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ENERGETIC AND EXERGETIC EFFICIENCIES OF BIOMASS GASIFICATION PROCESSES

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ABSTRACT

A promising way to use biomass for the production of heat, electricity and other biofuels is through biomass gasification. In the gasification process, the chemical energy of the solid fuel is converted into the chemical and thermal energy of the gas produced. The paper presents the energy and exergy analysis results concerning a biomass gasification process. The use of exergy efficiency gives a clear picture of the quality of energy conversion of biomass into product gas. Energetic efficiency values are higher than the values obtained by the exergetic efficiency analysis.

KEYWORDS: biomass, energy, exergy, efficiency, gasification

1. Introduction

Because of the continuous rise of the cost of fossil energy resources, biomass looks as one of the most promising and viable alternatives, being classified as the third energy source after coal and oil. It is renewable and neutral concerning carbon dioxide emission issue. Biomass resources include wood and wood waste, agricultural crops and their waste by-products, municipal solid waste, residues from agro-industrial and food processes, aquatic plants such as algae and water weeds [1].

A promising way to use biomass for production of heat, electricity and other biofuels is through biomass gasification. In the gasification process, the chemical energy of the solid fuel is converted into the chemical and thermal energy of the gas produced [2]. Gasification is partial thermal oxidation which results in a high proportion of gaseous products (CO_2, water, CO, hydrogen and gaseous hydrocarbons), solid products (small quantities of char), ash and condensable compounds (tars and oils). The gas produced is easier and more versatile to use than the original biomass. The oxidant or gasifying agents can be air, pure O_2, steam, CO_2 or their mixtures. Air is a cheap and widely used gasifying agent. This oxidant contains a large amount of nitrogen which lowers the heating value of the gas produced.

The heating value of the gas produced will increase if pure O_2 is used as the gasifying agent, but the operating costs will also increase due to O_2 production costs. If steam is used as the gasifying agent, the heating value and H_2 content of the gas produced can be increased. The use of CO_2 as the gasifying agent is promising because of its presence in the gas produced. CO_2 with a catalyst can transform char, tar and CH_4 into H_2 and CO, thus increasing H_2 and CO contents. A mixture of steam or CO_2 and air or O_2 can be used as the gasifying agent, and the partial combustion of biomass with air /O_2 provides the heat required for gasification [3]. The choice between gasifying agents depends more on the required gas compositions. For steam gasification, the gas produced contains mainly methane and carbon dioxide and for air gasification the main product gases are hydrogen, carbon monoxide and nitrogen.

The gasification process consists of the following steps: pre-heating, drying, pyrolysis, char gasification, char-oxidation and ash formation. Different gasifiers are employed in the gasification process: fixed bed, moveable bed and fluidized bed.

The objective of this paper is to determine the energetic and exergetic efficiencies of the biomass gasification process. To provide an efficient and effective use of fuels, it is essential to consider the quality and quantity of the energy used to achieve a given objective. According to the first law of thermodynamics, energy can never be lost. Energy conversion processes do not have energy losses, except for losses from the process system into the environment. The second law of thermodynamics should also be considered. Energy conversion processes are accompanied by an irreversible increase in entropy, which leads to a decrease in exergy (available energy). Thus, even though the energy is conserved, the quality of energy decreases because energy is converted into a different form of energy from which less work can be obtained [4].

Exergy is the expression for loss of available energy due to the creation of entropy in irreversible systems or processes. The exergy loss in a system or component is determined by multiplying the absolute temperature of the surroundings by the entropy increase. While energy is conserved, exergy is accumulated. The use of exergy efficiency gives a clear picture of the quality of energy conversion of biomass into product gas. The following results depending on the moisture content in the biomass and gasification temperature are presented: compositions, higher heating values, physical and chemical exergies of the product gas, and energy and exergy based efficiencies [2]. The fuels were characterised by means of the higher heating value (HHV), elemental analyses and energy density (Table 1).

The higher heating value, in [MJ/kg], was calculated by the following equation:

$$\mathrm{HHV} = 0.3491\mathrm{C}^{db} + 1.1783\mathrm{H}^{db} + 0.1005\mathrm{S}^{db} - 0.1034\mathrm{O}^{db} - 0.0151\mathrm{N}^{db} - 0.0211\mathrm{A}^{db}\ [\mathrm{MJ/kg}] \quad (1)$$

where C^{db}, H^{db}, O^{db}, N^{db}, S^{db} and A^{db} represent carbon, hydrogen, oxygen, nitrogen, sulphur and ash contents expressed in mass percentages on dry basis.

