 mm fuel size particle. Reaction zone temperature is 800°C-1100°C. Moisture content is flexible up to 50%. Exit gas temperature is up to 250°C. Tar concentration is high (50g/Nm3) [24].

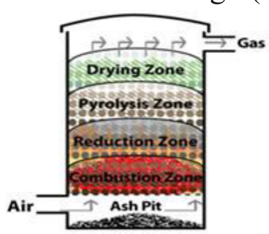


Fig-1: Updraft Gasifier

Downdraft gasifier

Feedstock and air moves in the lower part of gasifier. Producer gas is available from bottom side. It has lower thermal efficiency. Lower heating value is 4.5-5 Mj/Nm3. It can handle 20-100 mm fuel size particle. Moisture content is flexible up to 12%. Exit gas temperature is up to 600-800°C. Tar concentration is low (0.01-6 g/Nm3).

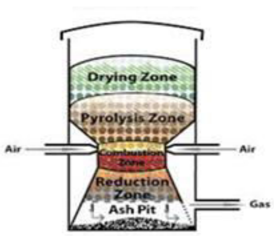


Fig-2: Downdraft gasifier

Crossdraft gasifier

Feedstock is supplied from top side and air is supplied from cross side. Producer gas is available from cross side of gasifier. Lower heating value is 4-4.5 Mj/Nm3. It can handle 5-20 mm fuel size particle. Moisture content is flexible up to 10-12%. Exit gas temperature is up to 1250°C. Tar concentration is high.

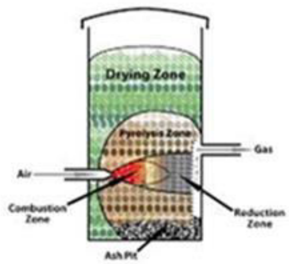


Fig-3: Crossdraft gasifier

Fluidized bed gasifier

Feedstock and bed both perform as a fluid. This performance is achieved with the help of fluidized medium (O2, air, stem). Silica is used as a bed material. Fluidized bed gasifier is useful for coal gasification. One main advantage of fluidized bed gasifier is its consistent temperature. According to velocity of fluidized medium, fluidized bed gasifier is classified in to bubbling fluidized bed gasifier and circulating fluidized bed gasifier [15] .

- **Bubbling fluidized bed gasifier:** Bubbling bed works below 1m/s gas velocities. Height of bed is 1-2 m. It can handle below 6 mm coal size particle. Reaction zone temperature is 800°C-1000°C. Exit gas temperature is up to 850°C. Tar concentration is 6-12 g/Nm3. Cold gas efficiency is up to 90%.

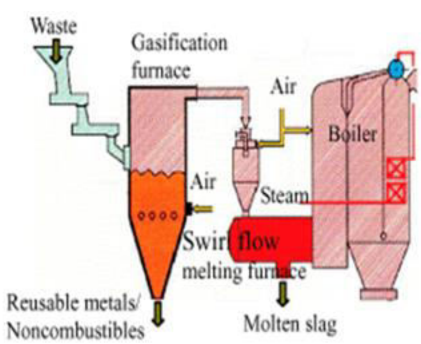


Fig-4: Bubbling fluidized bed gasifier

- **Circulating fluidized bed gasifier:** Feedstock is burned in the fast way. Circulating bed works at 3-10 m/s gas velocity. Height of bed is 10-30 m. It can handle below 6 mm coal size particle. Tar concentration is up to 8 g/Nm3. Cold gas efficiency is up to 96%.

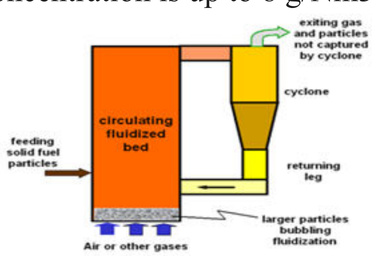


Fig-5: Circulating fluidized bed gasifier

DOWNDRAFT MODELING PARADIGMS

The gasifier is developed either on experimental observation or mathematical model. Experimental observation is reputable and secure but costly and time consuming. Mathematical modeling is most suitable approach which depicts real life position and time saving. Mathematical equations are applied in to the gasifier for intimating producer gas composition and also check effect of moisture content, reaction temperature and equivalence ratio.

