INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 2, Issue 3, 2011 pp.551-578
Journal homepage: www.IJEE.IEEFoundation.org

Investigations in gasification of biomass mixtures using thermodynamic equilibrium and semi–equilibrium models

Buljit Buragohain, Pinakeswar Mahanta and Vijayanand S. Moholkar

Center for Energy, Indian Institute of Technology Guwahati, Guwahati – 781 039, Assam, India.

Abstract

Biomass gasifiers with power generation capacities exceeding 1 MW have large biomass consumption. Availability of a single biomass in such large quantities is rather difficult, and hence, mixtures of biomasses need to be used as feed–stock for these gasifiers. This study has assessed feasibility of biomass mixtures as fuel in biomass gasifiers for decentralized power generation using thermodynamic equilibrium and semi–equilibrium (with limited carbon conversion) model employing Gibbs energy minimization. Binary mixtures of common biomasses found in northeastern states of India such as rice husk, bamboo dust and saw dust have been taken for analysis. The potential for power generation from gasifier has been evaluated on the basis of net yield (in Nm^3) and LHV (in MJ/Nm^3) of the producer gas obtained from gasification of 100 g of biomass mixture. The results of simulations have revealed interesting trends in performance of gasifiers with operating parameters such as air ratio, temperature of gasification and composition of the biomass mixture. For all biomass mixtures, the optimum air ratio is ~ 0.3 with gasification temperature of 800^oC. Under total equilibrium conditions, and for engine–generator efficiency of 30%, the least possible fuel consumption is found to be 0.8 kg/kW–h. As revealed in the simulations with semi–equilibrium model, this parameter shows an inverse variation with the extent of carbon conversion. For low carbon conversions (~ 60% or so), the specific fuel consumption could be as high as 1.5 kg/kW–h. The results of this study have also been compared with previous literature (theoretical as well as experimental) and good agreement has been found. This study, thus, has demonstrated potential of replacement of a single biomass fuel in the gasifier with mixtures of different biomasses.

Copyright © 2011 International Energy and Environment Foundation – All rights reserved.

Keywords: Biomass gasification, Thermodynamic equilibrium, Producer gas, Decentralized power generation.

1. Introduction

In recent years, biomass gasification has emerged as the most viable option for decentralized power generation in India [1, 2]. The estimated potential for power generation through this option is about 50 GW [3]. The major arguments for adopting biomass gasification over other options such as wind and solar are: (1) abundant and even distribution of biomass in the country throughout the year at cheap rates, (2) low capital investments and (3) simple technology with ease of operation by unskilled or semi–skilled labor [2, 4]. In addition, biomass gasification has a closed carbon cycle with no net addition of greenhouse gases to environment. Ministry of New and Renewable Energy of Government of India has been promoting implementation of this technology through various programs and financial incentives for electrification of remote villages and hilly areas [5]. The most popular gasifiers are atmospheric and downdraft type with either dual fuel or 100% producer gas engine–generator sets. Most of these gasifiers mainly use wood chips as fuel, although several new designs have been developed that can use alternative fuels such as coconut shells and briquettes. Typical capacity of these gasifiers ranges from 5 to 250 kW [6, 7]. For capacities higher than 1 MW, fluidized bed gasifier is the most feasible design [8]. These gasifiers have the merits of fuel flexibility, uniformity of temperature over reactor volume, low tar content of producer gas and high overall carbon conversion. Typical specific consumption of biomass fuel in these gasifiers is 1 to 1.2 kg/kWh [1]. Thus, the annual biomass requirement of a typical 5 MW gasifier plant (with capacity utilization factor of 70%) is more than 35,000 tons. It is rather unlikely, in any region of the country, that a single biomass would be available through out the year in such large quantities to meet the fuel demands of the plant, and thus, mixtures of different biomasses that are available in different seasons would have to be used. This necessitates a thorough study of the performance of gasifier in terms of fuel flexibility, i.e. variation in the quality and quantity of the producer gas resulting from gasification of biomass mixtures of different compositions. Such a study would provide important guidelines for design and scale–up of fluidized bed gasifiers with biomass mixtures as fuel input.

This paper tries to address this issue with equilibrium thermodynamic models. We assess gasification characteristics of mixtures of three representative biomasses, which are available in abundance in the northeastern states of India [9], viz. rice husk, saw dust and bamboo dust. In addition, we also evaluate the gasification process with semi–equilibrium models, in which we take into consideration partial conversion of carbon in the biomass. In the next section, we have described the aim and approach of this study in greater detail.

2. Aim and approach

In the context of the present study, where we are concerned with biomass gasification for decentralized power generation, the principal outcome would be the LHV of the producer gas resulting from biomass gasification. The ultimate analyses of the individual biomasses considered in this study are given in Table 1(A). In addition to biomass fuel, we must consider other important parameters that influence the content and quality of the producer gas resulting from gasification. These are: (1) temperature of gasification and (2) air or equivalence ratio, which is the ratio of actual oxygen supplied for gasification to the oxygen required for complete combustion of biomass [10, 11]. From a previous study of gasification of individual biomasses (viz. rice husk, bamboo dust and saw dust) [12], we have established that the most suitable ranges of these parameters are: temperature = 700–1000°C and air ratio = 0.2–0.4. We, therefore, chose four representative temperatures, viz. 700, 800, 900 and 1000°C and three air ratios, viz. 0.2, 0.3 and 0.4 for the simulations. Although we vary the air ratio and temperature of gasification independently in simulations with permutation–combinations of the values mentioned, it should be noted that under practical situation, the air ratio and temperature of gasification are related or interdependent parameters. Most of the gasifiers operate adiabatically and higher air ratio would result in greater biomass conversion and would lead to higher gasification temperature.

Moreover, we consider binary biomass mixtures for analysis (i.e. biomass mixtures comprised of any two of the three biomasses mentioned above). We combine these two individual biomasses in three proportions in weight percent as 25%–75%, 50%–50% and 75%–25%. Thus, we have nine combinations of biomass mixtures. The elemental analysis of these mixtures of biomasses along with a representative molecular formula for the biomass mixture is given in Table 1(B).

Determination of the energy content of biomass mixture: Prior to simulations of the gasification of the biomass mixtures, it is essential to estimate the energy content of these mixtures. It is basically this energy that appears in two forms after gasification, viz. the “chemical” energy which is the LHV of the producer gas resulting from gasification process and the “physical” energy which is the net enthalpy change or heat release from the gasification process. For this purpose we have chosen two correlations as follows:

(1) A general correlation for all solid fuels such as coal, biomass etc. [13]:

$$\text{HHV(MJ/kg or kJ/g)} = 0.3491\,C + 1.1783\,H + 0.10055\,S - 0.1034\,O - 0.151\,N - 0.0211\,A \tag{1}$$

(2) A specific correlation for HHV of biomasses only [14]:

$$\text{HHV (kJ/kg)} = 3.55\,C^2 - 232\,C - 2230\,H + 51.2\,C\times H + 131\,N + 20{,}600 \tag{2}$$

where C, H, S, O, N and A represent carbon, hydrogen, sulfur, oxygen, nitrogen and ash content of the biomass expressed in mass percentages on dry basis. The values of these parameters for the three biomasses are given in Table 1(A). To estimate the energy content of the biomass mixture, we first determine the HHV per gram of the individual biomasses with above correlation and add up the values of HHV in kJ as per the mixture composition. Table 1(B) lists the energy content of the nine biomass mixtures considered in this study. It could be inferred from Table 1(B) that HHV predicted by specific correlation of Friedl et al. [14] are somewhat higher than those predicted by general correlation of Channiwala and Parikh [13]. Sheng and Azevedo [15] have also reported a similar correlation for HHV of biomass as that of Friedl et al. [14].

Table 1. Elemental compositions
(A) Individual biomasses (ultimate analysis)

Biomass	Composition in weight percent (Dry Basis)					Molecular Formula
	Carbon	Hydrogen	Nitrogen	Oxygen	Ash	
Saw dust	52.28	5.2	0.47	40.85	1.2	$CH_{1.193}N_{0.007}O_{0.585}$
Rice husk	37.03	5.25	0.09	40.94	16.69	$CH_{1.699}N_{0.003}O_{0.828}$
Bamboo dust	39.88	5.5	0.89	47.92	5.81	$CH_{1.657}N_{0.018}O_{0.904}$

(B) Biomass mixtures (Basis: 100 g of total biomass mixture)

Biomass Components	Mixture Composition	Elemental Composition (gatoms)				Molecular Formula**	Net Energy Content (kJ per 100 g)	
		C	H	N	O		Ref. [13]	Ref. [14]
Rice Husk **(RH)** Saw Dust **(SD)**	RH = 25%, SD = 75%	4.039	5.213	0.027	2.555	$CH_{1.291}N_{0.007}O_{0.633}$	1867	1920
	RH = 50%, SD = 50%	3.721	5.225	0.02	2.556	$CH_{1.404}N_{0.005}O_{0.687}$	1729	1785
	RH = 75%, SD = 25%	3.404	5.238	0.013	2.557	$CH_{1.539}N_{0.004}O_{0.751}$	1590	1649
Bamboo Dust **(BD)** Rice Husk **(RH)**	BD = 25%, RH = 75%	3.145	5.313	0.021	2.668	$CH_{1.689}N_{0.007}O_{0.848}$	1468	1537
	BD = 50%, RH = 50%	3.205	5.375	0.035	2.777	$CH_{1.677}N_{0.011}O_{0.866}$	1485	1560
	BD = 75%, RH = 25%	3.264	5.438	0.049	2.886	$CH_{1.666}N_{0.015}O_{0.884}$	1502	1584
Bamboo Dust **(BD)** Saw Dust **(SD)**	BD = 25%, SD = 75%	4.098	5.275	0.041	2.664	$CH_{1.287}N_{0.010}O_{0.650}$	1884	1944
	BD = 50%, SD = 50%	3.84	5.35	0.049	2.774	$CH_{1.393}N_{0.013}O_{0.722}$	1762	1832
	BD = 75%, SD = 25%	3.582	5.425	0.056	2.885	$CH_{1.515}N_{0.016}O_{0.805}$	1641	1720

** *The molecular formula represents the mixture of two biomasses as a single entity. All biomasses are assumed to contain 10% w/w moisture.*

These nine combinations of biomass mixtures coupled with three air ratios and four temperatures mentioned above constitute 108 conditions for which we do simulations with thermodynamic equilibrium model. The elemental compositions (or elemental vector input) for the 27 mixtures for gasification process (i.e. 9 combinations of biomass mixtures, along with gasification medium, i.e. air, for 3 different air ratios) are given in Table 2 (please note that this elemental input also includes moisture content of biomass, assumed to be 10% w/w).

2.1 Incomplete carbon conversion

In a fluidized bed biomass gasifier, the residence time of the biomass mixture is small as it is carried out of the riser section with the gasification air. Therefore, kinetics of various chemical reactions in the gasification process comes into the picture. The major result of short residence time of biomass is incomplete conversion of carbon in it. Several authors have established that biomass gets devolatilized and pyrolysed almost instantly as it enters the riser section near the bottom [16–20], where the temperatures are quite high (~ 900–1100 K). The major products of pyrolysis process are char, tar (or heavy hydrocarbons), CO, CO_2, H_2, H_2O, CH_4 and C_2H_6+C_2H_4 [16,19]. Char essentially comprises of carbon, which is then oxidized by the oxygen present in gasification medium [11]. However, the oxidation may not complete till the biomass leaves the riser section of fluidized bed gasifier. This incomplete conversion of carbon leads to reduction in the quality as well as quantity of producer gas. In this paper, we have also tried to assess this effect with approach of semi–equilibrium model. In this approach, we reduce the moles of carbon in the elemental vector input (given in Table 2). The number of input moles of other three elements, viz. H, N and O are kept unchanged, or in other words, conversion of these elements is assumed to be complete. This approach is known as semi (or quasi)–equilibrium model [21–23]. In this category, however, we have considered binary biomass mixtures with even composition only (i.e. 50%–50% w/w fraction of two biomasses in the mixture). Moreover, we have considered only one air ratio (= 0.3) and temperature of gasification (800°C or 1073 K). These parameters have been chosen in view of practical values of carbon conversions observed in fluidized bed gasification, as explained in the next paragraph.

Lv et al. [24] have given experimental values of carbon conversion in a fluidized bed using pine saw dust (particle size 0.3–0.45 mm, feed rate = 0.512 kg/h) as feed–stock. For an air ratio range of 0.19–0.27, and gasification temperature of 800°C, the carbon conversion efficiency of the gasifier varied between 70.6–90.6%. On the basis of these experimental observations, we have chosen 3 representative values for carbon conversion in our simulations, viz. 60%, 70% and 80% (or 0.6, 0.7 and 0.8). This range is slightly on lower side than that reported by Lv et al. [24], and thus, our simulations give a rather "conservative" estimate of the performance of the biomass gasification process.

In view of this, we have chosen three representative values for carbon conversion (CC), viz. 0.6, 0.7 and 0.8. The gatom of carbon in the elemental vector input in the semi–equilibrium model are CC × C, where C are gatom of carbon in the biomass mixtures as given in Table 2 (i.e. elemental vector input in the equilibrium model). The balance carbon, i.e. (1–CC) × C, is assumed to be remain unconverted, and appears as elemental carbon (C) species in the products of biomass gasification.

