Energetic and exergetic analyses of a solid waste power plant using Aspen Plus

Alperen Tozlu, Emrah Özahi, and Ayşegül Abuşoğlu

***Abstract*—** Municipal solid waste management becomes an important role for the energy recovery from the waste when taking into consideration of energy requirement of the world. Meanwhile municipal solid waste disposal methods have been used as a renewable power source in recent years especially in developed countries. The most common technology landfilling is one of the simple and practical method among the disposal methods in worldwide. Internal combustion engines are used to generate electricity from LFG which is also preferred to generate electricity are most commonly lean fuel burn turbocharged designs. In this paper, starting from a historical overview of LFG driven power plants, the thermodynamic analysis is presented for a Jenbacher 416 GS type landfill gas engine which uses LFG gas produced by Gaziantep Municipal Solid Waste Power Plant. Operation of the municipal solid waste power plant is described in details.

***Keywords*—** *Municipal solid waste, LFG, gas engine, thermodynamic analysis.*

I. Introduction

THE amount of municipal solid waste (MSW) have increased dramatically in Gaziantep as a result of industrial facility, economic development and refugee population in the city. Until the end of 1990s, there was only one unsanitary landfill that had serious environmental problems because of uncontrolled gas emissions and air pollution. MSW management in Gaziantep city has been directed positively into feasible practice during the past years. Sanitary landfill was constructed in 1996 and electricity production was started in 2008. This plant which has 5.66 MW installed power produces a portion of 1.25% of total power demand of Gaziantep.

When recent studies are considered, Holanda and Balestieri [1] proposed two cogeneration schemes for the burning of municipal solid wastes, associated or not with natural gas, and examined their technical and economic feasibilities. The proposed scheme involved a steam-based cycle using MSW combustion: the technical and economic feasibility evaluation was concluded especially because of its environmental and social benefits. The second scheme was based on a combined cycle which had a turbine burning natural gas in its topping unit and a conventional steam-generator burning MSW in its bottoming unit. Because of the longer payback periods of second proposed scheme, first proposed scheme was considered as more feasible in the study. Sevimoğlu and Tansel [2], investigated the performances of gas engines operated with landfill gas (LFG) are affected by the impurities in the LFG, reducing the economic viability of energy recovery. The aim of study was to characterize the trace compounds in the LFG at the Odayeri Landfill, Istanbul, Turkey which was used for energy recovery. The composite gas samples were collected and analyzed for trace compounds (hydrocarbons, siloxanes, and volatile halogenated hydrocarbons) over a 3-year period. According to authors, pretreatment of LFG was necessary to protect the engines at the waste-to-energy facilities with persistence levels of siloxanes and volatile halogenated hydrocarbons and also decreases the operating costs associated with engine repairs. Barigozzi et al. [3] focused on a waste-to-energy plant located in Italy, that produces electric power and thermal energy from the non-recyclable fraction of municipal and industrial solid waste. The condenser system was organized with an air condenser and a water cooled condenser, coupled with a wet cooling tower in this plant. It is claimed that how the net power output can be maximized by properly regulating the combined wet and dry units of the combined cooling system in the study. A detailed model of the steam cycle was performed by means of a commercial code (Thermoflex) and resulted that as a general rule, heat rejection was more efficient in the water cooled condenser (WC) than in the air cooled condenser (AC). Conversely, the AC turned out better than WC when a small amount of steam was sent to condensation, in the coldest period of the year.

Bove and Lunghi [4] analyzed different landfill gas (LFG) energy recovery systems, including traditional and innovative technologies, with a technoeconomic and an environmental comparison. Their results showed that although internal combustion engines gives the poorest environmental performance, they are the most widely used technology due to economical reasons. In contrary to this, fuel cells are the cleanest energy conversion systems, but the relative investment cost is still too high to compete with traditional energy

This work is supported by **TUBITAK** (The Scientific and Technological Research Council of Turkey) with the project under the grant number of **114M142**. The authors would like to thank **TUBITAK,** and **CEV** (Clean Energy & Vehicles) Energy. The authors would also like to thank University of Gaziantep Scientific Research Project Administration Unit and ÖYP for their support under the grant no. **RM.15.01**.