THERMODYNAMIC EQUILIBRIUM MODEL

Chemical equilibrium is resolve by two ways, either equilibrium constant or Gibbs free energy minimization method. Stoichiometric or non stoichiometric method is used for the development of thermodynamic equilibrium model. The model has remarkable work at higher temperature and intimate maximum output of desired product. It cannot depend upon gasifier geometry and intimate the effect of hydrodynamic variables [45] .

Stoichiometric Equilibrium Model

In this model, chemical reaction and species are formed as one unit. Species which contain carbon, hydrogen, oxygen are taken into consideration for starting purpose. The model can be configurated either for global gasification reaction or can be classified into sub-model for drying, pyrolysis, oxidation and reduction.

Ref	Authors	Feedstock used	Computational method	Results
2	Bhavanam et al.	Solid waste gasification	Matlab with newton Jacobi iteration	To predict syngas (CO+ H_2) ER 0.3 CO & H_2 is highest in syngas
7	Melgar et al.	Rubberwood	Newton raphson algorithm	Maximum H_2 achieved at gasification fuel/air ratio =3 and moisture content =27.5
28	Hua et al.	With or without Char Considering Reduction zone is considered and simulated	Trial and error method	considering char model is more general and widely applicable than without char model
33	Koroneous et al.	Cotton stalks	Trial and error method	By increasing moisture content,CV of producer gas decrease

Table-1: Review of thermodynamic equilibrium model for downdraft gasifier

Non-stoichiometric Equilibrium Model

In this model, Gibbs free energy minimization method is used. In this method specific reaction mechanism is not required, only feedstock elemental composition is required which is available from ultimate analysis of feedstock.

KINETIC MODEL

It can provide standard time for the reaction to intimate products from a gasifier where as equilibrium model provide limited time for the reaction. Superficial velocities, length of reactor, reaction rate, residence time and diffusion rate are used while framing kinetic model. Kinetic model can intimate outline of gas composition, temperature, and entire performance of gasifier. At low reaction temperatures (<800 °C), kinetic model is set up more suitability than equilibrium model. It unites the reactor hydrodynamics and kinetics reactions in the gasifier. Knowledge of reactor hydrodynamics is required due to physical mixing method in the kinetic modeling. Reaction kinetics is used with bed hydrodynamics. Char gasification is defined by shrinking core, volumetric reaction rate and shrinking particle models.

Ref	Authors	Feedstock used	Computational method	Results
49	Ratnadhariya et al.	Wood	computer programming in Turbo-C	C/H biomass ratio 0.719 is suitable for pyrolysis & C/H biomass ratio 0.7 to 0.861 is suitable for gasification
56	Sharma et al.	Char	Tri-diagonal matrix algorith	Intimate product gas composition and unreacted char
59	Sivakumar et al.	Wood	short time increment method with reduction zone	Effective reaction take place over a length of 280 mm of reduction zone.

Table-2: Review of kinetic model for downdraft gasifier

COMPUTATIONAL FLUID DYNAMICS (CFD) MODEL

CFD uses algorithms and numerical analysis to solve complex chemical reactions, heat and mass transfer, design optimization and flow fields visualization, which finally enhance gassifier efficiency and performance. Calculations are performed with the help of computers to simulate the reaction of gases and liquids with surfaces by dividing it into small cells. The navier stokes equation is the basis for CFD model, define any single-phase fluid flow (either gas or liquid). CFD model play a significant role for the modeling of fluidized-bed gasifier and predict accurate gas production and temperature with the help of hydrodynamics [19] .

Ref	Authors	Feedstock used	Computational method	Parameters studied
11	Rogel et al.	pine wood pellets for stratified gasifier	Eulerian Approach	Producer gas composition and LHV,temperature profiles, carbon conversion efficiency , efficiency of reactor
19	Fletcher et al.	saw dust, cotton trash for entrained flow gasifier	Discrete particle model employed and lagrangian approach applied	Exit gas composition is very limited
30	Janajreh et al.	Woody biomass	Discrete particle model employed and lagrangian approach applied	Cold gas efficiency, reactor temperature, carbon conversion efficiency

Table-3: Review of CFD model

ARTIFICIAL NEURAL NETWORKS (ANNS) MODEL

Artificial neural networks are basically neural network having artificial intelligence, exchange information between each other. It is identifying by the interconnection pattern (across different neural layers), learning process and activation function. It can give numerical results, not analytical solution. The input layer has inputs and weights values. Weights are employed to transform data from one layer to another layer. The information is operated at the nodes and then sum up; the result is preceded through an activation function. The result is the node's "activation value," which is multiplied by the specific weight and transfered to the next node.

