Energy Conversion and Management 151 (2017) 753–763

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Comprehensive exergy analysis of a gas engine-equipped anaerobic digestion plant producing electricity and biofertilizer from organic fraction of municipal solid waste

Mohamad Reza Barati[a], Mortaza Aghbashlo[a,*], Hossein Ghanavati[b,c,*], Meisam Tabatabaei[b,c,*], Mohammad Sharifi[a], Ghasem Javadirad[d], Ali Dadak[a], Mohamad Mojarab Soufiyan[a]

[a] Department of Mechanical Engineering of Agricultural Machinery, Faculty of Agricultural Engineering and Technology, College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran
[b] Biofuel Research Team (BRTeam), Karaj, Iran
[c] Microbial Biotechnology Department, Agricultural Biotechnology Research Institute of Iran (ABRII), Agricultural Research, Extension, and Education Organization (AREEO), Karaj, Iran
[d] Caspian Motor Technology (CaMoTec) Company, Iran

ARTICLE INFO

Keywords:
Anaerobic digestion plant
Biogas
Biofertilizer
Electric power
Exergy
Organic fraction of municipal solid waste

ABSTRACT

This study was devoted to comprehensively investigating the exergetic performance of a gas-engine equipped anaerobic digestion plant producing electric power as well as biofertilizer from organic fraction of municipal solid waste (OFMSW). The main aim of the current survey was to reveal the reasons and sources of thermodynamic losses occurring in the plant based on real operational data. The required data for the analysis were collected from a local OFMSW anaerobic digestion plant located in Tehran, Iran. After writing energy and exergy balances for all components of the plant, their exergetic performance parameters were measured individually. An attempt was also undertaken to quantify the contributions of the products to the overall exergetic efficiency of the plant. The exergetic value of the net electric power was determined at 1596.0 kW, while the chemical exergetic content of the biofertilizer was found to be 8758.3 kW. The overall exergetic efficiency of the plant was determined at 72.8%. The contributions of the electric power and the biofertilizer to the overall exergetic efficiency of the plant were found to be 15.4% and 84.6%, respectively. Generally, the exergetic analysis presented herein could provide important guidelines and methodological blueprints for future investigations in order to develop thermodynamically-efficient and environmentally-benign waste-to-energy plants.

1. Introduction

During the last decade, population growth, increased urbanization, rapid industrialization, and societal lifestyle changes have led to constant increases in municipal solid waste (MSW) production worldwide. Nowadays, the collection, processing, and disposal of MSW are the most challenging and sometimes controversial issues faced by local governments around the world [1,2]. In general, MSW could potentially include any or all of five different groups of wastes, i.e., biodegradable wastes, hazardous wastes, composite wastes, recyclable wastes, and inert waste [3]. Conventional waste disposal methods such as landfilling and dumping as the most widely-practiced low cost treatment approaches have been shown to be unsuitable and unsustainable due to land availability limitations in metropolitan cities as well as several environmental concerns such as gas emissions and leachate production. Therefore, there is an emergent need to shift towards environmentally, economically, and socially sound MSW tackling systems in order to ensure the protection of the public health and the environment. On the other hand, the organic fraction of MSW (OFMSW) can be regarded as a renewable source of energy to not only partially diminish non-renewable energy consumption but also to slightly mitigate greenhouse gas emissions. In better words, a circular bioeconomy is expected to evolve progressively in the coming decades in order to address a range of sustainability-related challenges such as climate change, resource depletion, and expanding populations [4].

Today, various waste-to-energy options such as incineration, pyrolysis, gasification, mechanical treatment, refuse-derived fuel, and anaerobic digestion are available for treating MSW in order to recover

* Corresponding authors at: Biofuel Research Team (BRTeam), Karaj, Iran (H. Ghanavati, M. Tabatabaei).
E-mail addresses: maghbashlo@ut.ac.ir (M. Aghbashlo), ghanavatih@abrii.ac.ir, ghanavatih@yahoo.com (H. Ghanavati), meisam_tab@yahoo.com, meisam_tabatabaei@abrii.ac.ir (M. Tabatabaei).

http://dx.doi.org/10.1016/j.enconman.2017.09.017
Received 1 June 2017; Received in revised form 10 August 2017; Accepted 7 September 2017
0196-8904/

Nomenclature

A	ash percentage (%)
C	carbon percentage (%)
C_p	specific heat capacity (kJ/kg K)
ex	specific exergy (kJ/kg)
$\dot{E}n$	energy flow rate (kJ/s)
$\dot{E}x$	exergy flow rate (kJ/s)
h	specific enthalpy (kJ/kg)
H	hydrogen percentage (%)
i	numerator
$\dot{I}P$	exergetic improvement potential rate (kJ/s)
$\dot{m}$	mass flow rate (kg/s)
M	molar mass (g/mol)
n	specific mole (mol/kg)
N	nitrogen percentage (%)
O	oxygen percentage (%)
P	pressure (kPa)
$\dot{Q}$	heat flow rate (kJ/s)
R	gas constant (kJ/kg K)
$\overline{R}$	universal gas constant (kJ/mol K)
s	specific entropy (kJ/kg K)
S	sulfur percentage (%)
T	temperature (°C or K)
$\dot{W}$	work flow rate (kJ/s)
x	mass fraction (−)
y	mole fraction (−)
y^*	exergy destruction ratio (−)