Table 2. Elemental vector input (in gatom) for simulations (Basis: 100 g of total biomass mixture + air for gasification)

Biomass: RH (25%) + SD (75%)				**Biomass: RH (50%) + SD (50%)**				**Biomass: RH (75%) + SD (25%)**			
Element / Elemental Ratio	AR			Element / Elemental Ratio	AR			Element / Elemental Ratio	AR		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
C	4.039	4.039	4.039	C	3.721	3.721	3.721	C	3.404	3.404	3.404
H	6.324	6.324	6.324	H	6.336	6.336	6.336	H	6.349	6.349	6.349
N	6.180	9.257	12.334	N	5.696	8.534	11.373	N	5.212	7.812	10.411
O	4.736	5.549	6.362	O	4.611	5.361	6.111	O	4.487	5.173	5.860
H/C	1.566	1.566	1.566	H/C	1.703	1.703	1.703	H/C	1.865	1.865	1.865
O/C	1.173	1.374	1.575	O/C	1.239	1.441	1.642	O/C	1.318	1.520	1.722
Biomass: BD (25%) + RH (75%)				**Biomass: BD (50%) + RH (50%)**				**Biomass: BD (75%) + RH (25%)**			
Element / Elemental Ratio	AR			Element / Elemental Ratio	AR			Element / Elemental Ratio	AR		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
C	3.145	3.145	3.145	C	3.205	3.205	3.205	C	3.264	3.264	3.264
H	6.424	6.424	6.424	H	6.486	6.486	6.486	H	6.549	6.549	6.549
N	4.773	7.150	9.526	N	4.819	7.211	9.602	N	4.864	7.271	9.679
O	4.479	5.107	5.735	O	4.596	5.228	5.860	O	4.714	5.350	5.986
H/C	2.043	2.043	2.043	H/C	2.024	2.024	2.024	H/C	2.006	2.006	2.006
O/C	1.424	1.624	1.824	O/C	1.434	1.631	1.828	O/C	1.444	1.639	1.834
Biomass: BD (25%) + SD (75%)				**Biomass: BD (50%) + SD (50%)**				**Biomass: BD (75%) + SD (25%)**			
Element / Elemental Ratio	AR			Element / Elemental Ratio	AR			Element / Elemental Ratio	AR		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
C	4.098	4.098	4.098	C	3.840	3.840	3.840	C	3.582	3.582	3.582
H	6.386	6.386	6.386	H	6.461	6.461	6.461	H	6.536	6.536	6.536
N	6.226	9.318	12.410	N	5.787	8.656	11.525	N	5.348	7.994	10.640
O	4.863	5.670	6.487	O	4.846	5.604	6.362	O	4.838	5.537	6.237
H/C	1.558	1.558	1.558	H/C	1.683	1.683	1.683	H/C	1.825	1.825	1.825
O/C	1.187	1.384	1.583	O/C	1.262	1.459	1.657	O/C	1.351	1.546	1.741

Note: All biomasses are assumed to contain 10% w/w moisture. The elements C, H, N and O are given in gatom while the elemental ratio is dimensionless.

3. The mathematical model

Mathematical models for the biomass gasification are of two types, viz. kinetic and equilibrium. Kinetic models take into account the rate expressions for various simultaneous and parallel reactions among various species generated from devolatilization and pyrolysis of biomass such as char, tar, H_2, CO, CO_2, CH_4 and H_2O. Various authors have determined the rate constants for these reactions for various ranges of temperatures (for detailed reaction scheme with related literature review we refer the reader to the work of Corella and Sanz [20] and the monograph by Souza–Santos [25]). We would like to specifically mention that significant deviations exist between the rate constants obtained by various authors. Moreover, not all possible chemical reactions might have been studied. The equilibrium models on the other hand, are more convenient as the input data required for them (Gibbs free energy, enthalpy of formation, heat capacity) is easily available. Moreover, these models predict the limiting (maximum) performance of the gasifier for given range of temperature, air or equivalence ratio and pressure, and thus, give rather conservative estimate of gasifier performance. This feature helps identifying the "parameters spaces" or "niche areas" in the practical operating range of the gasifier, where improvement can be made. The actual performance of gasifier may deviate from that predicted by the model due to several other factors that influence the gasification process, which are not accounted by the equilibrium models such as residence time of biomass, particle size of biomass and the transport parameters (i.e. heat and mass transfer coefficients and hydrodynamics of gasifier). But overall trend in various parameters (e.g. the yield, composition and LHV of producer gas), stay essentially unchanged. Therefore, the equilibrium models form highly useful and practical qualitative guidelines for the design, optimization and improvement of the gasification process [26–28].

There are two approaches in the thermodynamic equilibrium models: (1) solving the chemical equilibriums for all reactions in the system in conjunction with material balance; (2) minimization of the Gibbs free energy of the system with presumption of the product species (or the species that prevail in the system at equilibrium). Comparing among the two approaches, the second one is more useful in situations where all the possible reactions that can occur in the system (along with their equilibrium constants at various temperatures and pressures) are not known. The technique of Gibbs energy minimization also has the merit of handling feed streams with unknown molecular formulae and unknown chemical species. We have taken the second approach to predict the equilibrium composition of the species resulting from the gasification of different biomass mixtures (with varying composition) under given conditions of temperature and pressure. In the technique of Gibbs energy minimization, the input to the thermodynamic model is given in terms of elemental vector, which could be determined from the ultimate analysis of biomass, and given air or equivalence ratio. In past two decades, several authors have studied gasification of various solid fuels (biomass, coal, municipal waste etc.) using both approaches [8,21–23,29–39].

For the simulations, we have used a software FACTSAGE (Fact Web [40], Bale et al. [41]). This software employs the algorithm SOLGASMIX proposed by Eriksson [42] for calculation of thermodynamic equilibrium. We give below the main equations of this model. These equations can be solved using an iterative procedure (method of Lagrangian multipliers) for calculation of equilibrium composition of a chemical system, i.e. mole numbers and fractions of gas / condensed phase species at equilibrium that could result from reactant species (or set of elements with predetermined gatoms) at a specific temperature and pressure, for which the total free energy of the system is at its minimum (with constraint of mass balance equations). For the solution algorithm and other details, we refer the reader to the original paper by Eriksson [42].

3.1 Equations for Gibbs energy minimization

For a system comprising of mixture of i species, the total Gibbs free energy (G) is:

$$G = \sum_i x_i g_i \tag{3}$$

x_i is the mole number of a substance or species in the mixture, and g_i is the chemical potential written as:

$$g_i = g_i^0 + RT \ln a_i \tag{4}$$

We assume ideal behavior for the gaseous species, and hence, the activities a_i are equal to the partial pressure p_i:

$$a_i = p_i = (x_i / X)P \tag{5}$$

X represents total number of moles in the gas phase and P is the total pressure of the system, respectively. The condensed substances are assumed to be pure, and hence, their activities are equal to unity. With these quantities, we define a new dimensionless quantity (G/RT) as:

$$G/RT = \sum_{i=1}^{m} x_i^g [(g^0/RT)_i^g + \ln P + \ln(x_i^g / X)] + \sum_{i=1}^{s} x_i^c (g^0/RT)_i^c \tag{6}$$

Superscripts g and c represent gas phase and condensed phase, respectively, while m and s represent the total number of substances in the gas phase and condensed phase, respectively, at equilibrium. R is the ideal gas constant. The value of (g^o/RT) for a certain substance is calculated using the expression:

$$(g^o/RT) = (1/R)[G^o - H_{298}^o)/T + \Delta_f H_{298}^o / RT \tag{7}$$

Superscript ^{o} refers to the thermodynamic standard state; subscript $_{298}$ refers to the reference temperature (25°C = 298.15 K); subscript $_f$ denotes the formation of a compound from the elements in their standard states. The mass balance among various species can be written as:

$$\sum_{i=1}^{m} a_{ij}^g x_i^g + \sum_{i=1}^{s} a_{ij}^c x_i^c = b_j \, (j = 1, 2, ...l) \tag{8}$$

where a_{ij} represents the number of atoms of the j^{th} element in a molecule of the i^{th} substance, b_j is the total number of moles of the j^{th} element, and l is the total number of elements. The method involves a search for a minimum value of the free energy G of a system (or equivalently G/RT as given in equation 6) subject to the mass balance relation as subsidiary conditions. For solution of this system of equations, Lagrange's methods of undetermined multipliers can be used.

Since the equilibrium composition has been obtained, the heat generation or the total heat of a process can be computed, using values of $\Delta_f H_{298}^o$, C_p and $(H^o - H_{298}^o)$ as follows:

The energy necessary for pre–heating the initial mixture (HP) from the initial temperature T_1 K to the reaction temperature T K, added to the heat of reaction (HR), gives the total heat (HT): $HT = HP + HR$. HP and HR are given by the following expressions:

$$HP = \sum_i x_i^* (H^o - H_{T1}^o)_i \tag{9}$$

where x^* denotes the number of moles in the initial mixture, and:

$$(H^o - H_{T1}^o)_i = \int_{T_1}^{T} (C_p)_i \, dT \tag{10}$$

$$HR = \sum_i (\Delta_f H_T^o)_i (x_i - x_i^*) \tag{11}$$

where $(\Delta_f H_T^o)_i = (\Delta_f H_{298}^o)_i + [(H^o - H_{298}^o)_i - (H^o - H_{298}^o)_{elements}]$. Other notations in equations 9–11 are: H = enthalpy (heat content); T = absolute temperature of the system; x^* = number of moles in the initial mixture; C_p = heat capacity at constant pressure as a function of temperature; $\Delta_f H_{298}^o$ = heat of formation at 298.15 K; $\left(G^o - H_{298}^o\right)/T$ = free energy function; $\left(H^o - H_{298}^o\right)$ = heat content function.

4. Results of simulations

We have presented the results of gasification of biomass mixtures in two parts: (1) simulations with equilibrium models and (2) simulations with semi–equilibrium models. In both of these parts, we have first assessed the principal characteristics of the producer gas (viz. net yield of producer gas in Nm^3 per 100 g of biomass mixture, hydrogen and carbon monoxide content of the gas in gmoles and the LHV of the gas in MJ/Nm^3) resulting from gasification of biomass, followed by net thermal energy available for power generation (in kJ per 100 g of biomass mixture) and net enthalpy change (or heat of reaction in kJ per 100 g of biomass mixture) in the gasification process. Next, we have presented the fractional distribution of carbon and hydrogen in the gasification mixture (biomass mixture + air) among various species in the producer gas such as CO, CO_2, H_2, H_2O, CH_4 and C (i.e. unconverted carbon). Figures 1–10 and Table 3 depict the simulation results of gasification of biomass mixtures with equilibrium models, while Table 4 and Figure 11 summarizes simulation results of gasification of biomass mixtures with semi–equilibrium models.

Table 3. Simulation results for the gasification of biomass mixtures (Basis: 100 g of total biomass mixture)

(A) Net thermal energy ($\Delta H_{th,P}$, kJ) content of producer gas

(A) Biomass: RH (25%) + SD (75%)				(A) Biomass: BD (25%) + SD (75%)				(A) Biomass: BD (25%) + RH (75%)			
Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
700	1570	1604	1382	700	1594	1612	1389	700	1411	1244	1069
800	1844	1616	1386	800	1853	1624	1393	800	1427	1249	1071
900	1848	1617	1386	900	1857	1625	1393	900	1428	1249	1071
1000	1848	1617	1386	1000	1857	1625	1392	1000	1428	1249	1071
(B) Biomass: RH (50%) + SD (50%)				(B) Biomass: BD (50%) + SD (50%)				(B) Biomass: BD (50%) + RH (50%)			
Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
700	1548	1481	1275	700	1596	1498	1290	700	1421	1252	1077
800	1702	1491	1278	800	1721	1507	1292	800	1437	1258	1078
900	1704	1491	1278	900	1723	1508	1292	900	1437	1258	1078
1000	1705	1491	1278	1000	1723	1508	1292	1000	1437	1258	1078
(C) Biomass: RH (75%) + SD (25%)				(C) Biomass: BD (75%) + SD (25%)				(C) Biomass: BD (75%) + RH (25%)			
Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
700	1527	1359	1169	700	1569	1384	1190	700	1431	1260	1083
800	1560	1367	1172	800	1588	1391	1192	800	1446	1266	1085
900	1562	1367	1172	900	1590	1391	1192	900	1446	1266	1085
1000	1562	1367	1171	1000	1590	1391	1192	1000	1446	1265	1085

(B) Net enthalpy change (ΔH, kJ) in the gasification process

(A) Biomass: RH (25%) + SD (75%)				(A) Biomass: BD (25%) + SD (75%)				(A) Biomass: BD (25%) + RH (75%)			
Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
700	-5.10E+02	-6.10E+02	-7.79E+02	700	-5.25E+02	-6.30E+02	-8.00E+02	700	-5.30E+02	-6.55E+02	-7.87E+02
800	-3.85E+02	-5.53E+02	-7.23E+02	800	-4.03E+02	-5.72E+02	-7.43E+02	800	-4.80E+02	-6.10E+02	-7.40E+02
900	-3.45E+02	-5.07E+02	-6.70E+02	900	-3.63E+02	-5.26E+02	-6.90E+02	900	-4.46E+02	-5.70E+02	-6.95E+02
1000	-3.08E+02	-4.63E+02	-6.18E+02	1000	-3.25E+02	-4.81E+02	-6.38E+02	1000	-4.12E+02	-5.31E+02	-6.50E+02
(B) Biomass: RH (50%) + SD (50%)				(B) Biomass: BD (50%) + SD (50%)				(B) Biomass: BD (50%) + RH (50%)			
Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
700	-5.02E+02	-6.19E+02	-7.75E+02	700	-5.33E+02	-6.58E+02	-8.17E+02	700	-5.48E+02	-6.75E+02	-8.08E+02
800	-4.10E+02	-5.65E+02	-7.22E+02	800	-4.48E+02	-6.05E+02	-7.63E+02	800	-4.99E+02	-6.29E+02	-7.60E+02
900	-3.73E+02	-5.22E+02	-6.72E+02	900	-4.09E+02	-5.60E+02	-7.12E+02	900	-4.63E+02	-5.89E+02	-7.15E+02
1000	-3.37E+02	-4.80E+02	-6.23E+02	1000	-3.72E+02	-5.16E+02	-6.61E+02	1000	-4.29E+02	-5.49E+02	-6.69E+02
(C) Biomass: RH (75%) + SD (25%)				(C) Biomass: BD (75%) + SD (25%)				(C) Biomass: BD (75%) + RH (25%)			
Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio			Temp (^oC)	Air Ratio		
	0.2	0.3	0.4		0.2	0.3	0.4		0.2	0.3	0.4
700	-4.95E+02	-6.27E+02	-7.71E+02	700	-5.48E+02	-6.87E+02	-8.34E+02	700	-5.67E+02	-6.95E+02	-8.29E+02
800	-4.36E+02	-5.78E+02	-7.21E+02	800	-4.92E+02	-6.36E+02	-7.82E+02	800	-5.17E+02	-6.49E+02	-7.81E+02
900	-4.00E+02	-5.37E+02	-6.74E+02	900	-4.54E+02	-5.93E+02	-7.33E+02	900	-4.82E+02	-6.08E+02	-7.35E+02
1000	-3.66E+02	-4.96E+02	-6.27E+02	1000	-4.18E+02	-5.51E+02	-6.85E+02	1000	-4.47E+02	-5.68E+02	-6.89E+02

4.1 Trends in simulation results (equilibrium model)

From the data presented in Figures 1–10 and Table 3, we identify following trends in various characteristics of producer gas obtained from gasification of biomass mixtures at different conditions.