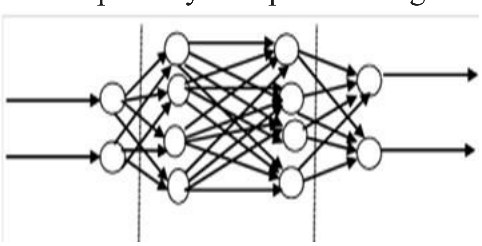


Fig-6: Schematic of "Artificial neural networks" "[15] .

Ref	Authors	Feedstock used	Computational method	Parameters studied
38	Arnavat et al.	Woody biomass for CFB and BFB	Matlab with the Neural Network Toolbox	CO, CO_2, CH_4, H_2 measured
57	Sreejith et al.	Wood sawdust Fluidized bed gasifier	Matlab with the Neural Network Toolbox	Product gas composition ,heating value and thermodynamic efficiencies

Table-4: Review of Artificial neural networks(ANN) model

ASPEN PLUS MODEL

ASPEN Plus is the optimization software for chemical process developed by MIT. Biomass feedstock decomposition, reactions of volatiles, gasification of char, and gas solid separation stages are considered in the simulation of ASPEN PLUS [29].

1. **Biomass feedstock decomposition:** RYield is used to decompose biomass feedstock. Here feedstock is divided into non volatile and volatile components known as pyrolysis. Carbon, hydrogen, oxygen, nitrogen, sulfur are volatile components and ash, solid carbon are non-volatile components. When stoichiometric and kinetics reaction are not identified but products data are present, this model is applicable.
2. **Reactions of volatiles:** RGIBBS Model is applicable for volatile reactions by considering gibbs free energy minimization. When pressure and temperature are identified but stoichiometric reaction is not identified, this model is applicable. A Separation column model is utilized before the RGIBBS models to discrete volatiles and solids.

3. **Gasification of char:** RCSTR Model used kinetic reaction to perform char gasification. It is a constant-mix up tank reactor applicable to char gasification due to its handling characteristics of equilibrium and kinetic reactions. FORTRAN code is used to divide RCSTR into equal volume of CSTR. One RCSTR is used for the simulation of the bed and freeboard regions.

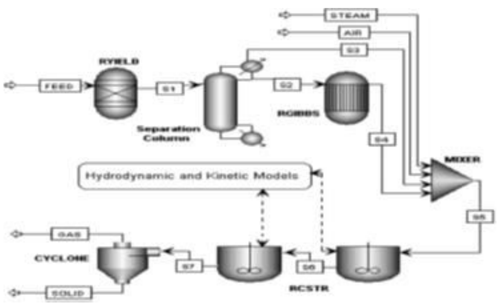


Fig-7: ASPEN Plus model with fluidized bed gasification process.

LITERATURE SURVEY

Mendiburu et al. presented non-stoichiometric thermodynamic equilibrium model to analyze influence of different parameter on gas composition and also studied brazilian Pinus elliottii gasification with model M2 and M4. Results obtained from Lagrange multipliers technique are acceptable. Carbon conversion efficiency is increased with the rise in equivalence ratio (ER) and decrease lower heating value of the synthesis gas. Equivalence ratios (ER) maintain just above 0.30 and moisture contents lower than 15%.

Khadse et al. Presented thermodynamic equilibrium model for the gasification of Saw dust, Bagasse, Subabul, Rice husk and measuring gross calorific values. Air and Steam used as a gasifying agent and gas is produced in the form of CO, CO2, H2 and CH4. Gross calorific value of bagasse is maximum and Gross calorific value of Subabul is minimum at lower temperature (<1000 K). At air 0.1 moles and steam/air=8, feedstock produce higher gross calorific values.