Table 1. *Fuel properties*

Fuel sample	Ultimate analysis (wt% of wet fuel with ash)							Higher heating value, HHV	Energy density
	C	H	N	S	O	Moisture	Ash	[kJ/kg]	[GJ/Nm^3]
Acacia wood log	49.6	6.0	0.9	0.1	33.8	5.4	4.2	20793.11	14.97
Sawdust	50.0	5.9	1.8	0.0	33.6	6.0	2.6	20845.66	15.78

2. Energy and exergy calculations

The energy distribution of the biomass conversion process can be obtained from the energy balance [5]:

$$\sum_{IN} H_j = \sum_{OUT} H_k + Q_{losses} \quad (2)$$

where $\sum_{IN} H_j$ and $\sum_{OUT} H_k$ are enthalpy flow of all entering and leaving material streams, respectively, and Q_{losses} is the energy lost during the gasification process.

$$\sum_{IN} H_j = H_{air} + H_{dry\ biomass} + H_{biomass\ moisture} + H_{steam} \quad (3)$$

$$\sum_{OUT} H_k = H_{produced\ gas,dry} + H_{unconverted\ carbon} + H_{steam} \quad (4)$$

$$Q_{losses} = f \cdot \left(\sum_{IN} H_j \right) \quad (5)$$

This energy balance is responsible for the determination of the temperature of the system for a given air-to-fuel ratio, or the other way around.

The exergy balance of the biomass conversion process can be represented in the following form:

$$\sum_{IN} E_j = \sum_{OUT} E_k + I \quad (6)$$

where $\sum_{IN} E_j$ and $\sum_{OUT} E_k$ are exergy flows of all entering and leaving material streams, respectively.

$$\sum_{IN} E_j = E_{air} + E_{dry\ biomass} + E_{biomass\ moisture} + E_{steam} \quad (7)$$

$$\sum_{OUT} E_k = E_{produced\ gas,dry} + E_{unconverted\ carbon} + E_{steam} \quad (8)$$

The difference between all entering exergy streams and that of leaving streams is called irreversibility (I), and it is given by the following equation [6]:

$$I = T_0 S_{gen} \quad (9)$$

where S_{gen} is the rate of entropy generation.

The reference state was taken as t_0 = 25°C and p_0 = 0,1013MPa.

For the exergy flow the amounts of chemical exergy and physical exergy are considered:

$$E = E_{ch} + E_{ph} \quad (10)$$

The standard specific chemical exergy of a pure chemical compound ε_{ch} is equal to the maximum amount of work obtainable when a compound is brought from the environmental state, characterized by the environmental temperature T_0 and environmental pressure p_0, to the dead state, characterized by the same environmental conditions of temperature and pressure, but also by the concentration of reference substances in standard environment. The specific chemical exergy of the mixture is determined by:

$$\varepsilon_{ch.M} = \sum_i x_i \varepsilon_{ch,i} + RT_0 \sum_i x_i \ln x_i \qquad (11)$$

The specific physical exergy can be calculated as:

$$\varepsilon_{ph} = (h - h_0) - T_0(s - s_0) \qquad (12)$$

where h and s are enthalpy and entropy of a system at given temperature and pressure, and h_0 and s_0 are enthalpy and entropy of a system at the environmental temperature and pressure.

$$(h - h_0) = \int_{T_0}^{T} c_p dT \qquad (13)$$

$$(s - s_0) = \int_{T_0}^{T} \frac{c_p}{T} dT - \int_{p_0}^{p} \frac{R}{p} dp \qquad (14)$$

3. Energy and exergy efficiencies

The energetic efficiency of a gasification process can be determined as:

$$\eta = \frac{LHV_{gas}}{LHV_{biomass}} \qquad (15)$$

where LHV_{gas} and $LHV_{biomass}$ are the net heats of combustion (lower heating values) of gas and biomass, respectively.

The exergetic efficiency of a gasification process is the ratio between the chemical exergy of the gas produced and the biomass feed:

$$\psi = \frac{\varepsilon_{ch,gas} + \varepsilon_{ph,gas}}{\varepsilon_{ch,biomass}} \qquad (16)$$

The specific chemical exergy of the biomass is calculated from the correlations for technical fuels using the LHV, calorific value of sulfur, C_s, and mass fractions of organic material, z_{org}, sulphur, z_s, water, z_w, and ash, z_A, in the biomass:

$$\varepsilon_{ch,biomass} = z_{org}(\beta \cdot LHV_{org}) + z_s(\varepsilon_{ch,S} - C_S) + \\ + z_w \varepsilon_{ch,water} + \varepsilon_A \varepsilon_{ch,ash} \qquad (17)$$

β is the chemical exergy coefficient and defined for solid hydrocarbons fuel (for O/C < 2) as

$$\beta = \frac{1.044 + 0.0160H/C - 0.3493O/C(1 + 0.0531H/C)}{1 - 0.4124O/C} + \\ + \frac{0.0493N/C}{1 - 0.4124O/C} \qquad (18)$$

where C, H and O are the solid compounds of the species in the wood; their proportions are given in Table 1.