Net gas yield (Figure 1): For all biomass mixtures, the net gas yield increases with air ratio; however, the temperature rise from 700–1000^{o}C does not affect the gas yield. For biomass mixtures containing saw dust (which has higher carbon content than other two biomasses), the gas yield slightly reduces as the proportion of the saw dust in the mixture reduces. However, for mixtures of rice husk and bamboo dust, the gas yield is practically independent of the mixture composition.

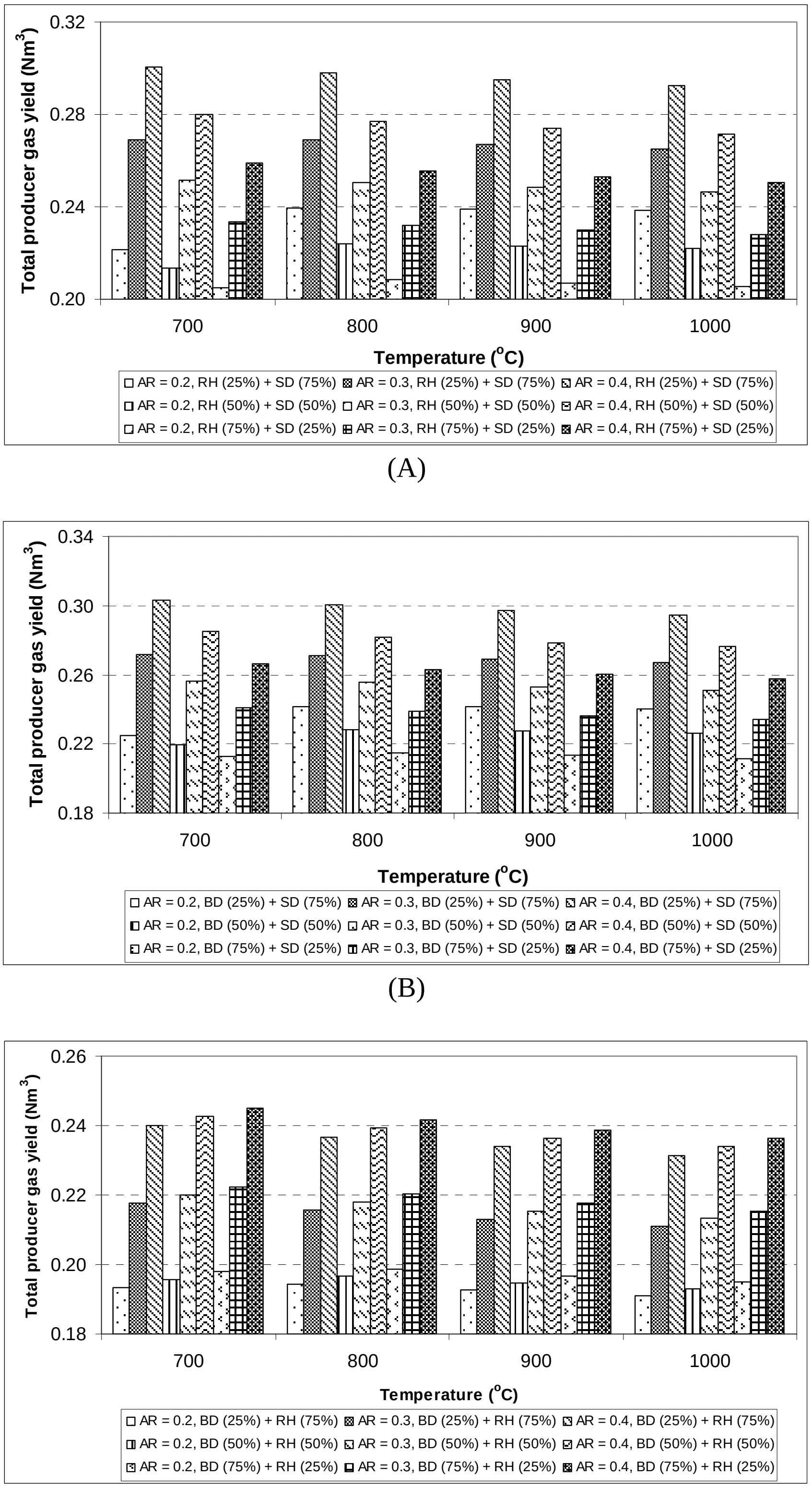
Hydrogen content of producer gas (Figure 2): For a given gasification temperature, the hydrogen content of the producer gas decreases with air ratio for all biomass mixtures. On the other hand, for a given air ratio, the hydrogen content does not show a common trend with gasification temperature. For AR = 0.2, the hydrogen content rises till 900°C and thereafter decreases, whereas for AR = 0.3 and 0.4, the hydrogen content reduces continuously with rising gasification temperature. No particular trend can be seen for hydrogen with constituents of the biomass mixture. For a given combination of temperature and air ratio, the hydrogen content of producer gas varies by less than ±10% with composition of the mixtures. Even among mixtures of different biomasses (RH+SD; SD+BD or RH+BD), the hydrogen content of producer gas shows insignificant variation.

Carbon monoxide content of producer gas (Figure 3): For a given gasification temperature, the CO content of the producer gas reduces with air ratio. This trend is consistent for all nine mixtures of biomasses. Similarly, for all nine mixtures, the CO content of producer gas increases with temperature at a constant air ratio. For biomass mixtures constituting saw dust, at any combination of air ratio and gasification temperature, the CO content is significantly higher (by about 25–40%) than the corresponding value for mixtures of rice husk and bamboo dust. Moreover, for biomass mixtures comprising saw dust, the CO content reduces with the proportion of saw dust in the mixture. This effect is clearly attributed to higher carbon content of saw dust than rice husk and bamboo dust.

LHV of producer gas (Figure 4): The major combustible components of the producer gas are CO and H_2. It is thus obvious that the trend in the LHV of the producer gas is similar to that of hydrogen and carbon monoxide. For a given gasification temperature, the LHV reduces with increasing air ratio; whereas, for a given air ratio, the LHV increases with gasification temperature. For biomass mixtures comprising saw dust, the LHV values for any combination of air ratio and gasification temperature are higher than the corresponding values for mixtures of rice husk and bamboo dust. Moreover, for mixtures of saw dust, the LHV at any air ratio and temperature reduces with proportion of saw dust in the mixture. These trends are essentially same as that of CO content.

Net thermal energy content of producer gas (Table 3A): The thermal energy content of producer gas resulting from gasification of 100 g of biomass mixture can be obtained by product of net yield of the gas (in Nm^3) and the LHV of the gas (in MJ/Nm^3). This energy is essentially the potential of the producer gas for generation of power (through engine–generator sets operating on dual fuel or 100% producer gas). This parameter shows same trends as the LHV. It reduces with increasing air ratio for a particular gasification temperature, and increases with gasification temperature for a particular air ratio. Moreover, thermal energy content of producer gas is higher for mixtures containing saw dust and varies directly with the proportion of the saw dust in the mixture.

Net enthalpy change in gasification (Table 3B): This is the net energy released by the gasification reaction system in the process of attaining equilibrium (and hence, this parameter is similar to the heat of reaction). One can infer from Table 3(B) that for a given air ratio, net enthalpy change reduces with gasification temperature while for a particular gasification temperature it increases with air ratio. Enthalpy change for any combination of temperature and air ratio are lower for biomass mixtures comprising saw dust (as compared to the mixtures of bamboo dust and rice husk). Moreover, for mixtures of saw dust, the enthalpy change shows inverse variation with the proportion of saw dust in the mixture for any particular air ratio and gasification temperature. Interestingly, these trends are exactly opposite to the trends in LHV of the producer gas – reasons for which are explained in section 5.



(A)

(B)

(C)

Figure 1. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Variation in total producer gas yield for different biomass mixtures with air ratio and temperature. (A) Mixtures of rice husk and saw dust. (B) Mixtures of bamboo dust and saw dust. (C) Mixtures of bamboo dust and rice husk

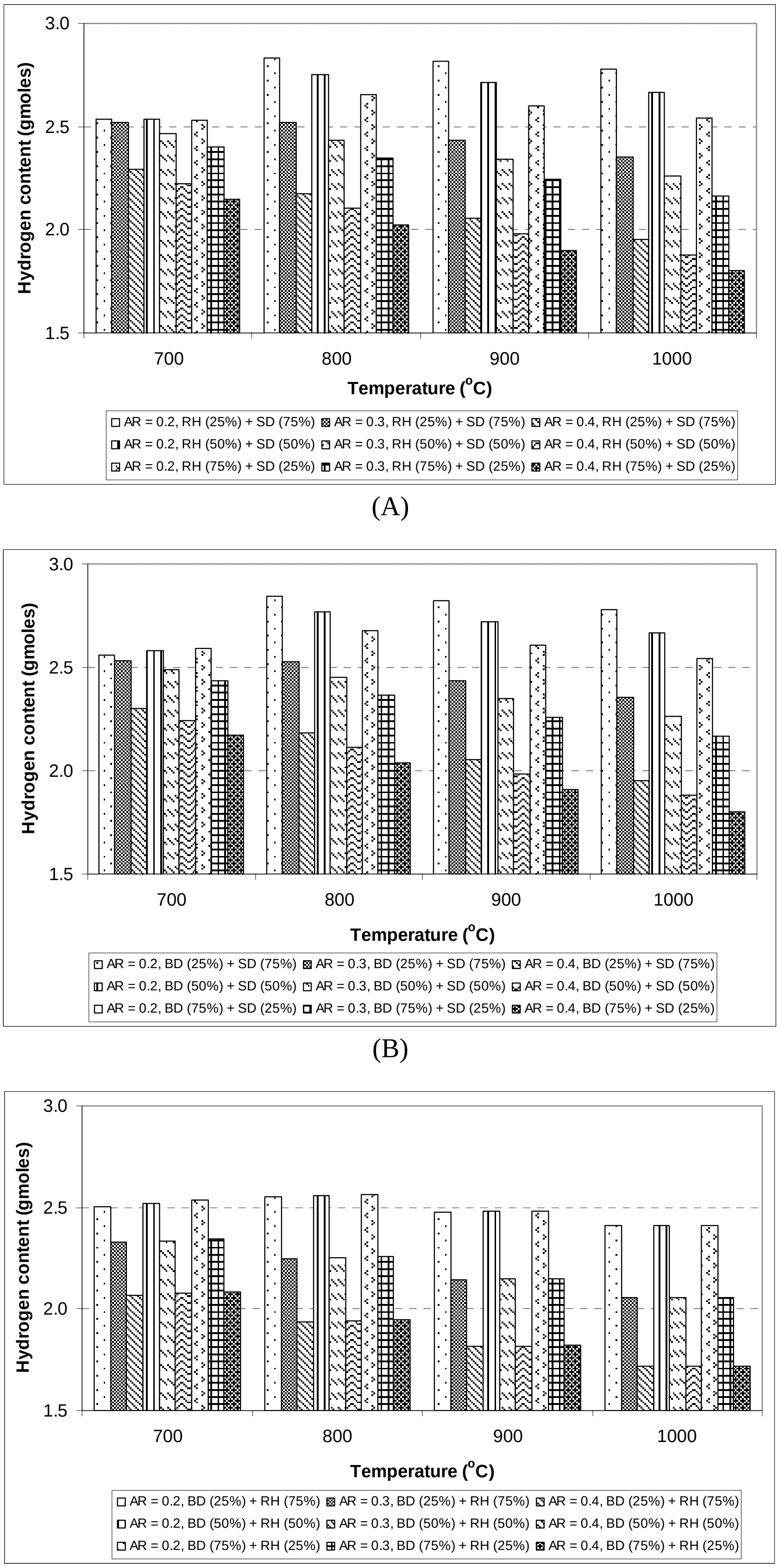
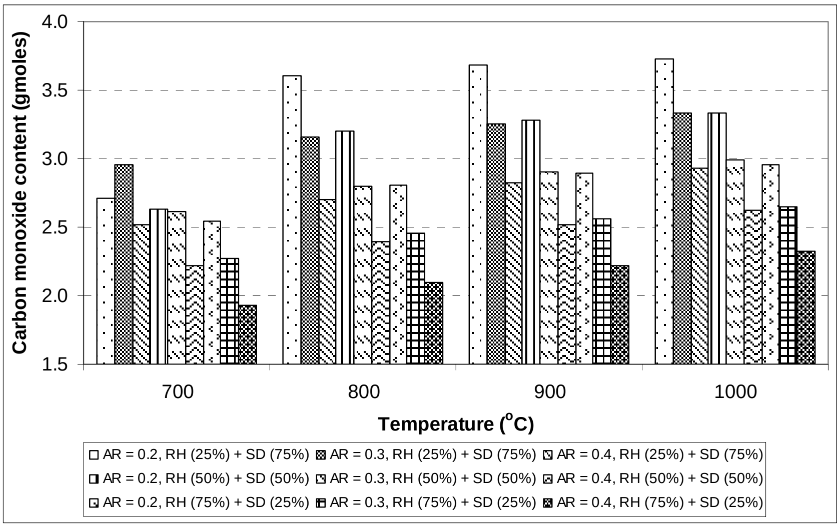
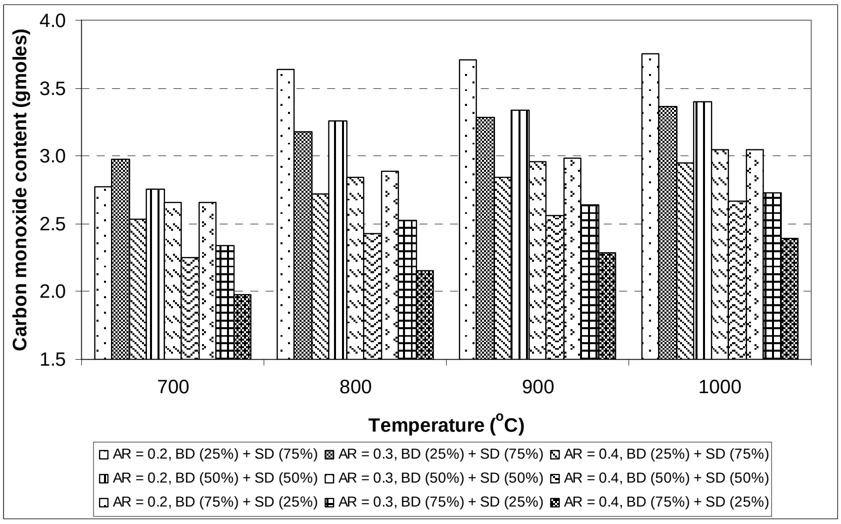