Antonopoulos et al. presented non stoichiometric equilibrium model for agricultural residue (olive wood, miscanthus, and cardoon) for measuring composition of producer gas. Influence of reaction temperature and moisture content was checked with the producer gas composition. As temperature increased from 800°C-1200°C, lower heating value (MJ/Nm3) of feedstock increased. As moisture content increased from 0 - 45%, lower heating value (MJ/Nm3) of feedstock decreased.

Kaya et al. used gibbs energy minimization evaluation in chemical equilibrium model for hydrogen production from coal gasification and to determine the syngas composition of various coal gasifier systems. Results predict that if minor modification is made in the value of carbon conversion then satisfactory predictions achieved. Turkish lignite (Tuncbilek) is used for hydrogen production from the simulation of this model.

Ghassemi et al. presented modify equilibrium model and measure influence of different parameter on biomass (pine sawdust, rice husk) gasification. Temperature has remarkable effect on cold gas efficiency at low temperature and has minor effect on syngas heating value. Improving air with O_2 increases higher heating value (HHV) of gas. Influence of Moisture content on cold gas efficiency and HHV has negative value.

Echegaray et al. presented thermodynamic equilibrium model for the gasification of agro-industrial wastes (grape stalk, grape marc, peach pit) in fluidized bed gasifier. Ideal value of equivalence ratio is 0.1 and when equivalence ratio is increased H_2 and CO contents decreases. The ideal value of moisture content is 30%. The ideal value of gasification temperature for the biomass is between 650°C -750°C. Hydrogen production is more in air-steam gasification than air gasification.

Ramanan et al. presented equilibrium model for the gasification of cashew nut shell char and measuring effect of reaction temperature (RT), equivalence ratio (ER) and moisture content (MC) on producer gas composition. With the enlargement of equivalence ratio, (H_2O + N_2) and CO_2 are enhancing and H_2, CH_4 and CO are diminishing. With the enlargement of reaction temperature, H_2 and CO are enhancing and CH_4, (N_2+ H_2O), CO_2 are diminishing.

Dutta et al. used five biomass (Bamboo, gulmohar, neem, dimaru and shisham) in thermodynamic equilibrium model with downdraft throated gasifier. Gasification of bamboo gives highest producer gas components (H_2 = 21.43 %, CO = 24.28 %, CH_4 = 0.78 % at 20 % moisture) and gives highest calorific value (18.4 MJ/kg).

Shabbar et al. studied about coal gasification process. Bituminous coal is converted into syngas (CO and H_2) through three gasification process (air-steam, air and solar steam). Gasification of solar steam has higher potential than air-steam, air process.

Jarungtammachote & Dutta presented non stoichiometric equilibrium model for the gasification process on regular (central jet) and revised (circular split and spout-fluid) spouted bed gasifier. Composition of producer gas is measured with the help of Gibbs free energy minimization method. The revised model give higher heating values usually higher than those from experiments due to the CO content in the producer gas. Jarungtammachote and Dutta used thermodynamic equilibrium model with equilibrium constant for intimation of composition of producer gas in a waste downdraft gasifier. When moisture content increases, second law efficiency, calorific value, reaction temperature are decreases.

Li et al. presented coal gasifier of circulating fluidized bed with gibbs energy minimization method. A (Carbon-Hydrogen-Oxygen) ternary diagram which is a function of pressure and temperature is used for plotting formation of carbon boundary. The RAND algorithm has been employed in this model.

Zainal et al. used thermodynamic equilibrium model for the intimation of composition of producer gas for different biomass in downdraft gasifier and determined calorific value. Newton raphson method is used to solve equation. With the rise in moisture content, calorific value of product gas decrease and with the rise in temperature, calorific value of product gas decrease.

SUMMARY OF LITERATURE SURVEY

Thermodynamic equilibrium method is suitable for measuring composition of producer gas. Methane reaction and water gas shift reaction used to improve model. Temperature play important role on cold gas efficiency. Enriching Air with oxygen increase higher heating value. Optimal gasification temperature in 650°C - 750°C. Optimal equivalence ratio is between 0.15-0.30. When moisture content increase, H2, CH4, CO2 and (N2+ H2O) increases while CO decrease. When moisture content increase, second law efficiency, calorific value decrease.