4. Results and discussion

The energetic efficiencies are shown in Figure 1. which shows are a comparison between the results obtained for acacia wood logs and sawdust gasification. The highest value for energy efficiency is obtained from burning sawdust.

The value of energy efficiency is influenced primarily by the boiler load, the operating conditions and then by the fuel type. As observed, efficiency ratios are higher than the values obtained by the exergetic efficiency analysis. This could be explained by the fact that the β factor used to calculated the exergy input of the biomass is higher than 1 and thus, decreases the final efficiency value.

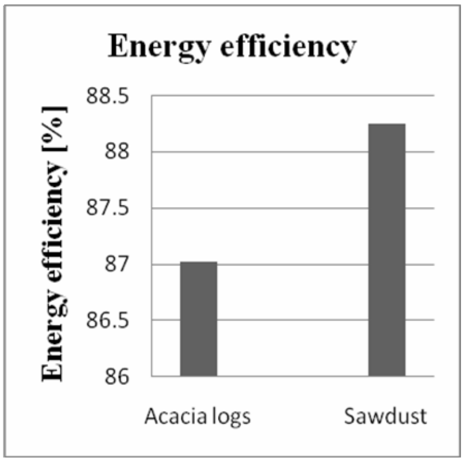

Fig. 1. *Energy efficiency*

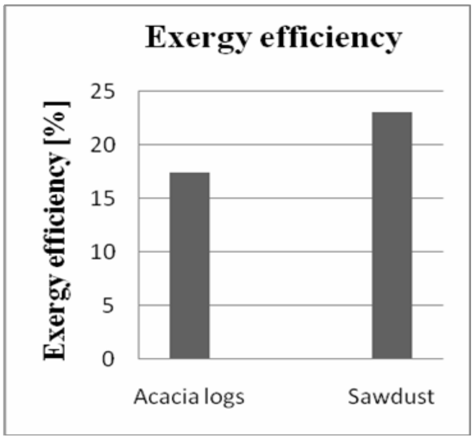

Fig. 2. *Exergy efficiency*

The exergy contained in the biomass is converted by gasification into the chemical and the physical exergy of the produced gas, and part of the exergy of the biomass is lost due to process irreversibilities. The exergetic efficiency shows the ratio between the exergy of useful gasification products and the feedstock exergy. This way different fuels can be compared based on the degree of utilization of their chemical exergy. Figure 2 shows that the exergetic efficiency is higher for sawdust than for acacia wood logs. The exergetic efficiencies of gasification process are lower than the energetic efficiencies.

The moisture content in the biomass is the main problem related to the gasification process. If it is too high, then there will not be enough energy (low temperatures) to start up the process. To take place, gasification needs temperature above 800K.

The moisture content is responsible for an increase in the destruction of exergy inside the reactor, as a result of an increase of the energy required to evaporate the moisture. Despite the increase in H_2 formation, the influence of thermal losses is similar to that of moisture. It reduces the energy available in the process and increases exergy destruction (heat transfer to the environment). Prins et al. [4] state that the main source of exergy destruction, in the gasification and oxidation processes, is the presence of chemical reactions. Following them, heat transfer between products and reactants is a second major source of exergy destruction. In this sense, pre-heating air and/or biomass might reduce such destruction, due to lower temperature differences between products and reactants. However, this reduction is quite small if compared with the increase of exergy destruction due to moisture or thermal losses [5].

5. Conclusions

In order to substitute fossil fuels by renewable fuels, solid biofuels could replace coal as a gasification feedstock. Biomass is a resource which is paid more attention these days and it is classified energy as third energy resource after coal and oil. The gasification process appears to offer attractive technology and friendly to utilize biomass in energy generation.

This paper shows the results of the energetic and exergetic analyses of the biomas gasification process. The exergy contained in the biomass is converted by gasification into the chemical and the physical exergies, of the producedgas, and part of the exergy of the biomass is lost due to process irreversibilities. The exergetic efficiency of the gasification process is lower than its energetic efficiency.

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