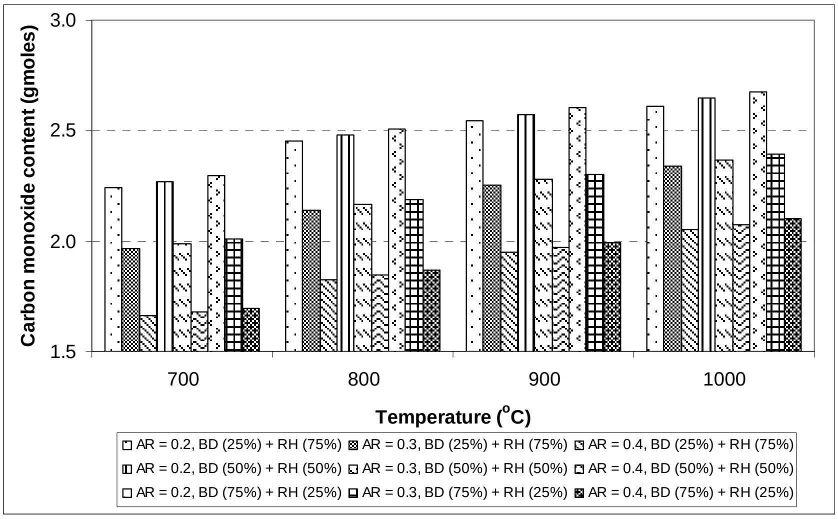
Figure 2. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Variation in hydrogen content in producer gas for different biomass mixtures with air ratio and temperature. (A) Mixture of rice husk and saw dust. (B) Mixture of bamboo dust and saw dust. (C) Mixture of bamboo dust and rice husk



(A)

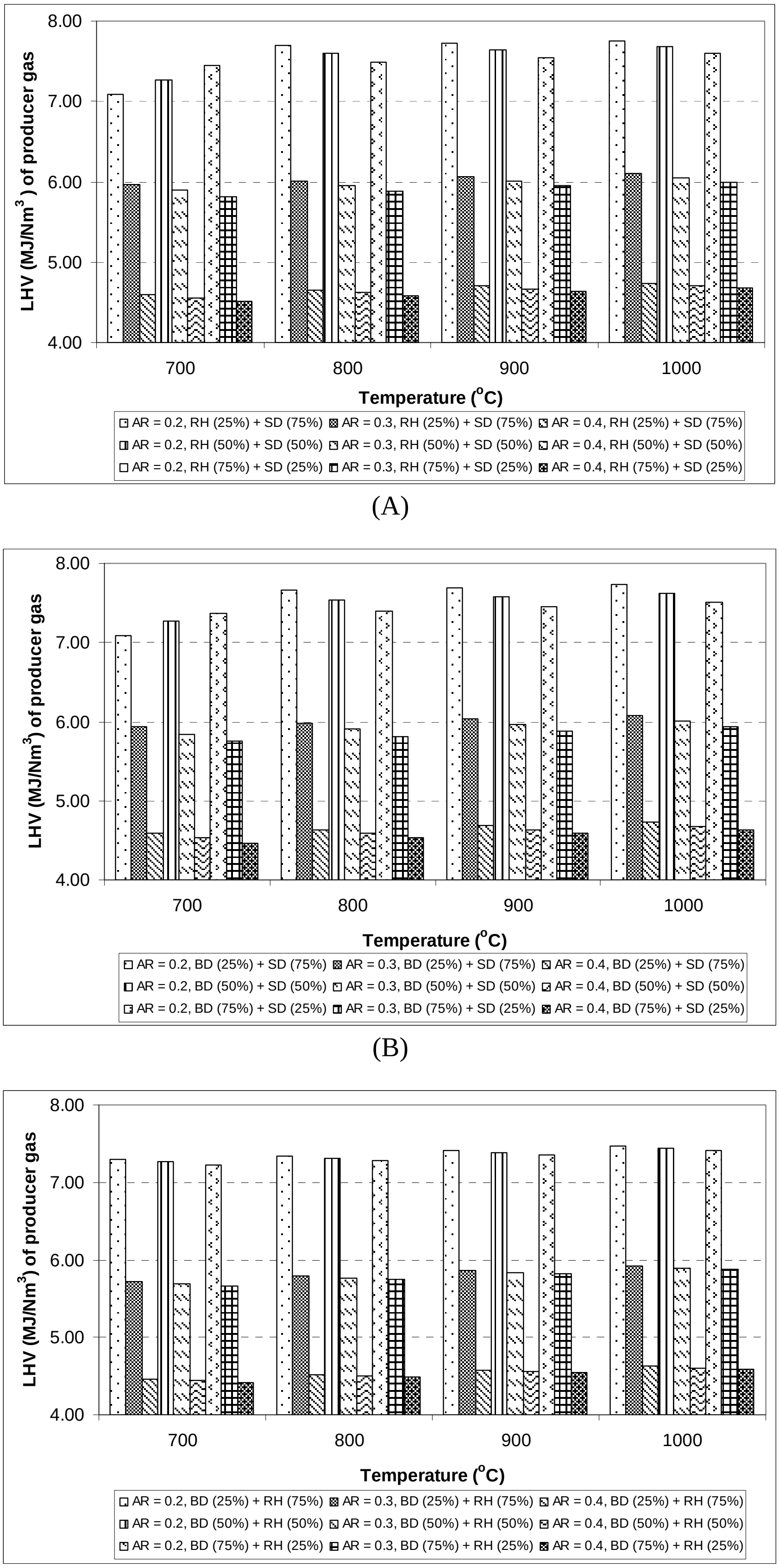


(B)



(C)

Figure 3. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Variation in carbon monoxide content in producer gas for different biomass mixtures with air ratio and temperature. (A) Mixtures of rice husk and saw dust. (B) Mixtures of bamboo dust and saw dust. (C) Mixtures of bamboo dust and rice husk



(A)

(B)

(C)

Figure 4. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Variation in LHV of producer gas for different biomass mixtures with air ratio and temperature. (A) Mixtures of rice husk and saw dust. (B) Mixtures of bamboo dust and saw dust. (C) Mixtures of bamboo dust and rice husk

4.2 Trends in carbon and hydrogen distribution (equilibrium models)

The fractional distribution of carbon in the gasification reaction mixture (biomasses + air) among various carbonaceous species present in the producer gas is given in Figures 5–7. As noted earlier, the principal carbonaceous species in the producer gas are CO, CO_2, CH_4 and unconverted carbon. From Figures 5–7, we can identify following trends in the fractional distribution among these species:

(1) For all nine biomass mixtures gasified at air ratios of 0.2–0.4 and temperatures of 700–1000°C, conversion of carbon is complete at equilibrium except for two cases, viz. mixture of rice husk (25%) & saw dust (75%) and mixture of bamboo dust (25%) & saw dust (75%) at air ratio of 0.2 and temperature of 700°C. We attribute this effect to three causes: (i) relatively high carbon content of saw dust, (ii) less availability of oxygen at air ratio of 0.2 and (iii) lower temperature of gasification.

(2) The fraction of carbon ending up as carbon monoxide shows inverse variation with air ratio at any given gasification temperature, and shows direct variation with gasification temperature at any given air ratio. The fraction of carbon appearing in the form of CO_2 shows exactly opposite trend.

(3) The fraction of carbon appearing in the form of methane is quite small for all biomass mixtures. This is basically a consequence of low moisture content (~ 10% w/w) of biomass. At high temperatures (≥ 800°C) and high air ratios, the amount of carbon forming methane is practically zero.

Distribution of hydrogen in the gasification mixture among three major species in the producer gas, viz. H_2, H_2O and CH_4, is given in Figures 8–10. The trends in fractional distribution of hydrogen can be summarized as follows:

(1) For air ratios of 0.2 and temperature 700–800°C, most of hydrogen in biomass ends up as H_2 in the producer gas, with small fractions forming H_2O and CH_4.

(2) As the temperature of gasification rises, the fraction of hydrogen appearing in the form of water vapor in producer gas increases with proportionate reduction in hydrogen in methane.

(3) As air ratio increases, the fraction of hydrogen ending up in water vapor increases with proportionate reduction in the fraction of hydrogen ending up as H_2. This effect is obviously attributed to greater presence of oxygen in the gasification mixture with increasing air ratio.

4.3 Trends in simulation results with semi–equilibrium model

As discussed in section 2.1, we restricted the conversion of carbon in the biomass mixture by certain percentage, which was determined on the basis of experimental results of Lv et al. [24]. The results of simulations are presented in Table 4 and Figure 11. Two major deviations from the equilibrium model are evident as follows:

(1) The net yield and LHV of the producer gas reduces as compared to the total equilibrium conditions. Obviously, these two parameters vary directly with extent of carbon conversion.

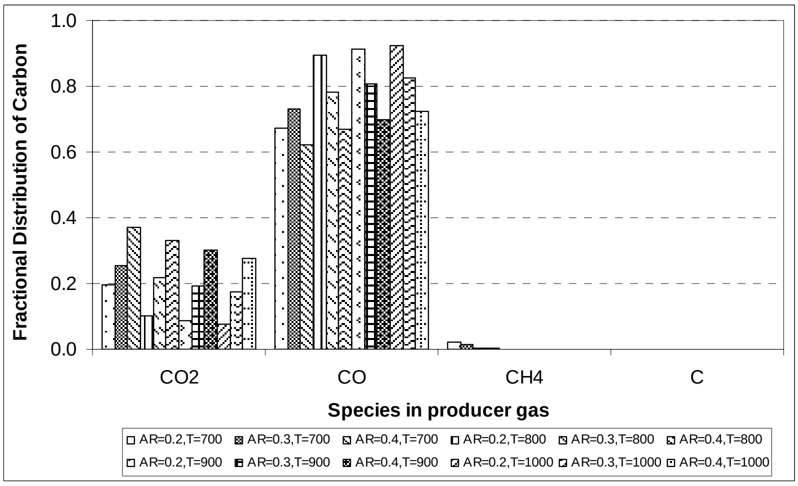
(2) Hydrogen and carbon monoxide content of the producer gas also reduces as compared to the equilibrium conditions, and again, these two parameters show direct variation with the extent of carbon conversion.

Table 4. Simulation results for gasification of biomass mixtures with semi–equilibrium model (incomplete carbon conversion; basis: 100 g of biomass mixture)

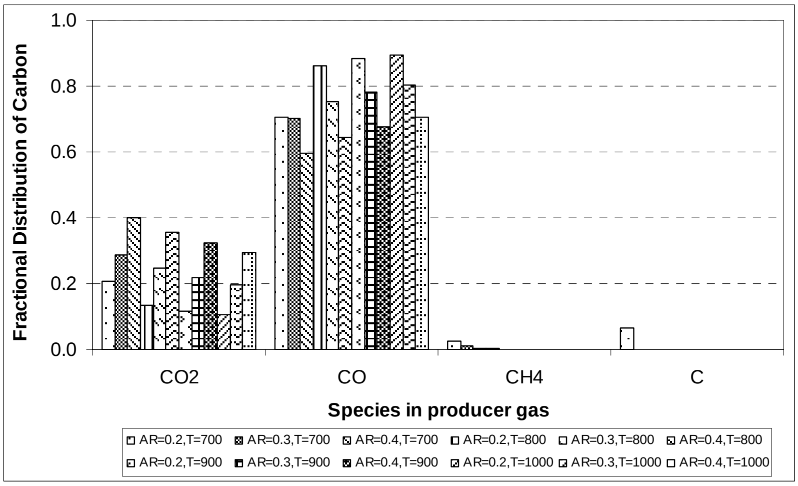
CC	H_2 moles	CO moles	ΔH (kJ)	Gas yield (Nm^3)	LHV (MJ/Nm^3)	ΔH_P (kJ)
(A) Biomass mixture: RH (50%) + SD (50%)						
60%	1.36E+00	9.10E-01	-8.01E+02	0.19	3.42	647
70%	1.69E+00	1.33E+00	-7.44E+02	0.21	4.17	858
80%	1.97E+00	1.79E+00	-6.85E+02	0.22	4.82	1069
(B) Biomass mixture: BD (50%) + RH (50%)						
60%	1.19E+00	6.67E-01	-8.15E+02	0.16	3.28	530
70%	1.51E+00	9.92E-01	-7.68E+02	0.18	4.02	712
80%	1.79E+00	1.35E+00	-7.30E+02	0.19	4.67	894
(C) Biomass mixture: BD (50%) + SD (50%)						
60%	1.33E+00	9.00E-01	-8.32E+02	0.19	3.32	636
70%	1.67E+00	1.33E+00	-7.76E+02	0.21	4.09	854
80%	1.97E+00	1.80E+00	-7.28E+02	0.23	4.76	1072

Abbreviations: CC – carbon conversion; LHV – Lower heating value; ΔH – net enthalpy change of the biomass gasification process; $\Delta H_{th,P}$ – net available thermal energy for power generation

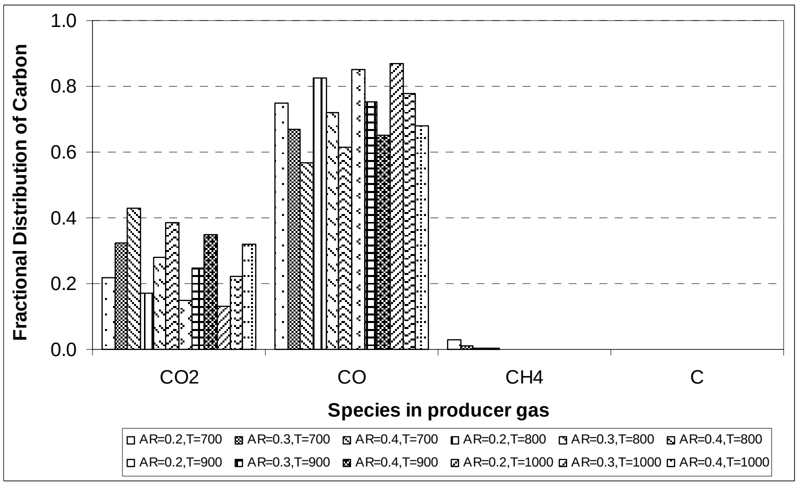
In addition, the net enthalpy change of gasification reduces, while the net thermal energy content of producer gas increases with increasing carbon conversion.