Subscripts

0	dead state
ave	average
A	absorption
ch	chemical
dest	destruction
in	input
k	*k*-th component
L	loss
OM	organic matter
out	output
overall	overall
ph	physical
tot	total

Greeks

ε	specific chemical exergy (kJ/mol)
η	universal exergetic efficiency (%)
ψ	functional exergetic efficiency (%)

its energy and to produce value-added chemicals [5]. Among the techniques developed to date, safe and economical handling of MSW by anaerobic digestion has gained increasing popularity worldwide within two last decades. In simple terms, OFMSW is digested and degraded by anaerobic microorganisms during a multi-stage process taking place in the absence of oxygen [6]. This method can produce biogas consisting of 60–70 vol% methane while a digestate is also generated which could be regarded as nutrient-rich fertilizer. The produced biogas is a viable fuel for electric power generation in the currently carbon-constrained world. Numerous publications can be found in the literature in which commercial anaerobic digestion plants treating the OFMSW have been analyzed and discussed from various perspectives [7–11].

According to the findings of the above-mentioned investigations, there is no doubt that the anaerobic digestion technology could be used to address the above-mentioned challenges in a cost-effective and environmentally-friendly manner. However, in spite of the promising results reported, it is still essential to use advanced engineering tools to improve the design and operation of anaerobic digestion plants for simultaneously resolving both energy and environmental problems. Amongst many engineering approaches developed to date such as emergy, life cycle assessment, energy, and exergy methods, exergy-based analyses have been proved to hold great potentials to achieve these goals [12,13]. Simply speaking, exergy is the maximum theoretical work that a given kind of energy or material can generate when it is brought to a complete equilibrium with a reference environment by reversible processes [14–16]. Exergy analysis can provide a sufficient deal of useful insights into the productivity and sustainability of energy and material conversion processes [17]. It is worth noting that exergy efficiency of an energy system can be directly linked to its sustainability and environmental features as elaborated by Dincer and Rosen [18] and Jafaryani Jokandan [19]. Today, exergy analysis has gained an international reputation as a powerful tool for designing, scrutinizing, optimizing, and retrofitting energy and material conversion systems [20].

In this regard, a substantial amount of research efforts have been devoted to the use of exergy-based approaches for analyzing and optimizing various waste-to-energy plants. For example, Farhad et al. [21] studied the exergetic performance of three solid oxide fuel cell systems producing electricity from wastewater-originated biogas processed using different methods, i.e., anode gas recirculation, steam reforming, and partial oxidation. Abusoglu et al. [22] presented exergy and exergoeconomic analyses of biogas production process from wastewater sludge. Xydis et al. [23] exergetically investigated electricity production from landfill-evolved biogas using a combined and heat power system. Siefert and Litster [24] exergetically and exergoeconomically studied a solid oxide fuel cell applied for electricity generated from biogas produced in a thermophilic anaerobic digester. Colmenar-Santos et al. [25] performed exergy and exergoeconomic analyses for a Stirling engine powered by steam generated by a boiler and a heat recovery system from the combustion of wastewater-originated biogas. Hosseini et al. [26] thermodynamically modelled an integrated biogas micro-power generation system including a gas turbine cycle and organic Rankine cycle for electricity generation. Ozdil and Tantekin [27] presented exergy and exergoeconomic analyses for an actual power plant consisting of a gas engine and a gas turbine generating electricity from wastewater-based biogas. Baldinelli et al. [28] exergetically compared two solid oxide fuel cell-based systems on the basis of biogas upgrading and reforming approaches for electricity production. Jack and Oko [29] analyzed a proposed steam reheat power plant driven by municipal waste incineration for a Nigerian city (Port Harcourt) from exergetic and exergoeconomic points of view. Prodromidis and Coutelieris [30] investigated a biogas-fed solid oxide fuel cell power plant consisting of three heat exchangers, a reformer, a cell-stack, and an afterburner from exergetic standpoint.

Although a number of investigations aimed at employing the exergy concept for analyzing OFMSW anaerobic digestion plants, those research attempts were only directed towards the biogas production process or electric power generation from biogas without presenting more informative details on the main units involved in the process such as digestion, desulfurization, and fertilizer recovery units. To the best of our knowledge, the exergetic performance analysis of electric power and biofertilizer production through anaerobic digestion of OFMSW has not been explored comprehensively yet. Therefore, this work was aimed at carrying out a comprehensive exergy analysis of a gas-engine equipped OFMSW anaerobic digestion plant in order to provide a better