Alperen Tozlu is with the Mechanical Engineering Department, University of Gaziantep, Gaziantep, 27310 TURKEY (corresponding author to provide phone: 0090-342-317-2524; fax: 0090-342-360-1104; e-mail: alperentozlu@gantep.edu.tr).

Emrah Özahi is with the Mechanical Engineering Department, University of Gaziantep, Gaziantep, 27310 TURKEY (e-mail: ozahi@ gantep.edu.tr).

Ayşegül Abuşoğlu is with the Mechanical Engineering Department, University of Gaziantep, Gaziantep, 27310 TURKEY (e-mail: ayabusoglu@gantep.edu.tr).

systems. Carolino and Ferreira [5] performed the first and second law analyses of a cogeneration system driven with the biogas produced in a MSW in Porto. Their 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. They stated that 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. According to the researchers the main potential for improvement in the plant is the harnessing of the energy in the exhaust gases. Ahrenfeldt et. al. [6] presented a series of different gasification process designs to give a better insight to the wide range of possibilities within this process. They focused on high reliability, flexibility and efficiency within cogeneration of energy from conversion of biomass and compared cogeneration processes with respect to production of heat-and-power, heat-power-and fuel or heat-power-and-fertilizer. They concluded that the optimal choice of technology for a given task depends on many factors including feed stock availability, know-how, project economy, local politics, environmental concerns and life cycle assessment considerations in addition to the desired product and process characteristics and demands. Abusoglu et al. [7] presented a thermoeconomic analysis and assessment of a municipal wastewater treatment system. Operation of an existing municipal wastewater treatment plant was described and a thermoeconomical methodology based on exergoeconomic relations and the specific exergy costing method was performed using actual operational plant data. Their results provided important information for identification of the sites with greater exergy destructions and consequently greater potential for improvements. Bianchi et. al. [8] investigated an innovative and promising strategy to improve waste conversion through integration of a conventional waste-to-energy (WTE). power plant with a gas turbine (GT). Their study focused on the feasibility of utilizing the hot gases leaving the GT to superheat the steam leaving the WTE steam generator, as well as heating the feed water returning to the steam generator of the WTE condenser. They presented detailed modifications to the WTE cycle and the resulting enhancement of its performance. Raj et al. [9] presented a detailed literature survey of cogeneration technologies based on renewable energy sources like biomass, solar energy, fuel cell, and waste heat. They investigated various designs, numerical and simulation models, key development areas, economic and environmental considerations in this paper which can be useful for the researchers in cogeneration technologies to make effective decisions and generate more ideas. Their comparative paper highlighted the gaps in cogeneration technologies where there is scope for future research. Verbruggen [10] proposed appropriate methods for measuring cogeneration or combined heat and power (CHP) activities based on design characteristics of the plants in their paper. He investigated that the co-generated electric output is a necessary and sufficient indicator of CHP advantage and performance. He remarked that regulators can extend this indicator, but should avoid the perverse effects of biased external benchmarking as the EU Directive entails. The purpose of Xydis [11] is to analyze exergeticaly the electricity production from a landfill in the area of Greece. Biogas production technology is more than–suitable for use and very valuable for the production of fuel that can act as substitute to the conventional sources of energy. This fuel can replace part of the natural gas used for power generation. An inactive landfill that has a major impact on global warming from the emission of methane is transformed into an energy production unit. The continuous new extensions of the landfill add on to the biogas production to the point of doubling the electricity production.

II. SYSTEM DESCRIPTION

Gaziantep Municipal Solid Waste Power Plant (GMSWPP) was installed in 1996, in Gaziantep, Turkey and the flow schematic of the power plant is given in Fig. 1. This power plant has 32.3 ha solid waste storage area and also 10,000,000 m^3 solid waste capacities which will fulfill the need until 2046.