NON-STOICHIOMETRIC EQUILIBRIUM MODEL DESIGN METHODOLOGY

MODEL ASSUMPTIONS

1. The reactor is considered as a zero dimensional.
2. There is ideal mingle of materials.
3. Consistent temperature in the reactor.
4. Residence time is prolonged and reaction rate is fast.
5. Natural air is taken as gasifying agent.
6. Gasifier process is autothermal.

The global gasification reaction can be explained as follows:

$$CHxOyNz+xa\cdot(O2+3.7\cdot N2)+Mp\cdot H2O=nCO\cdot CO+nN2\cdot N2+nCO2\cdot CO2+nH2\cdot H2+nCH4\cdot CH4$$

Where x,y and z are numbers of mole of hydrogen, oxygen and nitrogen per one mole of carbon in biomass. xa is the mole of air per mole of biomass and measured by equivalence ratio multiplied by stoichiometric air. Mp is the water inserted into reactor in the form of moisture of biomass.

BIOMASS PROPERTIES & FORMULATION

Biomass is a mixture of carbon, hydrogen, oxygen, nitrogen on elemental basis. Ultimate analysis is used to achieve elemental parameters. Biomass having chemical formula is *CcHhOo*. While considering carbon as a single atom formula can be expressed as follow:

$$c=1$$

$$h=C\%\cdot MHH\%\cdot Mc$$

$$o=C\%\cdot MOO\%\cdot Mc$$

Where *C*%,*H*% and *O*% are the proportional percentage of carbon, hydrogen and oxygen, available from the ultimate analysis. Moisture content weight fraction is expressed as:

$$MC=(mbiomassmwater)*100\%$$

Molecular biomass formula mass is calculated via:

$$Mbiomass=(Mc*c)+(2MH)*h+(2MO)*o$$

Where *MC*,*MH* and *MO* are the molecular mass of carbon, hydrogen and oxygen.

EQUIVALENCE RATIO (ER)

Equivalence ratio is defined as the ratio of supplied air-to-fuel ratio to stoichiometric air-to-fuel ratio. Stoichiometric air is the amount of air required for complete combustion of one unit fuel.

$$ER= (A/F)\ \text{supplied} /(A/F)\text{stoichiometric}$$

THERMODYNAMIC RELATIONSHIPS

Higher heating value can be determined for the solid fuel as follows:

$$HHV=0.3491C+1.1783H+0.1005S-0.1034O-0.0151N-0.0211Ash$$

Lower heating value is evaluated via:

$$LHV=HHV-9mH(hfg)$$

Where *mH* is the hydrogen mass fraction in the solid fuel, and *hfg* is the enthalpy of vaporization of water. Cold gas efficiency is defined as:

CGE=Heating value of feedstock Heating value in producer gas

CHEMICAL REACTIONS

Water-gas reaction: $C+H2O \rightarrow CO+H2$

Boudouard reaction: $C+CO2 \rightarrow 2CO$

Methane formation: $C+2H2 \rightarrow CH4$

Water-gas Shift reaction: $CO+H2O \rightarrow CO2+H2$

MINIMIZATION OF GIBBS FREE ENERGY

Equilibrium constants and gibbs free energy minimization approaches are used for the development of equilibrium models. In equilibrium constants approach specific chemical reactions is necessary to define.This is the disadvantage of this model.So this method is not suitable for complex problems. This point is makes the second method, minimization of the Gibbs free energy. In this method no chemical reaction need to be known to find the solution.[45]

The total Gibbs free energy of a system is defined as:

$$G_{total} = \sum_{i=1}^{N} n_i \Delta G^{\circ}{}_{f,i} + \sum_{i=1}^{N} n_i RTln\left[\frac{n_i}{\sum n_i}\right] = 0$$

[species (*i*= 1…N), $\Delta G^{\circ}{}_{f,i}$ the standard Gibbs energy of i species, R is gas constant]

Elemental balance:

$$\sum_{i=1}^{N} a_{ik} n_i - A_k = 0$$

where a_{ik} is the number of atoms of the k element and A_k is the total number of atoms of k_{th} element in reaction mixture.

The objective of this approach is to determine the values of n_i such that the G_{total} will be minimum.