(A)

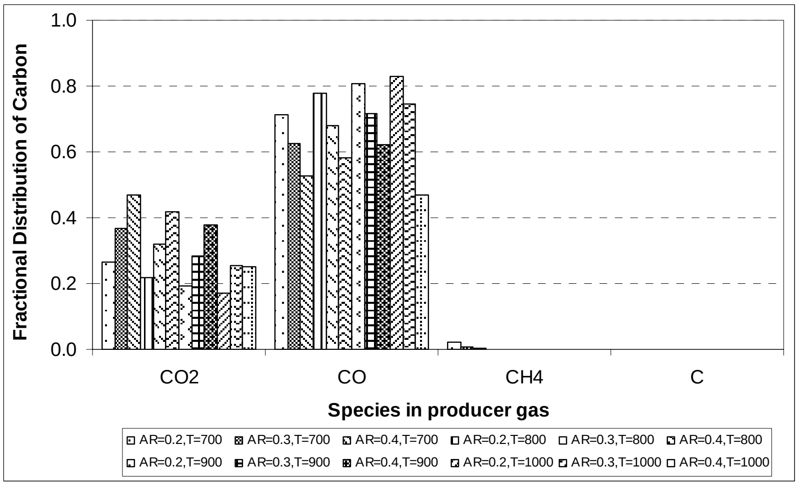


(B)

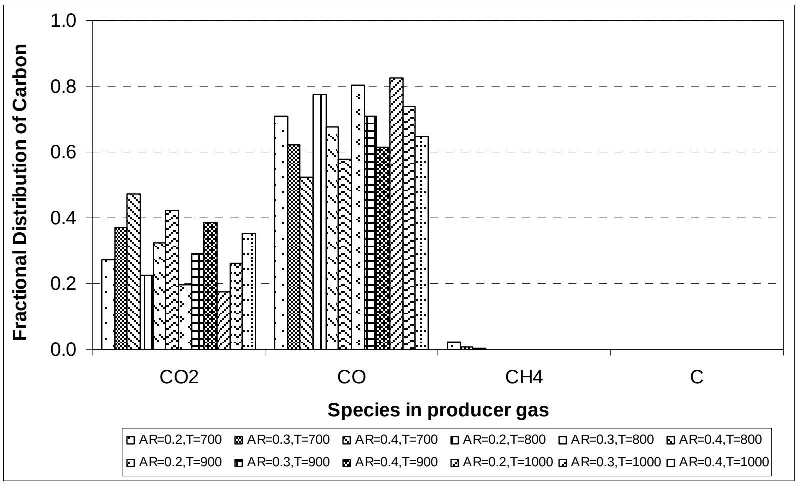


(C)

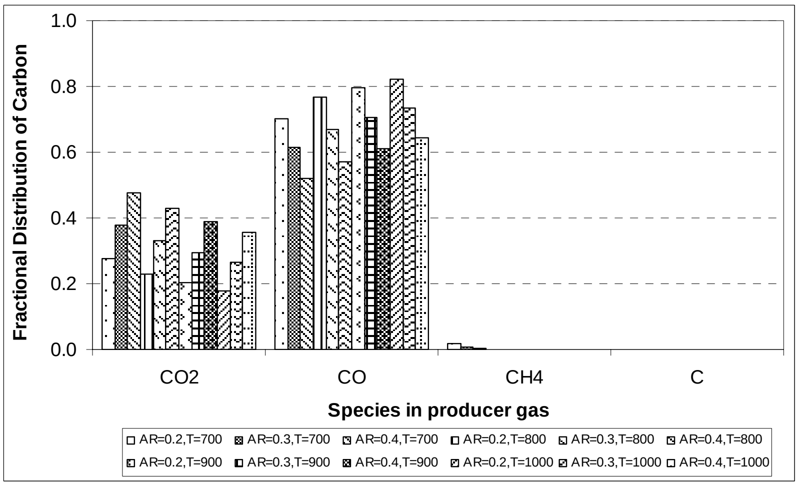
Figure 5. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Fractional distribution of carbon in the gasification mixture among various species in the producer gas for mixture of rice husk and saw dust. Compositions: (A) RH (25%) + SD (75%) (B) RH (50%) + SD (50%) (C) RH (75%) + SD (25%)



(A)

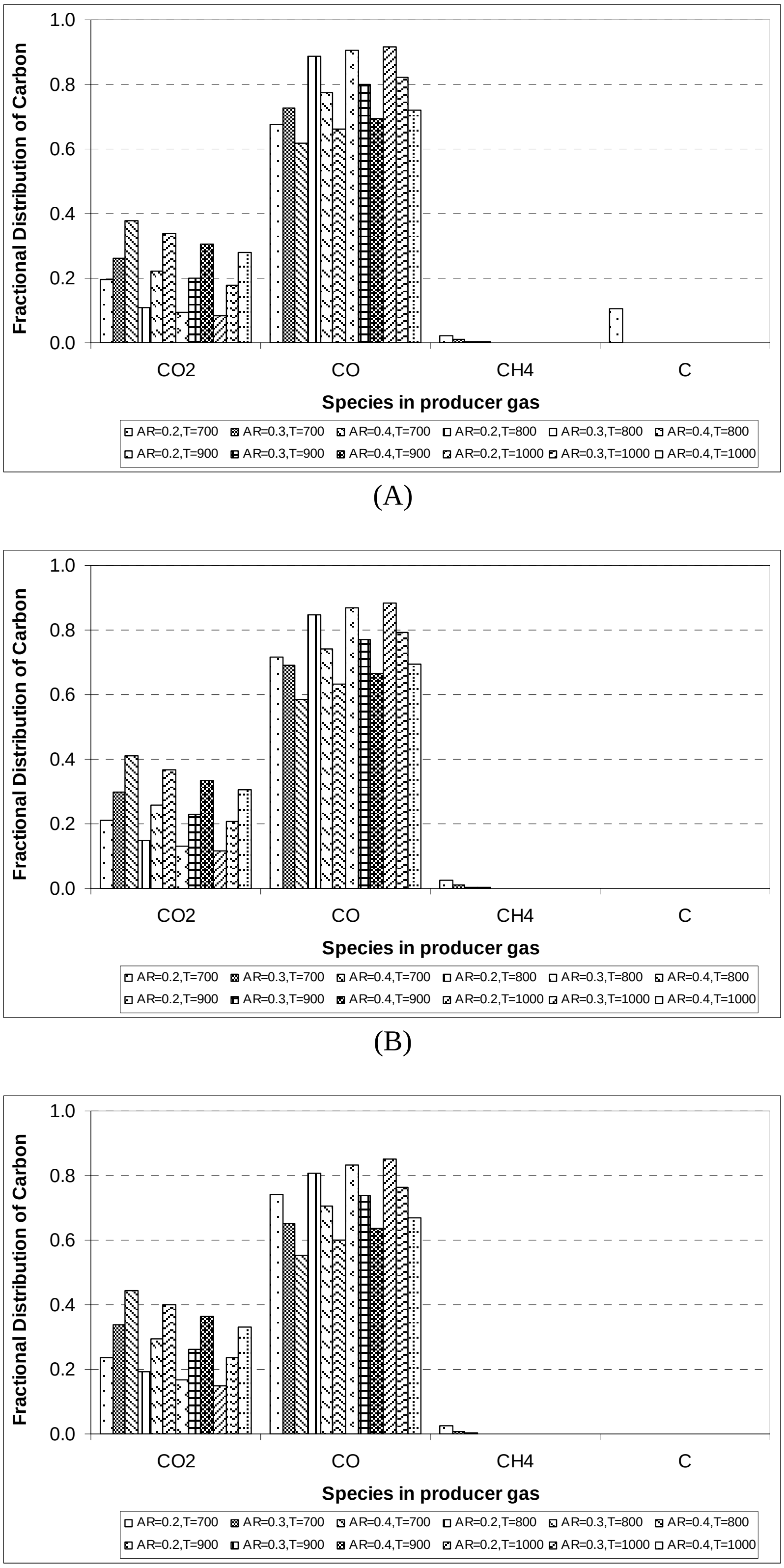


(B)



(C)

Figure 6. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Fractional distribution of carbon in the gasification mixture among various species in the producer gas for mixture of bamboo dust and rice husk. Compositions: (A) BD (25%) + RH (75%) (B) BD (50%) + RH (50%) (C) BD (75%) + RH (25%)

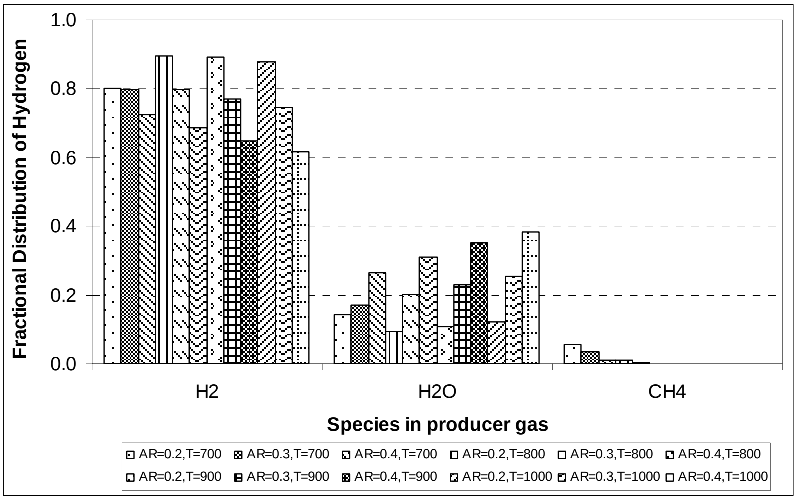


(A)

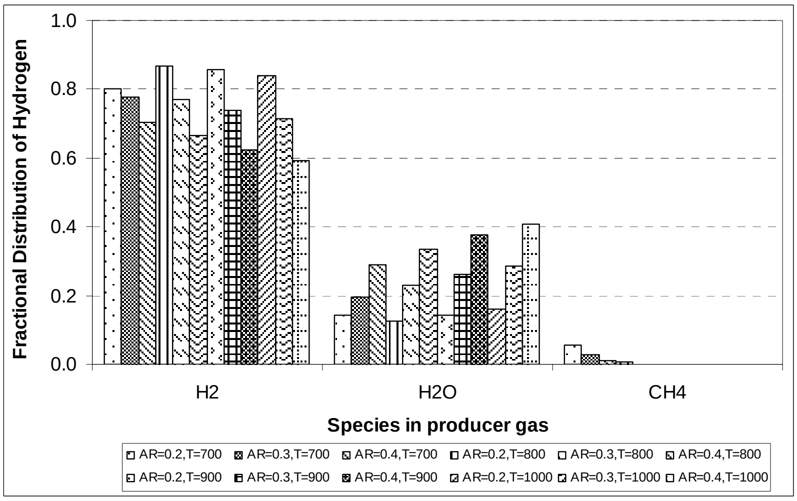
(B)

(C)

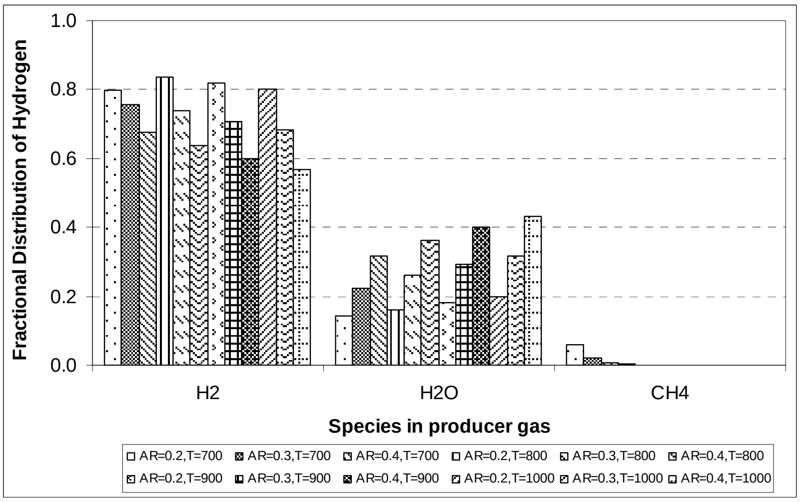
Figure 7. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Fractional distribution of carbon in the gasification mixture among various species in the producer gas for mixture of bamboo dust and saw dust. Compositions: (A) BD (25%) + SD (75%) (B) BD (50%) + SD (50%) (C) BD (75%) + SD (25%)



(A)

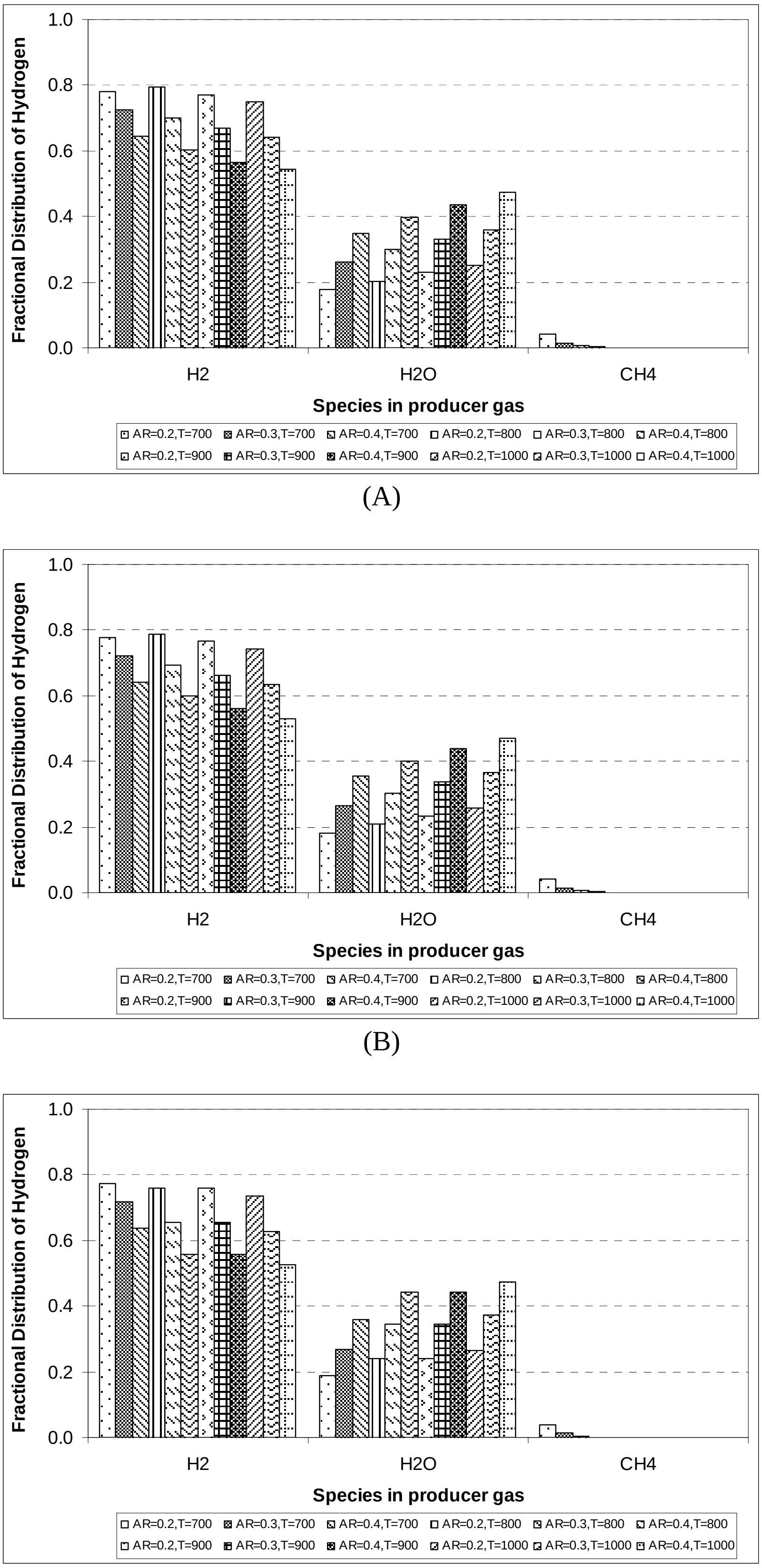


(B)



