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Full Length Article

Exergy analysis of alternative configurations of a system coproducing synthetic fuels and electricity via biomass gasification, Fischer-Tropsch synthesis and a combined-cycle scheme

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HIGHLIGHTS

- Simulation and exergy analysis of a base case and two alternative configurations.
- Exergetic efficiencies of 23.7–26.7% at the system level.
- Gasification and power generation as key subsystems in terms of irreversibility.
- Gasifier and gas combustor as main sources of inefficiency.
- Promotion of designs enhancing biofuel yields rather than electricity production.

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ABSTRACT

Lignocellulosic biomass gasification followed by the Fischer–Tropsch (FT) synthesis is becoming a promising pathway to produce synthetic biofuels, having the potential of being coupled with combined-cycle strategies in order to coproduce electricity. In this work, the thermodynamic performance of this type of bioenergy system is evaluated through exergy analysis. A base-case process combining biomass gasification, FT synthesis and a combined cycle is defined. Furthermore, two alternative configurations modifying the base-case process are considered: (i) autothermal reforming (ATR) of a fraction of the FT tail gas to increase the fuel yield, and (ii) combustion of a fraction of the conditioned biosyngas to increase electricity production. The biomass conversion plants are simulated using Aspen Plus® to obtain the data required for the assessment. The indirect gasifier and the gas combustor are identified as the main sources of irreversibility within the three process configurations, with exergy destruction ratios of 21% and 5–7%, respectively. The gasification subsystem is found to contribute over 50% to the overall exergy destruction, showing 68% efficiency. The power generation subsystem also shows a high contribution to the overall exergy destruction (19–28%) due to high fuel consumption and the significant thermodynamic irreversibility of the cycle. Depending on the plant configuration, overall exergetic efficiencies of 24–27% are attained. The ATR case leads to a higher yield of biofuels, at the expense of lower electricity production. This configuration enhances the exergetic efficiency of the system and thus its thermodynamic performance, in contrast to the alternative configuration for increased power generation.

1. Introduction

Concerns about energy prices, supply security and the environmental consequences of using fossil fuels have led to an increasing interest in alternative energy sources [1]. Within this context, renewable energies should play a leading role in order to green the energy sector and promote energy security and sustainability. Biomass-based systems could contribute to mitigating greenhouse gas (GHG) emissions [2], enhancing energy security and promoting the economic development of rural regions [3]. Biomass is a versatile feedstock that can be converted into a wide range of products (biofuels, electricity, heat, chemicals) through different conversion pathways. In particular, biofuels are renewable energy products capable of directly substituting fossil fuels in the currently oil-dependent road transport sector [4].

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There is great interest in lignocellulosic short-rotation plantations (poplar, willow, etc.), rather than in first-generation biomass (based on conventional food crops), in order to avoid competition with the food market while reducing the dependence on foreign energy. These crops can grow with low consumption levels (fertilisers, diesel, etc.) in relatively small areas [5,6]. Two main types of pathways are generally considered for the production of second-generation biofuels from lignocellulosic biomass: thermochemical and biochemical pathways [7,8]. In contrast to typical biochemical pathways, thermochemical routes are able to process the whole biomass to fuel, while common biochemical pathways convert only the cellulose and hemicellulose fraction of the biomass into fermentable sugars, leaving the lignin fraction as a residue. The main advantage of thermochemical pathways is not only the higher theoretical conversion of the reactions, but also the properties of the final fuel product. Synthetic fuels of high quality can be obtained, suitable for direct blending with fossil fuels in any share for use in vehicle engines.

The two main thermochemical pathways to convert lignocellulosic biomass into synthetic liquid fuels include biomass gasification followed by the Fischer–Tropsch (FT) synthesis, and biomass fast pyrolysis followed by bio-oil hydroupgrading [7]. In particular, biomass gasification leads to syngas production, which is a versatile feedstock that (unlike pyrolysis-derived bio-oil) can be easily processed to energy products. Lignocellulosic biomass gasification involves the thermochemical conversion of the fuel (i.e., the biomass feedstock) at elevated temperature in a gasification medium (air, oxygen and/or steam). The product is a gaseous fuel called syngas or biosyngas, containing carbon monoxide, hydrogen, carbon dioxide, methane, other light hydrocarbons, water, and trace amounts of other compounds such as char and tars [9,10]. When pure steam is used as the gasifying agent, a syngas with high hydrogen content is produced.

