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# Thermodynamic analysis of hydrogen rich synthetic gas generation from fluidized bed gasification of rice husk

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ABSTRACT

In the present work, the generation of hydrogen rich synthetic gas from fluidized bed steam gasification of rice husk has been studied. An equilibrium model based on equilibrium constant and material balance has been developed to predict the gas compositions. The equilibrium gas compositions are compared with the experimental data of the present group as well as of available literature. The energy and exergy analysis of the process have been carried out by varying steam to biomass ratio ($\psi$) within the range between 0.1–1.5 and gasification temperature from 600 °C to 900 °C. It is observed that both the energy and exergy efficiencies are maximum at the CBP (carbon boundary point) though the hydrogen production increases beyond the CBP. The HHV (higher heating value) and the external energy input both continuously increase with $\psi$. However, the hydrogen production initially increases with increase in temperature up to 800 °C and then becomes nearly asymptotic. The HHV decreases rapidly with increase in temperature and energy input increases. Therefore, gasification in lower temperature region is observed to be economical in terms of a trade off between external energy input and HHV of the product gas.



## 1. Introduction

The conservation of limited supply of fossil fuel, climate change and the increasing concern over global warming have prompted a search for new and cleaner methods of power generation particularly from renewable energy sources. Amongst the different sources of renewable energies, the most promising future energy source is biomass [1]. India has substantial biomass resources in the form of agricultural residues, which are currently used for domestic energy and fuel applications mostly through combustion. This is often, however, inefficient as well as contributing to local pollution from inadequately controlled gaseous emissions. Therefore, the gasification of biomass is possibly a more efficient way of biomass utilization. Biomass gasification is the thermo chemical conversion of solid biomass into the fuel gas which contains mainly hydrogen, carbon monoxide, carbon dioxide, methane and nitrogen. The product gas from the reactor also contains some contaminants like char particle, ash and some higher hydrocarbons or tar. A limited supply of oxygen, air, steam or a combination of these serves as gasifying agent. Biomass gasification by using air produces a gas with a lower Calorific Value (4–7 MJ/Nm$^3$), whereas gasification with steam and oxygen produces the gas having medium to higher Calorific Values (10–18 MJ/Nm$^3$) [2]. The gasification with oxygen is not popular due to the fact that it involves large investment for production of oxygen. The gasification with air dilutes the gas due to the presence of $N_2$ in the air. In recent years, the steam gasification of biomass has become an area of growing interest because it produces gaseous product having higher $H_2$ content. Besides, the steam gasification process has the following additional advantages: it is capable of maximizing the gas product with higher heating rate involved, advantageous residence time characteristics, and the efficient tar and char reduction brought about by steam reforming.

In biomass gasification, fluidized bed technology is widely used due to its various advantages which include high heat transfer, uniform and controllable temperature, favorable gas-solid contacting etc [3]. Mansaray et al. [4] have studied the air gasification of rice husk in a dual distributor type fluidized bed system. The effect of varying fluidizing velocity (0.22–0.33 m/s) and equivalence ratio (0.25–0.35) on the gasifier performance were discussed. Miccio et al. [5] studied the biomass gasification in fluidized bed and achieved a maximum C (carbon) post conversion of 70%. The gasification performance of sawdust in fluidized bed reactor was

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**Nomenclature**

| | |
|---|---|
| CBP | carbon boundary point |
| $C_p$ | specific heat at constant pressure, kJ/kmol K |
| daf | dry ash free |
| $E$ | exergy, kJ |
| $\Delta G_T^o$ | standard gibbs function of reaction |
| $\Delta g_{f,T,i}^o$ | standard gibbs function of formation, kJ/kmol |
| $H$ | enthalpy, kJ |
| $H_c$ | heat of combustion, kJ/kmol |
| $I$ | Irreversibility, kJ |
| $h_f^o$ | heat of formation, kJ/kmol |
| HHV | higher heating value |
| K | equilibrium constant |
| $m$ | mole of input steam |
| $n$ | mole of product gases |
| $P$ | partial pressure |
| $Q_{IN}$ | energy input as electricity which is converted to heat, kJ |
| $\overline{R}$ | universal gas constant, kJ/kmol K |
| $T$, $T_0$ | gasification and ambient temperature, K |
| $W_{IN}$ | exergy input, which is basically work input as electricity, kJ |
| $x$ | mole fraction |

