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First and second law thermodynamic analysis of air and oxy-steam biomass gasification



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ABSTRACT

Gasification is an energy transformation process in which solid fuel undergoes thermochemical conversion to produce gaseous fuel, and the two most important criteria involved in such process to evaluate the performance, economics and sustainability of the technology are: the total available energy (exergy) and the energy conserved (energy efficiency). Current study focuses on the energy and exergy analysis of the oxy-steam gasification and comparing with air gasification to optimize the H₂ yield, efficiency and syngas energy density.

Casuarina wood is used as a fuel, and mixture of oxygen and steam in different proportion and amount is used as a gasifying media. The results are analysed with respect to varying equivalence ratio and steam to biomass ratio (SBR). Elemental mass balance technique is employed to ensure the validity of results. First and second law thermodynamic analysis is used towards time evaluation of energy and exergy analysis. Different component of energy input and output has been studied carefully to understand the influence of varying SBR on the availability of energy and irreversibility in the system to minimize the losses with change in input parameters for optimum performance. The energy and exergy losses (irreversibility) for oxy-steam gasification system are compared with the results of air gasification, and losses are found to be lower in oxy-steam thermal conversion; which has been argued and reasoned due to the presence of N₂ in the air-gasification. The maximum exergy efficiency of 85% with energy efficiency of 82% is achieved at SBR of 0.75 on the molar basis. It has been observed that increase in SBR results in lower exergy and energy efficiency, and it is argued to be due to the high energy input in steam generation and subsequent losses in the form of physical exergy of steam in the product gas, which alone accounts for over 18% in exergy input and 8.5% in exergy of product gas at SBR of 2.7. Carbon boundary point (CBP), is identified at the SBR of 1.5, and water gas shift (WGS) reaction plays a crucial role in H₂ enrichment after carbon boundary point (CBP) is reached. Effects of SBR and CBP on the H₂/CO ratio is analysed and discussed from the perspective of energy as well as the reaction chemistry. Energy density of syngas and energy efficiency is favoured at lower SBR but higher SBR favours H₂ rich gas at the expense of efficiency.

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Nomenclature	
$E_{O_2_SEPARATION}$	energy spent for O_2 separation from air, kJ/kg
Ex_{in}	total exergy input during gasification, kJ/kmole
$E_{AUXILIARY_UNIT}$	energy spent on the auxillary units of gasifier. eg. water pump, water chiller, kJ/kg
Ex_{steam}	exergy spent on steam generation and superheating, kJ/kmole
Q_{STEAM}	energy spent on steam generation and superheating, kJ/kg
Ex_{char}	exergy of char, kJ/kmole
η_{en}	energy efficiency of gasifier, %
e_{DB}^{CH}	chemical exergy of dry biomass, kJ/kg
Ex	exergy, kJ/mole
x_i	mole fraction of ith specie
Ex_{ph}	physical exergy, kJ/kmole
s	entropy, kJ/(kmole K)
Ex_{ch}	chemical exergy, kJ/kmole
s_0	entropy at SRS, kJ/(kmole K)
h_i	enthalpy of ith specie, kJ/mole
$s_{i,0}$	entropy of the ith specie at SRS, kJ/(kmole K)
$h_{i,0}$	enthalpy of ith specie at SRS, kJ/kmole
I	irreversibility
R	universal gas constant, 8.314 kJ/(kmole K)
Abbreviation	
T_0	temperature at SRS, K
CBP	carbon boundary point
$\epsilon_{i,0}$	standard chemical exergy of ith specie at SRS, kJ/kmole
LHV	lower heating value
Ex_{gas}	exergy of hot syngas, kJ/kmole
ER	equivalence ratio
$Ex_{H_2O_gas}$	exergy of H_2O in hot syngas, kJ/kmole
SBR	steam to biomass ratio (on mole basis)
Ex_{O_2}	exergy spent in O_2 separation from air, kJ/kmole
SRS	standard reference state
Ex_{ch_mix}	component of exergy lost in, kJ/kmole gas due to mixture
SMFR	superficial mass flux rate, kg/(m ² s)

Introduction

With the growing demand for renewable fuel to substitute the fossil fuel, biomass gasification is emerging as an important technology to fill the gap [1]. Conversion of solid fuel to gaseous fuel helps in providing alternate fuel for many like IC engines, gas turbines, fuel cells etc. Apart from energy plantation; agro residue, municipal waste and organic industrial waste provides sustainable ways to extract energy from waste. Sadhan and Dasappa [2] have researched on one of the challenging issues of electrification in rural areas away from the power grid network. Based on the life cycle cost analysis, their study examined the economic feasibility of

decentralized off-grid renewable energy systems. Using 10 to 120 KW open top downdraft gasification system for study, they have found biomass gasification as a promising solution for rural electrification which is more cost effective than solar photovoltaic system and even grid extension [2]. Apart from the demand and usefulness, energy efficiency is one of the most important criteria to assess the performance and techno-economic viability of any technology.

In the gasification process, the first law of thermodynamics preserves the total energy of the system in converting solid to gaseous fuel in gasification is governed by the first law of thermodynamics, while the second law restricts the availability of energy (exergy) transformation of energy into useful form. In the case of gasification process, evolution of gaseous species increases the entropy and introduces irreversibility in the overall thermo-chemical conversion process. During the course of conversion, apart from the process irreversibility, the transformation of chemical energy in the solid fuel partly to thermal energy as sensible heat cannot be converted to desired output i.e., chemical enthalpy in the gaseous species. Evaluating the energy efficiency based on the energy output to the energy input and identifying the energy loss from the system to the environment is appropriate while considering the device. This approach may not be sufficient while evaluating the process and the device together as a system. Identifying the internal losses arising due to the irreversibility is important towards understanding any energy conversion process and probably helps in redesigning the system elements. Exergy analysis thus helps in evaluating the conversion process and provides an insight towards optimizing, by minimizing the losses, if any.

Peters et al. [3] have analysed the exergy efficiency of a fast pyrolysis bio-oil production plant using Aspen Plus software. Based on the analysis they have found the exergy efficiency is 71.2% and have also identified the components for the exergy losses. The areas that had been identified for improvement were biomass drier, milling process for size reduction and heat exchanger used for pre-heating the combustion air.

In the area of biomass gasification, researchers have performed exergy analysis based on equilibrium analysis [4–9]. Abuadala et al. [4] reports thermodynamic studies employing Engineering Equation Solver (EES) software. With the focus on H_2 production, from a gasifier reactor of 0.08 m diameter and 0.5 m height using sawdust as the fuel, exergy and energy efficiencies were estimated. The heat loss from the reactor was modelled assuming isothermal condition. Tar, generally an issue for gasification process and its utilization [10–14], was considered as a useful product (fuel) and modelled as benzene molecule in the system. Effects of varying the SBR (Steam to Biomass ratio) from 0.2 to 0.6 were studied, by varying steam flow rate from 4.5 kg/s to 6.3 kg/s and biomass feed rate from 10 kg/s to 32 kg/s. In the analysis, temperature was varied between 1000 and 1500 K and its influence on the H_2 yield, exergy and energy efficiency was also studied. The maximum exergy efficiency reported is about 65% with minimum near SBR of 0.4, and the authors have shown maximum specific entropy generation is between 0.37 and 0.42. The lower value of the exergy efficiency has been argued due to the increase in internal irreversibility with the varying SBR. Abuadala et al. [4] have also argued the saturation of H_2 yield

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