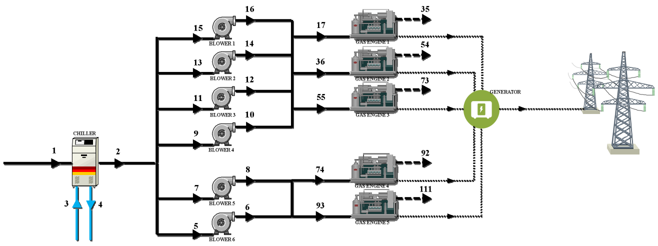

Fig. 1. Schematic layout of Gaziantep Municipal Solid Waste Power Plant

In GMSWPP, landfill gas (LFG) is created during the anaerobic decomposition of organic substances in municipal solid waste (MSW), industrial and medical wastes. The total MSW carried to GMSWPP is 1,500 tons which produce 20,203 m^3 landfill gas daily. All wastes which are collected in GMSWPP are subjected to mechanical segregation of plastic, metal and glass, and then rest of MSW is sent to sanitary landfilling area. On the other hand, medical waste is sterilized first as a pretreatment and then sent into landfilling area. MSWs which are buried underground in landfilling area are led to produce LFG for months. The produced LFG from the storage area is collected then transferred to 6 manifold stations. If the temperature of the LFG is higher than 40-45^oC, it is cooled through the chiller unit by means of chilled water which is showed in Fig.1. The LFG which is under 40-45^oC or which is cooled by chilled water (nearly to 15^oC) is sucked by using six blowers from chiller unit to five same V type configuration, and 16 cylinder coupled with generators Jenbacher 416 GS type landfill gas engine.

Schematic layout of one gas engine in GMSWPP is shown in Fig. 2. The electricity production process is summarized as follows: the produced LFG is transported to the gas engine with equivalent mass flow rates (0.152 kg/s) using six blowers. LFG and air combined in an air fuel tank then they delivered to the compressor supplied by turbine which are consists of turbocharger unit. LFG and air mixture is conducted to the power unit after their temperature decreasing to the 40^{o}C by using intercooler. In power unit there are one combustor, four heat exchanger and one power generator to produce electricity from the gas engine. This model is designed in Aspen Plus and analyzed in Engineering Equation Solver (EES) software programs. The exhaust gas which has temperature roughly 550-570^{o}C is discharged from the gas engine to the atmosphere after the turbocharger turbine.

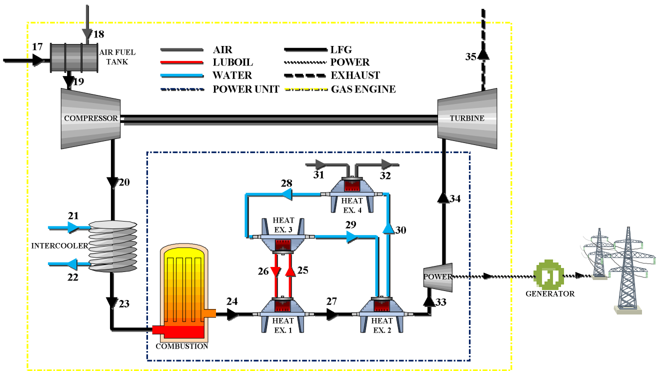

Fig. 2. Schematic layout of gas engine in Gaziantep Municipal Solid Waste Power Plant

The content of LFG (CH_4, O_2, CO_2, H_2S and other gases) is also another critical parameter to electricity production in landfill sites which is measured continuously and recorded. The average values of the components of LFG are given in Table I.

