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First and second law analyses to an energetic valorization process of biogas

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ABSTRACT

The limitations in the world sources of energy are being mitigated by the exploitation of renewable forms and by increases in the efficiency of energy utilization. Exergy analysis is a useful method for the design, evaluation, and improvement of energy systems, that uses conservation of mass and conservation of energy principles, together with the second law of thermodynamics.

This study covers first and second law analyses of a cogeneration system run with the biogas produced in a landfill. Such plant produces useful electrical and thermal energies, while protecting the environment from greenhouse emissions. The objectives were to identify locations where major irreversibilities occur, to evaluate their magnitudes, and to assess the energy and exergy efficiencies of the global system and of its constituent units.

The results show that the overall-plant first law efficiency is 37.9% and the exergy efficiency is 36.2%, which is far from the thermodynamic ideal limit. The internal combustion engine and one of the radiators are the most inefficient units, as judged by the parameters degree of thermodynamic perfection and exergy destruction quotient. The main potential for improvement in the plant is the harnessing of the energy in the exhaust gases.

1. Introduction

The world faces the challenging problem of scarcity of usable energy sources, particularly fossil fuels. The answers to this have been more efficient forms of energy utilization and the exploitation of new and renewable energy sources.

Landfills produce significant amounts of gaseous effluents, whose main components are methane (40–60%) and carbon dioxide. The former is a potential environmental hazard, as it has a greenhouse effect 25 times higher than carbon dioxide [1]. In fact, the emissions from solid waste landfills represent 5–20% of the overall anthropogenic generation of methane. However, this compound has a high chemical energy content, providing 33.8 MJ/m^3 when burned. Therefore, the harnessing of this energy has a double positive effect and leads to the inclusion of biogas as a renewable energy source [2].

Methane and landfill gas can be burned in internal combustion engines, and the resultant mechanical energy can turn an electric generator. However, the exhaust gases still have a high content of thermal energy, that can be used to produce additional electricity (via a steam generator and a turbine), or used in domestic or industrial heating [3]. The combination of electrical and thermal energy production is known as cogeneration. This approach has received great attention in recent years, as it enables significant energy savings [4]. In this article we will analyze a process of energetic valorization of biogas produced in a municipal waste landfill.

Different thermodynamic models and methods have been used in the analyses of energy system [5]. The resultant efficiency values enable the comparison among alternative technologies and can suggest adjustments and modifications toward energetic optimization [6,7]. In this regard, an evaluation based only on first law or energy balances considerations has limited significance, as different energy forms have distinct capacities for producing useful work, that is, different quality. The quantification of this quality, which involves also the second law, led to the definition of exergy [8]. This property has been increasingly used in the design, evaluation and optimization of energy systems [6,9]. It permits not only to point energy losses, but also to identify the irreversibilities that lead to exergy destruction (and entropy generation). Therefore, exergy-based efficiencies are much more meaningful than first law values. This study is centered on the evaluation of the exergetic performance of the above mentioned valorization process.

2. Materials and methods

2.1. Site and plant description

This Biogas Energetic Valorization Plant is located next to the municipal solid waste landfill run by the company *Suldouro* (Vila Nova de Gaia, Portugal). The overall plant encompasses currently three identical internal combustion engines GE Jenbacher

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J320 GS-L.L (Austria), coupled to generators *Stamford PE 734 C2* (EUA). Each assembly has a nominal electrical power output of 1048 kW. These engines are equipped with the gas mixture control system *Leanox*, which enables to run with poor mixtures. This system also increases the energetic efficiency and reduces the emissions of NO_x gases [10]. The main parts (designated from now on as *units*) and the main streams of one engine assembly are shown schematically in Fig. 1.

Treated landfill gas and air enter a gas mixer (MT) and the mixture is compressed in the compressor part (CP) of a turbocompressor. The exit stream is cooled in the heat exchanger PC1 and then headed to the internal combustion engine. Part of the gas is, however, returned to the compressor, expanding first in a valve (VAL). This circuit is a control feature of the engine. The motor (MT) encompasses 20 cylinders, totalizing 48.7 L. The exhaust gases from the motor pass through the turbine part (TB) of the turbocompressor, where they expand. The figure shows the two units of the turbocompressor separated, but in reality they are a single device with a common axle. The exhaust gases are then sent to the atmosphere. The set comprises also two liquid refrigeration circuits. The high temperature refrigeration circuit encompasses streams 13–16 (Fig. 1), and removes heat from the engine, via the internal oil/water heat exchanger (PC2), and via jacket cooling. The same circuit also cools the compressed gas mixture in a section of the heat exchanger PC1 (PC1a). The high temperature stream 14 is then cooled in the radiator PC3a. The low temperature refrigeration circuit cools only the gas mixture in PC1b and releases the heat in the radiator PC3b. The motor runs the generator (GER).