(C)

Figure 8. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Fractional distribution of hydrogen in the gasification mixture among various species in the producer gas for mixture of rice husk and saw dust. Compositions: (A) RH (25%) + SD (75%) (B) RH (50%) + SD (50%) (C) RH (75%) + SD (25%)

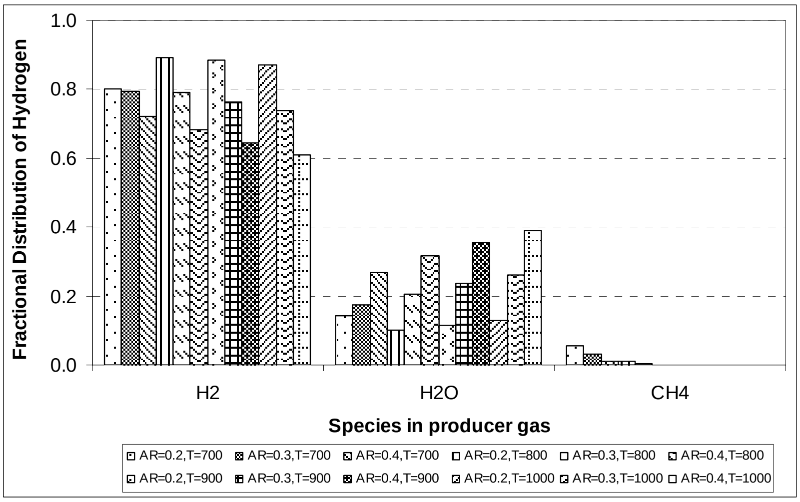


(A)

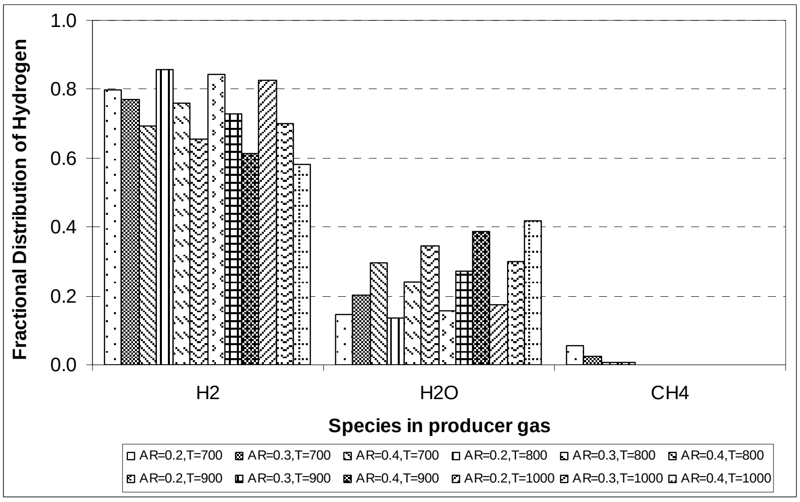
(B)

(C)

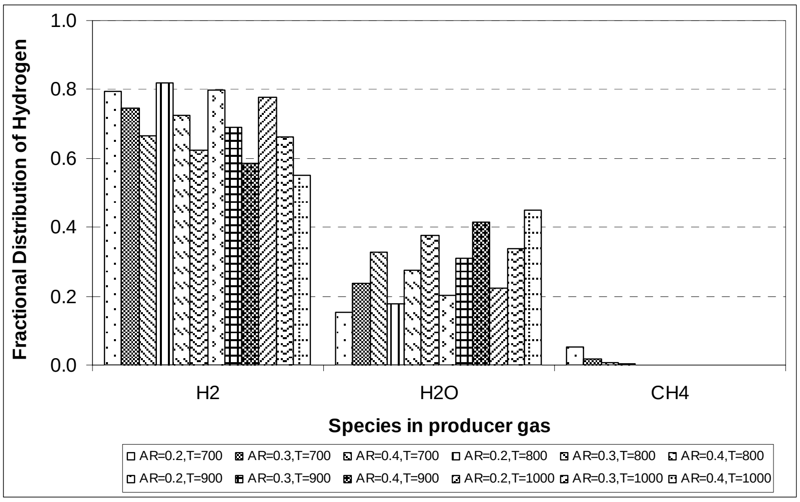
Figure 9. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Fractional distribution of hydrogen in the gasification mixture among various species in the producer gas for mixture of bamboo dust and rice husk. Compositions: (A) BD (25%) + RH (75%) (B) BD (50%) + RH (50%) (C) BD (75%) + RH (25%)



(A)

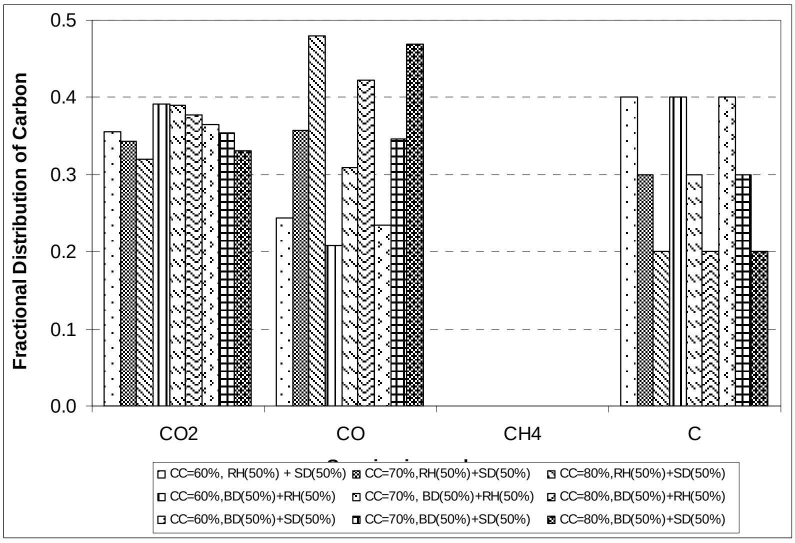


(B)

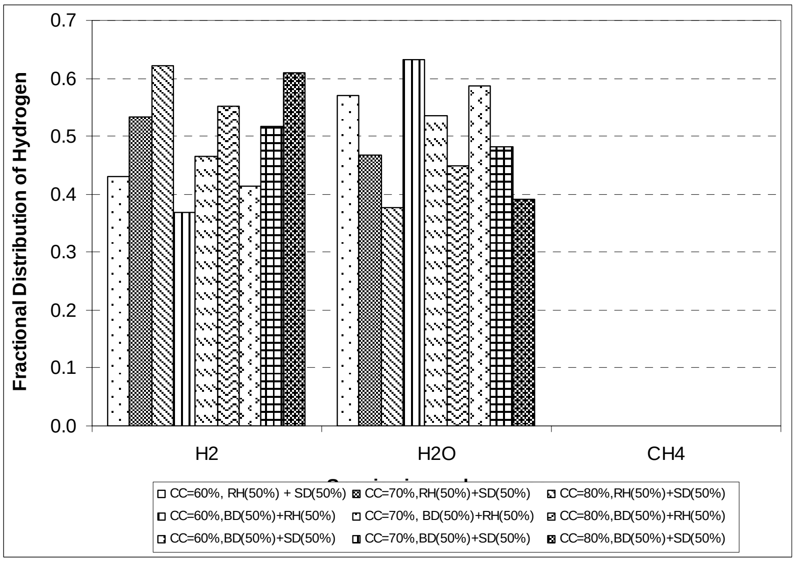


(C)

Figure 10. Simulations results for the gasification of biomass mixtures (Basis: 100g of total biomass mixture). Fractional distribution of hydrogen in the gasification mixture among various species in the producer gas for mixture of bamboo dust and saw dust. Compositions: (A) BD (25%) + SD (75%) (B) BD (50%) + SD (50%) (C) BD (75%) + SD (25%)



(A)



(B)

Figure 11. Simulations results for the gasification of biomass mixtures for incomplete carbon conversion (Basis: 100g of total biomass mixture) at AR = 0.3 and temperature = 800°C. The exact biomass compositions and extent of carbon conversions are given in the legends. (A) Fractional distribution of carbon in the gasification mixture among various species in the producer gas. (B) Fractional distribution of hydrogen in the gasification mixture among various species in the producer gas

4.4 Trends in distribution of carbon and hydrogen

As the carbon conversion increases, greater fraction of carbon in the biomass mixture ends up as CO in the producer gas. Quite interestingly, the fraction of carbon appearing in the form of CO_2 shows insignificant variation with carbon conversion. This trend is consistent for all biomass mixtures. Among the three biomass mixtures, those containing saw dust show greater fractional carbon distribution towards CO than CO_2.

The fractional distribution of hydrogen towards H_2 shows direct variation with extent of carbon conversion, with proportionate reduction in distribution towards H_2O. This effect is attributed to competitive consumption of oxygen in the gasification mixture by carbon undergoing oxidation to CO and CO_2. The fraction of hydrogen appearing in the form of CH_4 is practically zero for the conditions considered for present simulation.

4.5 Comparative assessment with previous literature

In this section, we compare our simulation results with previous literature. Our comparative assessment is two fold in that we first contrast our results with those reported in theoretical (or simulation) studies in biomass gasification, followed by comparison with results of experimental studies. The basis for comparison are three parameters, viz. (1) variation in product gas composition, (2) LHV of product gas, and (3) net product gas yield per unit biomass, with temperature and air (or equivalence) ratio. We would like to specifically state that a quantitative match between our results and the data reported previous theoretical as well as experimental literature is unlikely due to differences between the biomass type and gasification medium used these papers and the present study. Nonetheless, the trends observed in parameters mentioned above with gasification temperature and air ratio can be considered for comparison.

4.5.1 Comparison with theoretical or simulations studies

Table 5 gives composition and LHV of the product gas reported in six previous studies on gasification of different biomass materials. The temperature of gasification in these studies is in the range 700 – 900^{o}C with an equivalence ratio of 0.2 to 0.4. Also given in the table are our simulation results for gasification of mixtures of saw dust (which is a widely employed biomass for gasification in previous literature) with rice husk and bamboo dust. It could be inferred from Table 5 that both LHV and composition of product gas in our simulations is quite similar to that reported in previous literature. It could also be perceived that use of air–steam mixture as gasification medium [43] results in product gas with higher hydrogen content (and as a consequence has higher LHV) than gas obtained with air gasification (as considered in our study). In addition to the data presented in Table 5, we would like to cite following trends observed in previous studies that are in concurrence with our results:

1. Melgar et al. [38] have reported increasing CO content in the product gas with reduction in air ratio, and increasing CO_2 content at higher air ratios. Moreover, Melgar et al. [38] have also reported higher CH_4 content in product gas at low air ratios and low temperatures.
2. Schuster et al. [43] have reported leveling off of LHV of producer gas at gasification temperatures above 800^{o}C. They have also reported no presence of methane in the product gas at temperatures higher than 800^{o}C. All of these findings coincide with the results of simulations in this study.

Table 5. Comparison with simulations data

Reference	**Biomass**	**LHV (MJ/Nm^3)**	**CH_4**	**H_2**	**CO_2**	**CO**
			Volume (or mole) fraction			
Ruggerio and Manfrida [35]	Saw Dust	5.109	0.009	0.194	0.114	0.220
Zainal et al. [36]	Wood chips	4.72	0.006	0.216	0.120	0.196
Melgar et al. [38]	Pine Wood	N.A.	0.002	0.166	0.110	0.192
Schuster et al. [43]	Beech Chips (Air-steam gasification)	8.316	0.001	0.466	0.103	0.258
Jayah et al. [44]	Rubber Wood	N.A.	0.001	0.164	0.111	0.183
Present Study (Saw dust rich mixtures)	**SD - 75%, RH - 25%**	**6.01**	**0**	**0.225**	**0.078**	**0.282**
	SD - 75%, BD - 25%	**5.99**	**0**	**0.224**	**0.081**	**0.282**
Present Study (Saw dust mixtures with 80% carbon conversion)	**SD - 50%, RH - 50%**	**4.67**	**0**	**0.225**	**0.152**	**0.170**
	SD - 50%, BD - 50%	**4.76**	**0**	**0.210**	**0.136**	**0.192**

Note: Temperature of gasification: 700 – 900 ^{o}C; Air (or equivalence) ratio: 0.2 – 0.4.

4.5.2 Comparison with experimental results

Several authors have studied gasification of single biomasses and mixtures of coal and biomass in fixed and/or fluidized bed gasifiers. In this section, we make comprehensive comparison of results of our simulations with the experimental data reported in previous papers. Tables 6–8 present the data for the three parameters considered for comparison. Although quantitative match between the mole fractions of different species in product gas with those observed and the predictions of the equilibrium model is not possible for the reasons stated earlier, one can perceive that experimental trends in gas composition is in concurrence with the results of simulations. From Tables 6–8, we can identify following matching trends between experimental and simulations results:

1. For a fixed gasification temperature, increasing ER reduces mole fractions of H_2 and CO, with simultaneous rise in CO_2.