Lagrange multiplier method: Lagrange multiplier method is the most convenient and proximate way to solve these equations[16]

$$L = G_{total} - \sum_{k=1}^{w} \lambda_k \left[\sum_{i=1}^{N} a_{ik} n_i - A_k \right]$$

where λ is Lagrangian multipliers

Thermodynamic property: The standard Gibbs free energy of each chemical species can be obtained by subtracting the standard entropy multiplied by a specific temperature of the system from the standard enthalpy.

$$\Delta\overline{G^{o}}_{f,i} = \Delta\overline{H^{o}}_{f,i} - T\Delta\overline{S^{o}}_{f,i}$$

Where $\Delta G^{o}{}_{f,i}$ is the standard gibbs free energy of species i

$\Delta H^{o}{}_{f,i}$ is the standard enthalpy of species i

$\Delta S^{o}{}_{f,i}$ is the standard entropy of species i

ENERGY BALANCE:

Endothermic and exothermic reaction occurred in the gasifier. During exothermic reaction heat is released, some amount of heat is absorbed by endothermic reaction and rest of part is used to raise temperature of the gasifier known as sensible heat. Reaction temperature is the most important operational parameter which affect themodynamic calculation and chemical reaction. It is measured through energy balance equation or first law of thermodynamics which is as follow:

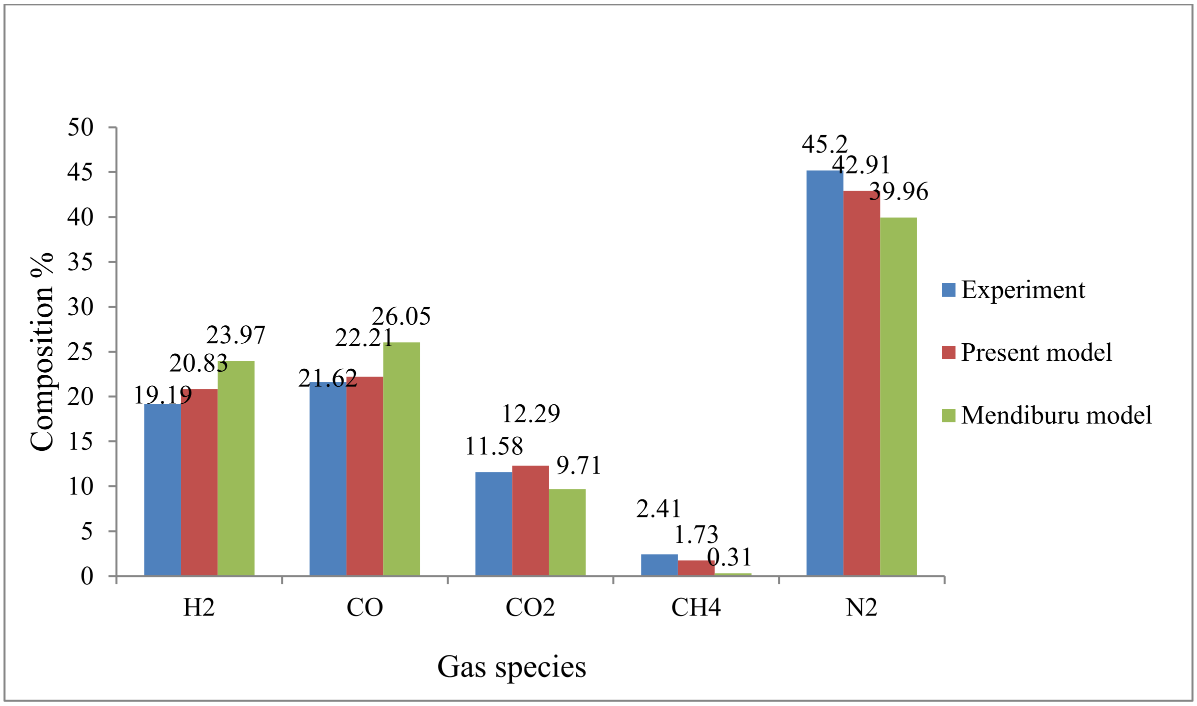
MATLAB PROGRAMMING IMPLEMENTATION

$$Q_{loss} + \sum_{reactant} n_r \overline{H^{o}}_r(T_r) = \sum_{product} n_p \overline{H^{o}}_p(T_p) + \Delta H$$

Initial temperature is assumed for the measurement of reaction temperature and employ to compute composition of producer gas. This producer gas species and assume temperature are substituted to calculate energy balance. If ΔH in equation [22] is negative, reaction temperature will be reduced automatically until ΔH tends to zero. If ΔH is positive, matlab programme will increase the value of temperature automatically. Composition of producer gas and energy balance are computed again after the adjustment of reaction temperature. This processes will be continued until ΔH tends to zero.

