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Exergy analysis of Portuguese municipal solid waste treatment via steam gasification

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ABSTRACT

The presented study focuses on a thermodynamic analysis conducted on steam gasification of Portuguese municipal solid wastes (MSW). Current literature addressing this issue is extremely scarce due to the complexity in handling MSW's heterogeneity. To fill this significant gap, a mathematical model built upon a reliable set of experimental runs from a semi-industrial gasifier was used to evaluate the effects of reactor temperature and steam-to-biomass ratio (SBR) on produced gas and tar content. Results from a previously studied biomass substrate were used as benchmark. Numerical results were validated with both experimental results and existing literature. Increase in gasification temperature led to a clear increase in both exergy values and exergy efficiency. On the other hand, increase in SBR led to a sharp increase in the exergy values when steam was first introduced, leading to relatively constant values when SBR was further increased. Regarding exergy efficiency, SBR led to a clear maximum value, which in the case of forest residues was found at SBR = 1, while for MSW at 1.5. In order to promote a more hydrogen-rich gas, data obtained from the numerical model was used to design an exergy efficiency optimization model based on the response surface method. Maximum hydrogen efficiency was found at 900 °C with a SBR of 1.5 for MSW and 1 for forest residues. Surprisingly, forest residues and MSW presented virtually the same maximum hydrogen efficiency.

1. Introduction

The potential threat created by climate change, due to high emission levels of greenhouse gases, has become a major motivation for renewable energy sources in general. Biomass is regarded as the renewable energy source with the highest potential to contribute to the energy needs of modern society. Its advantages compared to the fossil fuels are as follows: biomass is considered to be a carbon neutral fuel, making it possible to reduce carbon dioxide emissions [1]; its use may contribute to an increase in the energy security of the countries importing energy resources, decreasing their dependence on fossil and nuclear fuel supplies [2]; an increase in the energy use of biomass is an additional factor of economic support to the agriculture [2].

Another kind of biomass group is wastes being the municipal solid wastes (MSW) the largest waste stream around the world. The MSW management activities contribute to the generation of greenhouse gas and consequently to the climate change problem. Another environmental problem associated with MSW management systems is the potential generation of dioxins and furans associated to complete combustion [3].

Gasification is a waste-to-energy (WTE) conversion method that offers an attractive solution to both waste disposal and energy problems. However, gasification still has some economic and technical challenges, concerning the nature of the solid waste residues and its heterogeneity [4]. The greatest strength of gasification is the environmental performance, since emission tests indicate that gasification meets the existing limits and it can also have an important role in the reduction of landfill disposal [5].

As one of the most promising WTE technologies, gasification using preheated oxidizing agents such as air, oxygen, steam, or a mixture of these has been studied for decades and has been proven to produce a fuel gas with relatively high heating value [6], where additional heat provided into the gasification process improves the

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decomposition of solid fuel and the cracking of volatiles. Among oxidizing agents, steam gasification provides fuel gas with lower heating values in the range of 12–18 MJ/N m^3 [7], which is higher than those from air gasification, while being less costly than oxygen gasification.

Nevertheless, further research must be conducted to allow biomass gasification, and in particular MSW gasification, to become the mainstream method of treatment for these substrates. Exergy analysis is a concept that combines energy, environment and sustainable development notions, and has been used to identify opportunities for process improvement and to evaluate different process alternatives [8]. The application of exergy destruction and efficiency analysis to process design can help identify and understand the high efficient energy production systems [9].

Therefore, it is not surprising that exergy analysis of biomass-gasification based process have engrossed attention due to the potential of biomass as a feedstock or as energy resource. Many researchers [10–12] performed exergy analysis to study gasification performance of different types of biomass and different degrees of sophistication regarding the use of steam as an oxidizer agent. Hosseini et al. [10] performed energy and exergy analysis of the steam and air fed sawdust gasification. The results show that the adiabatic temperature of biomass gasification significantly changes with the type of the gasifying medium. In addition, the exergy and energy efficiencies are observed to be higher when air is the gasifying medium rather than steam, while the system performance and exergy efficiencies are dependent on the moisture content of the feed biomass. Ptasinski et al. [11] evaluated the exergetic efficiencies in an idealized gasifier in which chemical equilibrium is reached, ashes are not considered and heat losses are neglected. The gasification efficiencies are evaluated at the carbon boundary point. They show that the exergy efficiencies of biofuels are lower than the corresponding energetic efficiencies. For liquid biofuels, gasification at the optimum point is not possible, and exergy efficiency can be improved by drying the biomass. Sreejith et al. [12] presents energy and exergy analyses of steam gasification of four biomass materials (coconut shell, coir pith, bamboo and eucalyptus). The exergy model is formulated based on a Redlich–Kwong real gas equilibrium model. Parametric variations with steam-to-biomass ratio and gasification temperature are presented for energy and exergy efficiencies of gasification. They found that the least irreversible gasification process is for coir pith, followed by coconut shell, bamboo and eucalyptus with the corresponding exergetic efficiencies of 79.2%, 77.5%, 74.4% and 68.3%, respectively.