Table I. Volumetric composition of LFG produced in GMSWPP

Components	Chemical Formula	(%) Dry Volume
Methane	CH_4	50
Carbon dioxide	CO_2	29
Nitrogen	N_2	16.3
Oxygen	O_2	4
Other	-	0.7

III. THERMODYNAMIC ANALYSIS

Mass, energy and exergy balances for any control volume at steady state with negligible kinetic and potential energy changes can be expressed, respectively, by [12]

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (1)$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \quad (2)$$

$$\dot{E}x_{heat} - \dot{W} = \sum \dot{m}_e \psi_e - \sum \dot{m}_i \psi_i + \dot{E}x_d \quad (3)$$

where the subscripts e and i represent the exit and inlet states, $\dot{Q}$ and $\dot{W}$ are the net heat and work inputs, $\dot{m}$ is the mass flow rate, h is the enthalpy, $\dot{E}x_d$ is exergy destruction and $\dot{E}x_{heat}$ heat is the net exergy transfer by heat at temperature T, which are given by

$$\dot{E}x_d = T_0 \dot{S}_{gen} \quad (4)$$

$$\dot{E}x_{heat} = \sum \left(1 - \frac{T_0}{T} \right) \dot{Q} \quad (5)$$

The specific flow exergy is given by

$$\psi = (h - h_0) - T_0 (s - s_0) \quad (6)$$

$$\dot{E}x = \dot{m} \psi \quad (7)$$

where the subscript 0 stands for the restricted dead state. Isentropic efficiencies of turbine and compressor can be defined as [10]

$$\eta_t = \frac{w_a}{w_s} = \frac{h_i - h_e}{h_i - h_{es}} \quad (8)$$

$$\eta_{comp} = \frac{w_s}{w_a} = \frac{h_{es} - h_i}{h_e - h_i} \quad (9)$$

where w_a is the actual specific work, w_s is the isentropic specific work, the subscript *es* is reversibility for exit state. The thermal efficiency of a power plant can be evaluated by means of the following equation [13]

$$\eta_{th} = \dot{W}_b / \dot{m}_f \dot{Q}_{HV} \quad (10)$$

where $\dot{W}_b$ is break power, $\dot{m}_f$ is mass flow rate of fuel and $\dot{Q}_{LHV}$ is lower heating value of fuel in (10). The exergetic (second law) efficiencies of turbine and compressor are given as follows:

$$\varepsilon_t = \frac{w_a}{w_{rev}} = \frac{h_i - h_e}{h_i - h_e - T_0 (s_i - s_e)} \quad (11)$$

$$\varepsilon_{comp} = \frac{w_{rev}}{w_a} = \frac{h_e - h_i - T_0 (s_e - s_i)}{h_e - h_i} \quad (12)$$

where w_{rev}, reversible specific work is equal to the sum of specific exergy destruction and actual work. The exergetic efficiency of a heat exchanger in a power plant is measured by the increase in the exergy of the cold stream divided by the decrease in the exergy of the hot stream

$$\varepsilon_{he}=\frac{(\dot{E}x_e-\dot{E}x_i)_{cold}}{(\dot{E}x_i-\dot{E}x_e)_{hot}}=\frac{\dot{m}_{cold}\left[h_e-h_i-T_0(s_e-s_i)\right]_{cold}}{\dot{m}_{hot}\left[h_i-h_e-T_0(s_i-s_e)\right]_{hot}} \quad (13)$$

where $\dot{m}_{cold}$ and $\dot{m}_{hot}$ are the mass flow rates of the cold and hot streams, respectively.

In this study, Aspen Plus software program is used to evaluate thermodynamic analysis of GMSWPP using actual operating data that may be advantageous to optimize and improve electricity production. Energy and exergy analyses of the power plant are carried out by using actual operational data. Air and the exhaust gases are assumed as ideal gases. Heat transfer rates, work, exergy destructions and exergetic efficiencies are calculated using the governing equations given above.

Exergy efficiency of compressor is shown clearly less than turbine and power generator exergy efficiencies. The reason for the lower exergy efficiency of the compressor is related with exergy destruction value when compared to the turbine and power generator. The intercooler, heat exchangers 1 and 2 and chiller units have low exergy efficiencies. On the other hand blower, heat exchangers 3 and 4, and combustor have high exergy efficiencies. The energetic and exergetic analyses of all subcomponents are shown in Table II.