*Greek letters*

| | |
|---|---|
| $\psi$ | steam-to-biomass ratio |
| $\gamma$ | stoichiometric number |
| $\varepsilon_{chem}$ | standard chemical exergy |
| $\eta_I$ | first law (energy) efficiency |
| $\eta_{II}$ | second law (exergy) efficiency |
| $\Delta$ | difference |

studied by many authors [6–8]. The effects of gasification temperature, equivalence ratio, O/C ratio and steam-to-biomass ratio were studied on the product gas composition and heating value. The hydrogen yield potential was found to be the most sensitive with equivalence ratio by Turn et al. [6], whereas the temperature was reported to be the most important factor by Lv et al. [7], over the range of experimental condition studied. It was also observed by Li et al. [8] that the gas composition and heating value depend heavily on the O/C ratio. The air gasification of wood chips was also carried out by Lim et al. [9] in a bubbling fluidized bed gasifier and the performance was studied in terms of thermal output. They showed that the gas produced has an energy content of 4.75 MJ/m$^3$ at a bed temperature of 733 °C and equivalence ratio of 0.23. The resulting thermal efficiency was 61.32% with a thermal output of 355.55 kW$_{th}$.

Fluidized bed steam gasification was studied by Rapagna et al. [10,11] and naturally occurring catalytic substances were employed to enhance the yield of fuel gas and reduce its tar content. The reactions influencing the biomass steam gasification process were studied in an atmospheric fluidized bed gasifier by Franco et al. [12]. The effects of gasification temperature and steam/biomass ratio were investigated on the gas composition and HHV (higher heating value). Recently, fluidized bed gasification process with pure steam to produce hydrogen rich gas has been reviewed by Corella et al. [13]. It is reported that the biomass gasification with pure steam can generates 60 vol% (dry basis) hydrogen rich gases with tar content as low as 0.25 g/Nm$^3$.The present group of authors [14] have also studied the fluidized bed steam gasification of biomass experimentally and developed a correlation to predict the hydrogen yield.

The assessment of the gasification process by analyzing the first law (energy) efficiency and the second law (exergy) efficiency is an effective method for design and analysis of the process. A lot of works on energy and exergy analysis of biomass gasification in fixed bed reactor based on equilibrium modeling have been reported in the literature. Some authors have also used the equilibrium model to describe the biomass gasification in fluidized bed reactor. Equilibrium model provides a useful design aid in evaluating the possible limiting behavior of a complex reacting system that is difficult or unsafe to produce experimentally or in commercial operation [15,16] and also it is computationally inexpensive. Pellegrini et al. [17] used chemical equilibrium model to present the exergetic and energetic behavior of air gasification of sugarcane bagasse where a parametric study has been carried out to investigate the influence of many variables such as: gasification temperature, air temperature and moisture content. The equilibrium model was also developed by Jarungthammachote et al. [18] to calculate the product gas composition and second law analysis has been done for gasification of municipal solid waste in a downdraft waste gasifier. Prins et al. [19,20] have focused their study on the energy and exergy analysis of biomass gasification by using chemical equilibrium model. Their Study showed that the CBP (Carbon Boundary Point) was the optimum point of operation with respect to exergy-based-efficiency for both gasification with air and steam. The term CBP implies the situation where exactly enough gasifying agent is added to obtain complete carbon conversion. Ptasinski et al. [21] showed that the exergetic efficiency of gasification also depends on the chemical composition of biofuel used as feedstock. They showed that the exergetic efficiencies of vegetable oil, straw, treated wood, untreated wood and grass were comparable with coal, whereas the efficiencies of sludge and manure were considerably lower. The efficiency of biomass gasification was also analyzed by Ptasinski [22] by using triangular C–H–O diagram, considering a biomass fuel represented as $CH_{1.4}O_{0.59}N_{0.0017}$. It was observed that at the equivalence ratio of 0.26, the chemical and the total exergy of the gas reached maximum at CBP for an air-blown gasifier. The Exergy analysis for biomass-to-SNG (synthetic natural gas) conversion was presented by Jurascik et al. [23]. The analysis was made for a temperature range from 650 °C to 800 °C and the pressure range from 1 to 15 bar. The results showed that the largest exergy losses take place in the biomass gasifier, $CH_4$ synthesis part and $CO_2$ capture unit. The exergy analysis of hydrogen production from sawdust wood was analyzed by Abuadala et al. [24,25]. The analysis has been done by developing an equilibrium model. The results indicated that the hydrogen production from biomass steam gasification depends on the operating temperature, amount of steam added and the quality of the biomass. Kalinci et al. [26] studied the thermodynamic performance of an integrated gasifier-boiler power system with six different biomass fuels and showed that the exergy contents of different biomass fuels varied from 15.89 to 22.07 MJ/kg, respectively. A chemical equilibrium model has also been developed by Karamarkovic et al. [27] to study the air gasification of biomass in different gasification temperature by analyzing the energy and exergy associated with the process. It was reported that the gasification process at a given gasification temperature can be improved by the use of dry biomass and by the carbon-boundary temperature approaching the required temperature. A non-stoichiometric equilibrium model based on free energy minimization was developed by Li et al. [28]. It was showed that the gas composition and heating value vary primarily with temperature and the relative abundance of key elements,