2.2. Methodology

2.2.1. Design variables

The motor–generator set was modeled with 12 distinct units and with 18 main streams (Fig. 1). Table 1 lists the input data regarding temperature, pressure and molar flow rates of the streams. The temperature of stream 17 was, in fact, assumed, due to lack of data. The analyses used the following assumptions, among others:

- The reference state temperature and pressure are $T_0 = 298.15$ K and $P_0 = 101.3$ kPa. Air has the following composition: $y_{O_2} = 0.2054$; $y_{N_2} = 0.77253$; $y_{H_2O} = 0.0217$; $y_{CO_2} = 0.000337$. This is a slight modification of the one presented by Rivero and Garfias [11], considering the fraction of argon as nitrogen.
- The landfill gas has the following composition: $y_{CH_4} = 0.556$; $y_{CO_2} = 0.362$; $y_{O_2} = 0.009$; $y_{N_2} = 0.073$.
- The system operates under steady state conditions. The kinetic and potential energies of the streams are negligible.
- All gaseous streams are considered as ideal gas mixtures.
- The fluid in both refrigeration circuits has the same physical properties as water.
- The engine works at a load of 100% and the electric efficiency of the generator is 98%.

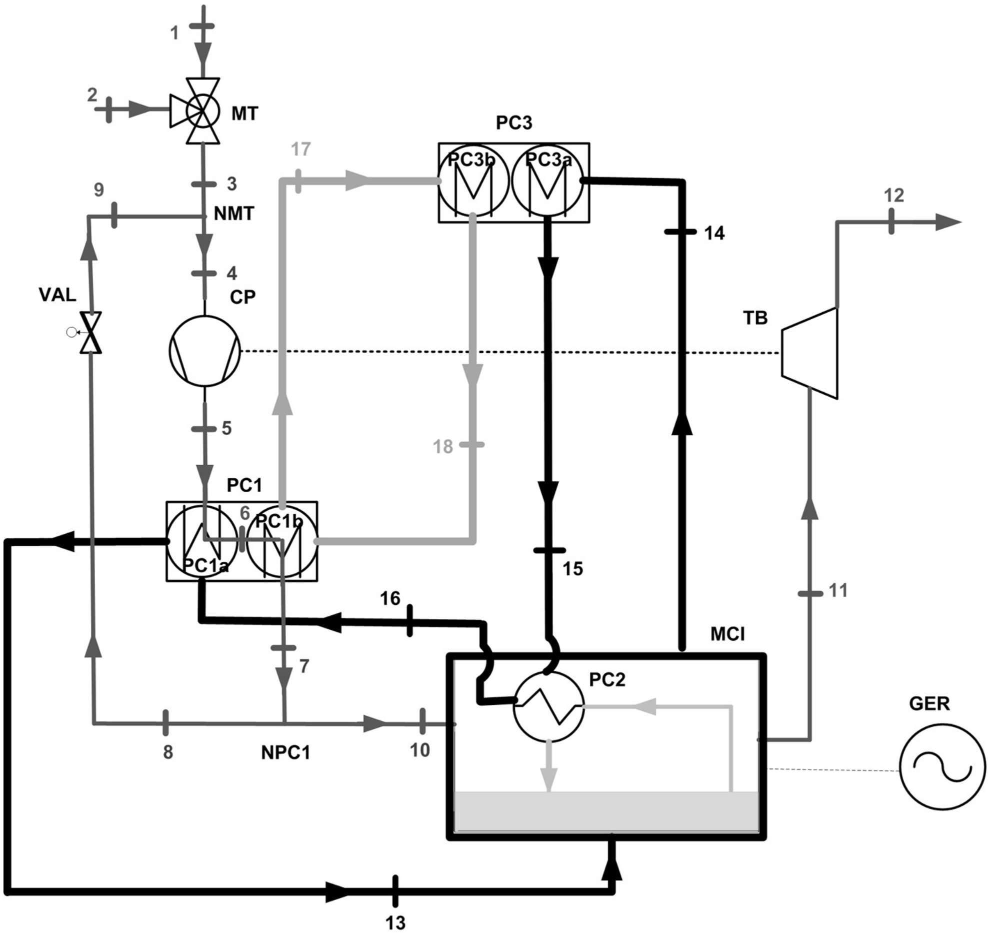

Fig. 1. Scheme of the Biogas Energetic Valorization Plant. CP – compressor; GER – generator; MCI – motor; MT – biogas/air mixer; NMT – entrance stream/recirculation stream mixer; NPC1 – steam splitter; PC1 – combustible mixture/water heat exchanger; PC1a – first subunit of PC1; PC1b – second subunit of PC1; PC2 – oil/water heat exchanger; PC3 – radiator; PC3a – first subunit of PC3; PC3b – second subunit of PC3; TB – turbine; VAL – valve.