2. The fraction of CH_4 in product gas obtained above 700°C is very small (< 1%).
3. For a given air ratio, the hydrogen content of product gas shows little variation with temperature (in the range 700–900°C), while CO content decreases.
4. The LHV of product gas shows inverse relation with air ratio at fixed gasification temperature. On the other hand, for a given air ratio, LHV increases with gasification temperature.
5. The net yield of the product gas increases with air ratio as well as temperature of gasification. Quite notably, the experimentally observed values of LHV and net product gas yield for single biomasses matches with calculated values for biomass mixtures in this study within an experimental variation of ± 15–20%.

Table 6. Comparison with experimental data on product gas composition
(A) Effect of air (or equivalence) ratio

Reference	Biomass	Temp (°C)	ER	CH_4	H_2	CO_2	CO
				Volume (or mole) fraction			
Jiang et al. [45]	Rice husk	770	0.16	0.005	0.009	0.162	0.036
			0.22	0.005	0.001	0.136	0.027
Present Study (Rice husk rich mixtures)	**RH - 75%, SD - 25%**	**800**	**0.20**	**0.001**	**0.306**	**0.068**	**0.324**
	RH - 75%, BD - 25%			**0.001**	**0.316**	**0.085**	**0.303**
Present Study (Rice husk mixtures with 80% carbon conversion)	**SD - 50%, RH - 50%**	**800**	**0.30**	**0**	**0.214**	**0.129**	**0.194**
	BD - 50%, RH - 50%			**0**	**0.225**	**0.152**	**0.170**
Lv et al. [24]	Pine Sawdust	800	0.19	0.078	0.323	0.179	0.379
			0.23	0.076	0.315	0.169	0.401
			0.27	0.067	0.318	0.199	0.384
Ergudenler and Ghaly [46]	Wheat Straw	800	0.25	0.049	0.074	0.136	0.170
Narvaez et al. [47]	Pine sawdust	800	0.26	0.027	0.095	0.150	0.130
Present Study (Saw dust rich mixtures)	**SD - 75%, RH - 25%**	**800**	**0.20**	**0.002**	**0.284**	**0.042**	**0.362**
	SD - 75%, BD - 25%			**0.001**	**0.283**	**0.045**	**0.361**
Maniatis et al. [48]	Pine Wood	800	0.30	0.051	0.105	0.166	0.131
van der Aarsen et al. [49]	Wood chips	800	0.31	0.045	0.111	0.159	0.134
Narvaez et al. [47]	Pine sawdust	800	0.32	0.030	0.070	0.135	0.140
Present Study (Saw dust rich mixtures)	**SD - 75%, RH - 25%**	**800**	**0.30**	**0**	**0.225**	**0.078**	**0.282**
	SD - 75%, BD - 25%			**0**	**0.224**	**0.081**	**0.282**
Present Study (Saw dust mixtures with 80% carbon conversion)	**SD - 50%, RH - 50%**	**800**	**0.30**	**0**	**0.214**	**0.129**	**0.194**
	SD - 50%, BD - 50%			**0**	**0.210**	**0.136**	**0.192**
Jiang and Morey [50]	Corn Cobs	800	0.42	0.021	0.109	0.129	0.147
Narvaez et al. [47]	Pine sawdust	800	0.44	0.032	0.095	0.151	0.137
Present Study (Saw dust rich mixtures)	**SD - 75%, RH - 25%**	**800**	**0.40**	**0**	**0.176**	**0.108**	**0.218**
	SD - 75%, BD - 25%			**0**	**0.175**	**0.111**	**0.218**

(B) Effect of gasification temperature

Reference	Biomass	ER	Temp (°C)	CH_4	H_2	CO_2	CO
				Volume (or mole) fraction			
Jiang et al. [45]	Rice husk	0.22	700	0.013	0.012	0.143	0.048
			750	0.005	0.010	0.119	0.026
Present Study (Rice husk rich mixtures)	**RH - 75%, SD - 25%**	**0.20**	**700**	**0.011**	**0.297**	**0.087**	**0.299**
			900	**0**	**0.302**	**0.059**	**0.336**
	RH - 75%, BD - 25%	**0.20**	**700**	**0.009**	**0.312**	**0.104**	**0.279**
			900	**0**	**0.309**	**0.075**	**0.318**
Lv et al. [24]	Pine saw dust	0.19	700	0.092	0.215	0.206	0.428
			800	0.075	0.322	0.186	0.376
			900	0.062	0.392	0.194	0.334
Narvaez et al. [47]	Pine saw dust	0.30	700	0.040	0.046	0.153	0.124
			750	0.039	0.078	0.141	0.138
			820	0.032	0.100	0.131	0.165
Present Study (Saw dust rich mixtures)	**SD - 75%, RH - 25%**	**0.30**	**700**	**0.005**	**0.225**	**0.092**	**0.264**
			900	**0**	**0.219**	**0.070**	**0.294**
	SD - 75%, BD - 25%	**0.30**	**700**	**0.005**	**0.224**	**0.095**	**0.264**
			900	**0**	**0.218**	**0.073**	**0.293**

The quantitative discrepancies between experimental and simulations results are as follows:
(1) Jiang et al. [45] have reported very low H_2 content in product gas as compared to Narvaez et al. [47] and Lv et al. [24]. This could be a consequence of low (per pass) biomass conversion in the gasifier.

(2) The CH_4 content of gas in all studies is somewhat higher than our simulation. In our opinion, this is an indication of non–equilibrium conditions in the gasification system – in that not all methane formed in the initial pyrolysis stage of gasification is converted to equilibrium quantities of CO, CO_2 and H_2O prior to exit from gasifier.

Table 7. Comparison with experimental data on LHV of producer gas
(A) Effect of air (or equivalence) ratio

Reference	Biomass	Temp (^{o}C)	ER	LHV (MJ/Nm^3)
Mansaray et al. [51]	Rice Husk	750	0.25	4.38
			0.35	3.15
Narvaez et al. [47]	Pine Sawdust	800	0.32	6.28
			0.44	4.59
Maniatis et al. [52]	Woodwaste	800	0.23	6.42
			0.30	5.59
			0.40	4.48
Ergudenler and Ghaly [46]	Wheat Straw	800	0.25	1.61
			0.40	2.40
Lv et al. [24]	Pine Sawdust	800	0.19	8.82
			0.27	7.28
Gulyurtlu et al. [53]	Pine Wood	800	0.21	5.60
			0.35	3.80
Present Study (Saw dust rich mixtures)	**SD - 75%, RH - 25%**	**800**	**0.20**	**7.70**
			0.30	**6.01**
	SD - 75%, BD - 25%	**800**	**0.20**	**7.67**
			0.30	**5.99**

(B) Effect of gasification temperature

Reference	Biomass	ER	Temp (^{o}C)	LHV (MJ/Nm^3)
Narvaez et al. [47]	Pine Sawdust	0.30	700	4.00
			800	5.50
Lv et al. [24]	Pine Sawdust	0.22	700	7.95
			900	7.36
Maniatis et al. [48]	Pine Wood	0.32	700	5.83
			800	6.23
Present Study (Saw dust rich mixtures)	**SD - 75%, RH - 25%**	**0.20**	**700**	**7.09**
			800	**7.70**
			900	**7.72**
	SD - 75%, BD - 25%	**0.30**	**700**	**5.94**
			800	**5.99**
			900	**6.04**

5. Discussion

Simulations of gasification of biomass mixtures with equilibrium and semi–equilibrium models give us an insight into the technicalities of the process and the relative influence of different operational parameters. An immediate conclusion that one can draw from simulation results is that the quality and quantity of producer gas resulting from gasification of biomass mixtures has high potential for power generation through dual fuel or 100% producer gas engines. This potential can be quantified as follows: if a gasifier consumes 100 g of 50%–50% w/w mixture of rice husk and saw dust per second (corresponding to 360 kg/h of gross consumption of mixture) for air ratio of 0.3 and gasification temperature of 800^{o}C, the maximum thermal energy available (as seen from Table 3A) in the producer gas after attainment of total equilibrium in the gasification system is 1491 kJ/s or kWth. Typical efficiency of dual fuel engine–generator sets available in the market is ~ 30%. Thus, maximum electrical power generated with the producer gas is $1491 \times 0.3 = 450$ kW$_e$. Under practical situation, the conversion of biomass in gasifier is not complete. As inferred from Table 4, the net thermal energy in the producer gas for 60%, 70% and 80% conversion (as same biomass consumption rate of 100 g/s) is 647, 858 and 1069 kW$_{th}$.

Table 8. Comparison with experimental data on net producer gas yield: Effect of gasification temperature and air (or equivalence) ratio

Reference	Biomass	ER	Temp (°C)	Yield (Nm³/100 g biomass)
Narvaez et al. [47]	Pine Sawdust	0.28 0.44	800	0.25 0.29
Maniatis et al. [52]	Woodwaste	0.23 0.40	800	0.18 0.27
Ergudenler and Ghaly[46]	Wheat Straw	0.25 0.40	800	0.16 0.24
Mansaray et al. [51]	Rice Husk	0.25 0.35	750	0.15 0.19
Yin et al. (2002)	Rice Husk	0.25	800	0.22
Present Study (Rice husk rich mixtures)	**RH - 75%, SD - 25%**	**0.20** **0.30**	**800**	**0.21** **0.23**
	RH - 75%, BD - 25%	**0.30**	**700** **900**	**0.22** **0.21**
Lv et al. [24]	Pine Sawdust	0.21 0.27	800	0.23 0.19
		0.22	700 900	0.14 0.25
Present Study (Saw dust rich mixtures)	**SD - 75%, RH - 25%**	**0.20** **0.30**	**800**	**0.24** **0.27**
	SD - 75%, BD - 25%	**0.30**	**700** **900**	**0.27** **0.27**

Under presumption that efficiency of engine–generator system stays unchanged, the net power generation through this producer gas is 190, 255 and 320 kW$_e$. From these figures one can also calculate the specific biomass consumption for electricity generation. For example, for 50%–50% w/w mixture of rice husk and saw dust, the minimum possible specific fuel consumption (for total equilibrium conditions) is 360/450 = 0.8 kg/kW–h. This consumption varies inversely with carbon conversion. For 60%, 70% and 80% carbon conversion, the typical consumption of biomass mixture (not including the recycled unconverted biomass) is 360/190, 360/255 and 360/320, i.e. 1.89, 1.41 and 1.13 kg/kW–h, respectively.

The value of specific fuels consumption reported in literature are higher than the calculated values in the present study by ± 5–20%. For gasification of rice husk alone, Lv et al. [24] have reported carbon conversion in the range of 0.7 to 0.9, while Mansaray et al. [51] have reported slightly lower values of 0.6 to 0.8. Yin et al. [54] have reported specific fuel consumption of 1.7–1.9 kg/kWh for rice husk gasification for electricity generation capacity of 800 kW or higher. However, for low capacity (~ 200 kW), the specific fuel consumption is reported to be as high as 3.5 kg/kW–h. Values of specific fuel consumption reported by Mansaray et al. [51] are in the same range (1.91 kg/kW–h). It should be noted that in addition to overall carbon conversion in the gasifier, the specific fuel consumption also depends overall efficiencies of gasifier, duel fuel or 100% producer gas engine and the generator set. Typical values of these are 55%, 33% and 88% [55]. Kapur et al. [55] have given following formula for estimation of specific fuel consumption for electricity generation through rice husk gasification using duel fuel engine with generator set:

$$Q_h = \left[\frac{1/DF - \left(1 - RF\right)}{\eta_g \times CV_h \times \eta_d \times \eta_a} \right] \times 3.6 \tag{12}$$

where DF – derating factor; RF – diesel replacement factor; CV_h – calorific value of rice husk; η_d – efficiency of diesel engine; η_a – efficiency of the duel–fuel generator; η_g – efficiency of gasification. With representative values (as given by Kapur et al. [55]) of $DF = 0.75$, $RF = 0.7$, $CV_h = 13.4$ MJ/kg, $\eta_g = 0.55$, $\eta_d = 0.33$ and $\eta_a = 0.875$, Q_h is calculated as 1.74 kg/kW–h. Nouni et al. [1] have reported specific fuel consumption in the range 1.1 to 1.68 kg/kWh for fixed bed downdraft gasifier of capacity 20–40 kWe employing either dual fuel or producer gas engine, and plant load factor ranging between 50 to 75%. It should be noted that “economy of scale” is another dominant aspect determining specific fuel consumption, in addition to various factors mention above. For large scale gasifiers in the range of 30 MWe or higher, the specific fuel consumption (either demolition wood or clean wood) could be as low as 0.9 kg/kW–h [56].

Another important factor is the net enthalpy change of gasification process (or the energy released in gasification). Part of this energy is absorbed by the gasification system itself and part is carried out of the gasifier by the producer gas. The absorbed heat helps maintaining the temperature of the gasifier. Moreover, the heat in the producer gas can be recovered through various means such as preheating of gasification air or drying of the biomass feed.

It can be seen from Table 3(A) that thermal energy content of producer gas essentially stays constant after 800^{o}C. Therefore, at first impression it appears that operation of gasifier at higher temperatures (900 or 1000^{o}C) may not fetch additional advantage. However, for a fluidized bed system where residence time of biomass is limited, higher gasification temperature can enhance single–pass conversion of biomass. Air ratio, on the other hand, has high influence on the process. For all biomass mixtures, rise of air ratio from 0.2 to 0.4 has been found to reduce the thermal energy content of producer gas by 30–40%. This result points out that low air ratios favor better performance of gasifier, but one must also take into consideration incomplete conversion of carbon even under total equilibrium conditions for air ratio of 0.2. This effect is more pronounced for biomass mixtures containing saw dust, which has higher carbon content than rice husk or bamboo dust.

The power generation capacity of gasifier is higher for biomass mixtures containing saw dust. Among all 9 biomass mixtures, the least power generation is seen for biomass mixtures containing higher proportions of rice husk. This effect is clearly attributed to high ash content of rice husk.