RESULT ANALYSIS AND VALIDATION:

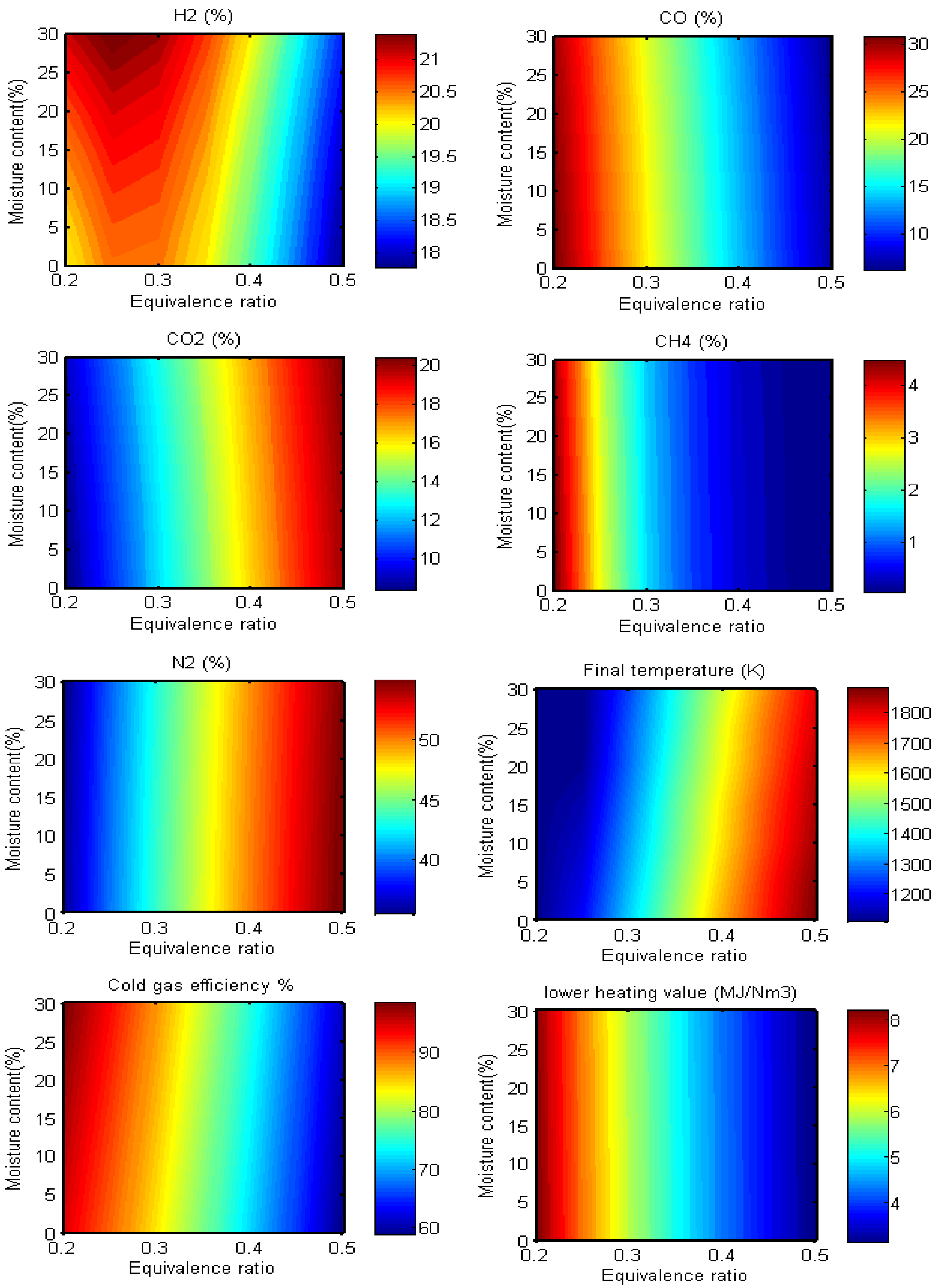
Hardwood:



Comparison with Wei et al. [66] experimental results and Mendiburu et al.[8] model.