Lignocellulosic biomass gasification followed by the FT synthesis is becoming a promising pathway to produce synthetic biofuels, having the potential of being coupled with other systems (e.g., combined-cycle power plants) to coproduce electricity [11–14]. Moreover, FT synthetic biofuels are free of sulphur, nitrogen and aromatics, allowing blending with conventional fuels [11,15]. Numerous alternative process schemes can be used for this type of bioenergy systems coproducing synthetic fuels and electricity.

Given the growing interest in biomass conversion systems, the evaluation of their viability is needed. The technical feasibility of bioenergy systems (thermodynamic perspective) affects their economic and environmental performances. In order that these systems become competitive with conventional technologies (fossil fuels), they have to operate efficiently. The thermodynamic behaviour of a system can be evaluated using exergy analysis, which is a useful methodology for optimising energy conversion processes [16]. Exergy is defined as the maximum theoretical useful work obtained when a system is brought into thermodynamic equilibrium with the environment by means of processes in which the system interacts only with this environment [17]. While thermodynamic processes are governed by the laws of mass and energy conservation, exergy is not generally conserved, but destroyed because of irreversibility within a system. Moreover, exergy is lost when the energy associated with a material or energy stream is rejected to the environment [18].

To date, only a few publications exist on the thermodynamic evaluation of processes combining gasification and FT synthesis. Prins et al. [19] carried out an exergy analysis of a biomass integrated gasification-FT process, while other authors [13,20–23] evaluated this type of processes from other perspectives (e.g., mass yields and energy balances based on heating values [13,23]) or with different process schemes (e.g., biowaste to produce separately synthetic natural gas, methanol, FT liquids, hydrogen or heat/electricity [21]). However, a detailed exergy analysis at the component level is not available in the literature. Furthermore, the evaluation of alternative configurations of the process for coproducing synthetic biofuels and electricity would give additional insights into the suitability of this type of bioenergy system. Such an analysis would support decision making by identifying the most efficient strategies according to thermodynamic criteria. This article presents an in-depth exergy analysis of three alternative processes based on lignocellulosic biomass gasification coupled with FT synthesis and power generation in a combined-cycle power plant.

2. Material and methods

2.1. Process description

A base-case process for the coproduction of synthetic biofuels and electricity is defined. As further detailed in Section 2.1.1, it includes biomass pre-treatment, syngas production via biomass gasification, biosyngas conditioning, hydrocarbon production through FT synthesis, refining of FT products and power generation through a combined-cycle strategy. Additionally, two modifications in the configuration of the base-case process are proposed in order to enhance the production of either electricity or biofuels (Section 2.1.2) [24]. These modifications include autothermal reforming of a fraction of the FT tail gas to increase the biofuel yield ("ATR case") and combustion of a fraction of the conditioned biosyngas to increase electricity production ("power case"). All cases are designed to be energy self-sufficient and they are assumed to process 2000 tonnes of dry biomass per day.

2.1.1. Base case

The biomass feedstock of the process is poplar, with the composition shown in Table 1. Fig. 1 (solid lines) shows a diagram of the process divided into sections: the gasification section, in which the biomass feedstock is converted into syngas; the syngas cleaning section, which includes scrubbing, compression, acid gas removal (AGR) and desulphurisation; the FT section, in which the syngas is converted into synthetic biofuels; and the power generation section, where steam and electricity are produced in order to satisfy the energy needs of the process, exporting surplus power.

In the gasification section, poplar biomass is milled and dried with a hot flue gas stream (direct dryer). The dried biomass is then introduced in a low-pressure indirect gasifier (biomass gasifier plus char combustor) to produce biosyngas, using steam as the gasifying agent. The gasifier operates at 1.6 bar and 870 °C [25]. This temperature is maintained by the circulating bed material (olivine), which is heated in the char combustor (where the char generated in the gasifier is burnt). The flue gas stream leaving

Table 1
Poplar biomass composition.

Ultimate analysis (% weight)		Proximate analysis (% weight)	
Ash	2.70	Moisture	50.00
C	50.18	Fixed carbon	12.49
H	6.06	Volatile matter	84.81
N	0.60	Ash	2.70
Cl	0.00		
S (organic)	0.03		
O	40.43		