6. Conclusion

This study as assessed the feasibility of use of biomass mixtures as fuel in biomass gasifiers for decentralized power generation equilibrium and semi–equilibrium (with limited carbon conversion) models employing Gibbs energy minimization. Binary mixtures of common biomasses found in northeastern states of India such as rice husk, bamboo dust and saw dust have been taken for analysis. The potential for power generation from gasifier has been evaluated on the basis of net yield (in Nm^3) and LHV (in MJ/Nm^3) of the producer gas obtained from gasification of 100 g of biomass mixture. The results of simulations have revealed interesting trends in performance of gasifiers with operating parameters such as air ratio, temperature of gasification and composition of the biomass mixture. For all biomass mixtures, the optimum air ratio is ~ 0.3 with gasification temperature of 800^{o}C. Under total equilibrium conditions, and for engine–generator efficiency of 30%, the least possible fuel consumption is found to be 0.8 kg/kW–h. This parameter shows an inverse variation with the extent of carbon conversion (or oxidation) achieved in the gasifier, which in turn depends on parameters such as air ratio, temperature of gasification and residence time of biomass in the gasifier. For low carbon conversions (~ 60% or so), the specific fuel consumption could be as high as 1.5 kg/kW–h. Comparative analysis of net yield (per unit biomass) and LHV of the product gas calculated in our simulations with experimental results published in previous literature confirms that performance of gasification process for decentralized electricity generation stays essentially same after replacement of single biomass (either saw dust or rice husk) by mixtures of these biomasses with bamboo dust in different proportions. This feature, obviously, adds to the flexibility of operations of gasifiers in different locations under different operating conditions.

On a whole, this paper has tried to get an insight into performance of gasifier employing biomass mixtures as fuel. The results of this study could form useful guidelines for design and optimization of medium to large scale biomass gasifiers employing biomass mixtures as feedstocks. Moreover, methodology presented in this paper can be easily extended for the analysis of gasification of mixtures of other biomasses than considered in this study.

Acknowledgments

Authors acknowledge financial support for this project by Department of Biotechnology (DBT), Govt. of India (project no.: BT/PR7071/PID/06/311/2006) and Ministry of New & Renewable Energy (MNRE), Govt. of India (project no. 19–22/2007–R&D/BE). Dr. V.S. Moholkar acknowledges valuable discussions with Dr. X. Li (University of British Columbia, Canada) regarding the equilibrium modeling of gasification. He also thanks University Library, Umea University (Sweden) for providing some important references for the SOLGASMIX model.

References

[1] Nouni M.R., Mullick S.C., Kandpal T.C. Biomass gasifier projects for decentralized power generation in India: a financial evaluation. Energ. Policy 2007, 35,373–1385.

[2] Nouni M.R., Mullick S.C., Kandpal T.C. Providing electricity access to remote areas in rural India: An approach towards identifying potential areas for decentralized power supply. Renew. Sust. Energ. Rev. 2008, 12, 1187–1220.

[3] Tripathi A.K. Renewable energy development in India, In: Multiple choice questions on renewable energy; New Delhi: TERI Press, 2008.

[4] Buragohain B., Mahanta P., Moholkar V.S. Biomass gasification for decentralized power generation: The Indian perspective. Renew. Sust. Energ. Rev. 2010, 14(1), 73–92.

[5] Ministry of New and Renewable Energy. 25 Years of Renewable Energy in India, New Delhi, 2007.

[6] McKendry P. Energy production from biomass (part 3): gasification technologies. Bioresour. Technol. 2002, 83, 55–63.

[7] Ghosh D., Sagar A., Kishore V.V.N. Scaling up biomass gasifier use: applications, barriers and interventions. Paper No. 103 (Climate Change Series), World Bank Environment Department, Washington, 2004.

[8] Bharadwaj A. Gasification and combustion technologies of agro–residues and their application to rural electric power systems in India. Ph.D. Dissertation, Carnegie Mellon University (Pittsburgh, USA), 2002.

[9] Biomass Atlas of India, Combustion Gasification and Propulsion Laboratory, Bangalore: Indian Institute of Science. Homepage: http://cgpl.iisc.ernet.in (accessed November 2009).

[10] Gumz W. Gas producers and blast furnaces: Theory and methods of calculations. Wiley, 1950.

[11] Desrosiers R. Thermodynamics of gas-char reactions. In: Biomass gasification – Principles and technology (Ed. Reed T.B.), Noyes Data Corporation, 1981.

[12] Buragohain B., Mahanta P., Moholkar V.S. Thermodynamic optimization of biomass gasification for decentralized power generation and Fischer–Tropsch synthesis. Energy 2010, 35 , 2557-2579.

[13] Channiwala S.A., Parikh P.P. A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel 2002, 81, 1051–1063.

[14] Friedl A., Padouvas E., Rotter H., Varmuza K. Prediction of heating values of biomass fuel from elemental composition. Anal. Chim. Acta 2005, 544,191-198.

[15] Sheng C., Azevedo J.L.T. Estimating higher heating value of biomass fuels from basic analysis data. Biomass Bioenerg. 2005, 28, 499-507.

[16] Jiang H.–M., Morey R.V. Pyrolysis of corncobs at fluidization. Biomass Bioenerg. 1992, 3(2), 81–85.

[17] Raveendran K., Ganesh A., Khilar K.C. Pyrolysis characteristics of biomass and biomass components. Fuel 1996, 75(8), 987–998.

[18] Janse A.M.C., de Jonge H.G., Prins W., van Swaaij W.P.M. Combustion kinetics of char obtained by flash pyrolysis of pine wood. Ind. Eng. Chem. Res. 1998, 37(10), 3909–3918.

[19] Di Blasi C., Signorelli G., Di Russo C., Rea G. Product distribution from pyrolysis of wood and agricultural residues. Ind. Eng. Chem. Res. 1999, 38, 2216–2224.

[20] Corella J., Sanz A. Modeling circulating fluidized bed biomass gasifiers: A pseudo–rigorous model with stationary state. Fuel Process. Technol. 2005, 86,1021–1053.

[21] Li X., Grace J.R., Watkinson A.P., Lim C.J., Ergudenler A. Equilibrium modeling of gasification: a free energy minimization approach and its application to a circulating fluidized bed coal gasifier. Fuel 2001, 80, 195–207.

[22] Li X. Biomass gasification in circulating fluidized bed, Ph.D. Dissertation, University of British Columbia (Vancouver, Canada), 2002.

[23] Kersten S.R.A. Biomass gasification in circulating fluidized beds. Ph.D. Dissertation, Twente University Press (Enschede, Netherlands), 2002.

[24] Lv P.M., Xiong Z.H., Chang J., Wu C.Z., Chen Y., Zhu J.X. An experimental study on biomass air–steam gasification in a fluidized bed. Bioresour. Technol. 2004, 95, 95–101.

[25] de Souza–Santos M.L. Solid fuels combustion and gasification: Modeling, simulation and equipment operation. Marcel Dekker Inc., 2004.

[26] Baron R.E., Porter S.H., Hammond O.H. Chemical equilibria in carbon-hydrogen-oxygen systems. MIT Press (Cambridge, USA), 1976.

[27] Reynolds W.C. The element potential method for chemical equilibrium analysis: Implementation in the interactive program STANJAN. Technical Report, Stanford University, Stanford, 1986.

[28] Smith W.R., Missen R.W. Chemical reaction equilibrium analysis: Theory and algorithms. John Wiley & Sons, 1982.

[29] Kovacik G., Oguztoreli M., Chambers A., Ozum B. Equilibrium calculations in coal gasification. Int. J. Hydrogen Energy 1990, 15(2), 125–131.

[30] Shesh K.K., Sunawala P.D. Thermodynamics of pressurized air–steam gasification of biomass. Indian J. Technol. 1990, 28(4), 133–138.

[31] Kinoshita C.M., Wang Y., Takahashi P.K. Chemical equilibrium computations for gasification of biomass to produce methanol. Energ. Source. 1991, 13(3), 361–368.

[32] Watkinson A.P., Lucas J.P., Lim C.J. A prediction of performance of commercial coal gasifiers. Fuel 1991, 70 , 519–527.

[33] Garcia E.Y., Laborde M.A. Hydrogen production by steam reforming of ethanol: thermodynamic analysis. Int. J. Hydrogen Energ. 1991, 16(5), 307–312.

[34] Alderucci V. Thermodynamic analysis of SOFC fueled by biomass derived gas. Int. J. Hydrogen Energ. 1994, 19(4), 369–376.

[35] Ruggiero M., Manfrida G. An equilibrium model for biomass gasification process. Renew. Energ. 1999, 16,106–1109.

[36] Zainal Z.A., Ali R., Dean C.H., Seetharamu K. Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. Energ. Conserv. Manage. 2001, 42, 1499-1515.

[37] Altafini C.R., Wander P.R., Barreto R.M. Prediction of working parameters of a wood waste gasifier through an equilibrium model. Energ. Conserv. Manage. 2003, 44, 2763-2777.

[38] Melgar A., Perez J.F., Laget H., Horillo A. Thermochemical equilibrium modeling of a gasifying process. Energ. Conserv. Manage. 2007, 48, 59-67.

[39] Mahishi M.R., Goswami D.Y. Thermodynamic optimization of a biomass gasifier for hydrogen production. Int. J. Hydrogen Energ. 2007, 32 (16), 3831-3840.

[40] FactWeb. Homepage: http://www.factsage.com (accessed November 2009).

[41] Bale C.W., Chartrand P., Degterov S.A., Eriksson G., Hack K., Mahfoud K., Melancon J., Pelton A.D., Petersen S. FACTSAGE thermochemical software and databases. Calphad 2002, 26 (2), 189–228.

[42] Eriksson G. Thermodynamic studies of high temperature equilibria – XII: SOLGAMIX, A computer program for calculation of equilibrium composition in multiphase systems. Chem. Scr. 1975, 8, 100–103.

[43] Schuster G., Loffler G., Weigl K., Hofbauer H. Biomass steam gasification – an extensive parametric modeling study. Bioresour. Technol. 2001, 77, 71–79.

[44] Jayah T.H., Aye L., Fuller R.J., Stewart D.F. Computer simulation of a downdraft wood gasifier for tea drying. Biomass Bioenerg. 2003, 25, 456–469.

[45] Jiang H., Zhu X., Guo Q., Zhu Q. Gasification of rice husk in a fluidized bed gasifier without inert additives. Ind. Eng. Chem. Res. 2003, 42, 5745–5750.

[46] Ergudenler E., Ghaly A.E. Quality of gas produced from wheat straw in a dual distributor type fluidized bed gasifier. Biomass Bioenerg. 1992, 3, 419–430.

[47] Narvaez I., Orio A., Aznar M.P., Corella J. Biomass gasification with air in an atmospheric bubbling fluidized bed. Effect of six operational variables on the quality of the produced raw gas. Ind. Eng. Chem. Res. 1996, 35, 2110–2120.

[48] Maniatis K., Bridgwater A.V., Buekens A. Fluidized bed gasification of wood. In: Research in Thermochemical Biomass Conversion (Ed. Bridgwater A.V., Kuester J.L.), pp. 1094–1105, Elsevier Applied Science, 1988.

[49] van der Aarsen F.G., Beenackers A.A.C.M., van Swaaij W.P.M. Thermochemical gasification in a pilot plant fluidized bed wood gasifier. Commun. Eur. Communities 1983, 8245, 425–429.

[50] Jiang H., Morey R.V. Air gasification of corncobs at fluidization. Biomass Bioenerg. 1992, 3, 87–92.

[51] Mansaray K.G., Ghaly A.E., Al–Taweel A.M., Hamdullahpur F., Ugursal V.I. Air gasification of rice husk in a dual distributor type fluidized bed reactor. Biomass Bioenerg. 1999, 17, 315–332.

[52] Maniatis K., Vassilatos V., Kyritsis S. Design of pilot plant fluidized bed gasifier. In: Advances in thermo-chemical biomass conversion Vol. 1 (Ed. Bridgwater A.V.), pp. 403–410, Blakie Academic and Professional, 1994.
[53] Gulyurtlu I., Franco C., Mascarenhas F., Cabrita I. Steam gasification versus fast pyrolysis to produce medium calorific value gaseous fuel. In: Advances in thermo-chemical biomass conversion Vol. 1 (Ed. Bridgwater A.V.), pp. 1187–1196, Blakie Academic and Professional, 1994.
[54] Yin X.L., Wu C.Z., Zheng S.P., Chen Y. Design and operation of a CFB gasification and power generation system for rice husk. Biomass Bioenerg. 2002, 23, 181–187.
[55] Kapur T., Kandpal T.C., Garg H.P. Electricity generation from rice husk in Indian rice mills: Potential and financial viability. Biomass Bioenerg. 1998, 14, 573–583.
[56] Faaij A., van Ree R., Waldheim L., Olsson E., Oudhuis A., van Wijk A., Daey–Ouwens C., Turkenburg W. Gasification of biomass wastes and residues for electricity production. Biomass Bioenerg. 1997, 12, 387–407.

Buljit Buragohain (b. 1978) is a research scholar at the Center for Energy in Indian Institute of Technology Guwahati. He obtained his B.E. (Mechanical Engineering, 2000) and M.Tech. (Energy Technology, 2002) degrees from Dibrugarh University and Tezpur University respectively. Thereafter, he worked as Project Engineer at Indian Institute of Technology Guwahati in Biogas Project sponsored by Ministry of New and Renewable Energy, Government of India. Since July 2005 he has been pursuing his Ph.D. degree in the field of Thermodynamic Optimization of Biomass Gasification process.
E–mail address: buljit@iitg.ernet.in; buljit@gmail.com

P. Mahanta (b. 1963) is working as Professor of Mechanical Engineering at Indian Institute of Technology Guwahati, India. He obtained B.Sc.(Engg) and M.Tech. degrees from REC Rourkela and I.I.T. Kharagpur in 1985 and 1993 respectively. Between 1986-2001, he worked as Assistant Executive Engineer of Government of Assam. After obtaining Ph.D. from I.I.T. Guwahati in 2000, he joined in the mechanical engineering department of I.I.T. Guwahati as a faculty member. Since 2004, he has been the Head of Center for Energy at I.I.T. Guwahati. His major research interests are in the area of Heat Transfer, Renewable Energy, Thermodynamics and Waste Heat Recovery.
E–mail address: pinak@iitg.ernet.in

V.S. Moholkar (b. 1972) is currently working as Associate Professor of Chemical Engineering at Indian Institute of Technology Guwahati, India. He obtained his B.Chem.Engg. and M.Chem.Engg. degrees from Institute of Chemical Technology, Mumbai in 1993 and 1996 respectively. After obtaining the Ph.D. degree in June 2002 from University of Twente, Netherlands, he worked as Assistant Professor in Chemical Engineering in BITS, Pilani for 2 years. He joined I.I.T. Guwahati in May 2004. He is affiliated to Center for Energy at I.I.T. Guwahati and has been working on thermochemical and biochemical conversion of biomass to liquid and gaseous biofuels. His major research areas in the field of biofuels are Biomass Gasification, Biodiesel synthesis, Biobutanol synthesis, Synthesis of green transportation fuels by Fischer-Tropsch route.
E–mail address: vmoholkar@iitg.ernet.in