All the available studies showed that exergy analysis can be an extremely useful tool for evaluating the effectiveness of the biomass gasification process. Unfortunately, due to the complexity of handle the heterogeneity of MSW, studies focusing on thermodynamic evaluations of these wastes are barely explored especially when it comes to analyzing steam as a gasifier agent.

In order to fill this significant gap on the current literature, the current study aims at analyzing MSW gasification from a second law analysis standpoint. To do so, a previously developed numerical model is used [13]. Results are validated with experimental data. Forest residues were used as benchmark for comparison with MSW. Influence of operational parameters on syngas composition and tar content is investigated. Their exergy values as well as process efficiency is analyzed. Finally, an optimization model is built to promote a more hydrogen-rich syngas.

2. Materials and methods

The developed mathematical model (presented in Section 4) was developed using experimental data collected in the gasification plant from the School of Technology and Management (ESTG) of the Polytechnic Institute of Portalegre (IPP). The plant has a semi-industrial fluidized bed gasifier with the capacity to process 100 kg/h and operates close to 850 °C. Having the ability to run tests in industrial-size conditions allows one to be much closer to realistic commercial size reactors since the hydrodynamic phenomena in a laboratory scale fluidized bed are not the same as on large scales [14]. Operation of the gasification plant is quite straightforward. First biomass substrate enters through the feeding system, which sends it to the gasifier. At the same time, preheated steam enters the gasifier via a series of diffusers regulating the flow rate. After the process is completed the syngas leaves the reactor at approximately 700 °C and passes through two heat exchangers – the first lowers syngas temperature to about 300 °C and the second to 150 °C. While this is happening ash and other produced wastes are first filtered out and then stored in a suitable tank. Finally, the syngas goes through a condenser which cools the gas to room temperature thus becoming ready to be used in another purpose. Extended detail on how the gasification plant is operated, including schematics of the reactor as well as the plant itself, can be found in [15].

2.1. Portuguese municipal solid waste and forest residues characterization

MSW was simulated according to the average proportion of organic components (dry basis) in actual MSW of Portugal [5] and used as feedstock for the simulations, as shown in Table 1. The characterization and analysis of Portuguese MSW (from now on we will be referring to as PMSW for simplicity) was carried out using data from the Oporto metropolitan area obtained from LIPOR (Intermunicipal Waste Management Service of Greater Porto), entity responsible for the management, treatment and recovery of solid waste municipal produced in the city.

It is assumed a MSW pre-treatment (in depth detail given in [16]) that gives rise to a refuse derived fuel which contains cellulosic and plastics only [5]. Cellulosic materials are mainly composed of cellulose, hemicelluloses, and lignin. Plastic residues are composed of polyethylene, polystyrene, and polyvinyl chloride.

A global chemical is obtained by dividing the values found in the ultimate analysis of each chemical element (C, H, O) by the value of the reference element carbon (C). This MSW global chemical formula was obtained based on its chemical characterization as shown in Table 1.

To properly assess the potential of PMSW a previously studied Portuguese biomass substrate will be used as benchmark. Forest residues [18] was selected for this purpose, since it reveled relevant energetic as well as economic benefits. In fact, previous studies have shown that both forest residues and MSW can be instrumental in replacing, or at least greatly diminish, fossil fuels [2,13]. According to Silva et al. [15], Portuguese territory is composed of about 35% of forest generating close to 113 thousand jobs (over 2% of active population) and 200 million euros per year in related economic activities. In addition, latest national reports

Table 1
MSW chemical composition.

Category	% Weight	Chemical formula
Cellulosic material	85.42	[a]
Polyethylene	10.99	$(C_2H_4)_n$
Polyethylene terephthalate	2.02	$(C_{10}H_8O)_n$
Polypropylene	0.81	$(C_3H_6)_n$
Polystyrene	0.76	$(C_8H_8)_n$

[a] It was considered the proportion of cellulose, hemicellulose and lignin found in Onel et al. [17].