Figure show producer gas composition of a hardwood with 12% moisture content and 0.29 equivalence ratio at 1300 ^{o}K gasification temperature. The characteristics of the producer gas depends on the percentage of CO, H_2, CH_4. Gas species composition obtained from this model is slightly deviating from experiemental result, this is due to heat transformation across gasifier wall and tar, particles consideration during experiement. Mendiburu considered hydrogen sulphide, silica in the global gasification reaction and carbon conversion to measure unconverted carbon in products. Figure 4-1 gives clear picture about comparision between experiemental result and numerical data.

"Root mean square error" is the prefered criteria used to determine the amount by which numerical results vary with the experimental results. It is the standard error that outlines the overall results. Root mean square error for Wei et al. experimental and Mendiburu's model are 1.35 and 2.8.



Effect of ER and MC on producer gas composition, FT, CGE, LHV

In general, if ER held constant and increase MC, H_2 and CO_2 content will increase whereas CO and CH_4 content decrease with lower gasification temperature [8]. Too low ER tends to decrease reaction temperature, which causes negative effect on biomass gasification. If ER is too high then consumption of combustible gases higher which causes decrease in the LHV of the end gas [18]. At higher equivalence ratio and higher moisture content, the water shift reaction tends to the formation of hydrogen and carbon dioxide, increasing the H_2 and CO_2 concentration under these conditions.

Figure show For MC = 30% and ER = 0.26, H_2 obtained its highest values 21.35%. Increasing of ER increasing H_2 up to certain value then decrease due to hydrogen oxidation, because of the presence of oxygen [27]. Percentage of CO reduces about 30-10% with the rise in moisture content from 0-30%. For MC = 0 and ER = 0.20, CO obtained its highest values up to 30%. Percentage of CO_2 increase about 10-20% with the rise in moisture content from 0-30%. CH_4 content has its maximum value upto 4.6% at MC = 0 and ER = 0.20. Increasing ER from 0.2-0.5, percentage of N_2 increased up to 55% due to increasing of air [27]. Maximum gasification temperature obtained up to 1850^oK at MC = 0 and ER = 0.50. Increasing ER from 0.2 to 0.5, reducing LHV of producer gas from 8 to 3MJ/Nm^3 and cold gas efficiency from 92 to 60% due to gasification process because it doesn't get enough time for carbon conversion. Increasing MC from 0 to 30%, decreasing lower heating value due to watergas reaction which produce H_2 and CO_2 from CO. Higher cold gas efficiency achieved with the lower equivalence ratio [40]

CONCLUSIONS

The object of the present work is to develop mathematical model for the downdraft gasifier based on non stoichiometric equilibrium approach. Matlab has been used as computational tool for present model. The model has been validated against the experimental data published in the open literatures. Data such as temperature, moisture content, equivalence ratio, producer gas composition and heating value are obtained from the experimental investigation. Then, the results of present model have been compared with the experimental data. Comparison of producer gas species between modeled value and experimental value reveals remarkable agreements. Some of the conclusions, which are summarized as following:

- Optimal equivalence ratio for the gasification process is between 0.2 – 0.35.
- Optimal moisture content is between 10 - 30%.
- Optimal temperature is between 1000-1350 ^oK.
- Increase moisture content from 0 to 30 %, H_2 increase up to 25% and CO_2 up to 18%.
- Increase moisture content from 0 to 30 %, decrease cold gas efficiency from 100 to 65%, and lower heating value from 8 to 3 MJ/Nm^3.
- Higher cold gas efficiency achieved with lower equivalence ratio.
- Increase equivalence ratio, N_2 increase up to 55%.
- Composition of H_2, and CH_4 decreases with increase in equivalence ratio.

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