Table II. Energetic and exergetic analyses of subcomponents

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}_F$ (kW)	$\dot{E}_P$ (kW)	$\dot{E}_D$ (kW)	ε (%)
Chiller	1.0	0.0	0.5	0.1	0.4	22.4
Blower	0.0	2.3	2.3	1.7	0.5	76.8
Compressor	0.0	248.3	248.3	197.4	50.9	79.5
Intercooler	196.8	0.0	36.9	12.8	24.1	34.7
Combustor	6730.9	0.0	6730.9	5976.1	754.8	88.8
Heat Ex. 1	132.0	0.0	105.5	26.5	79.0	25.1
Heat Ex. 2	1939.2	0.0	1646.2	390.3	1255.9	23.7
Heat Ex. 3	132.0	0.0	26.5	20.6	5.9	77.9
Heat Ex. 4	2170.6	0.0	410.9	306.2	104.7	74.5
Power Gen.	0.0	2664.0	3106.2	2664.0	442.2	85.8
Turbine	0.0	249.60	286.22	249.60	36.62	87.20
Energetic Efficiency						39.57 %

IV. COCLUSIONS

The amount of waste produced by inhabitants or industrial companies can be considered as one of the most serious environmental problems in the world. Waste to energy techniques are crucial to dispose waste and energy recovery from waste. For this reason, energy recovery from waste is an alternative source for energy production. In this study, energy and exergy analyses of the power plant are performed as well as the analyses of all subcomponents. The exergetic efficiencies of the compressor and the turbine of the turbocharger are 79.5% and 87.2%, respectively. This represents that a remarkable exergetic losses are shown from the turbocharger. The exergetic efficiencies of the heat exchangers, are calculated as 25.1%, 23.7%, 77.9%, and 74.5 respectively. It is clearly shown that heat exchanger 1 and 2 have low exergy efficiencies in contrast to heat exchangers 3 and 4. In addition to this chiller and intercooler have low exergy efficiencies likewise heat exchanger 1 and 2. On the other hand combustor has the maximum exergy efficiency when compare to other components of the power plant.

Thermodynamic analyses of all subcomponents are evaluated and the exergetic efficiency of the power plant is found to be 56.19%. Beside this, thermal efficiency of gas engine is evaluated as 39.6%. which is compatible with the technical specifications of the Jenbacher 416 type. Higher exergy destructions represent the most potential for possible improvements in the performance of the plant in the frame of the presented analysis. This study can be a guide for other researchers in order to perform thermodynamic analysis for any municipal solid waste power plant in recent years.

REFERENCES

[1] M. R. Holanda, J. A. P. Balestieri, "Cogeneration in a solid-wastes power-station: a case-study," *Applied Energy*. 63, 1999, pp. 125-139

[2] O. Sevimoglu, B. Tansel, "Composition and source identification of deposits forming in landfill gas (LFG) engines and effect of activated carbon treatment on deposit composition," *Journal of Environmental Management*., 128, 2013, pp. 300-305.

[3] G. Barigozzi, A. Perdichizzi, S. Ravelli, "Performance prediction and optimization of a waste-to-energy cogeneration plant with combined wet and dry cooling system," *Applied Energy*, 115, 2014, pp. 65-74.

[4] R. Bove, P. Lunghi, "Electric power generation from landfill gas using traditional and innovative technologies," *Energy Conversion and Management*, 47, 2006, pp. 1391–1401.

[5] C. G. Carolino, J. P. M. Ferreira, "First and second law analyses to an energetic valorization process of biogas," *Renewable Energy*, 59, 2013, pp. 58-64.

[6] J. Ahrenfeldt, T. P. Thomsen, U. Henriksen, L. R. Clausen, "Biomass gasification cogeneration - A review of state of the art technology and near future perspectives," *Applied Thermal Engineering*, 50, 2013, pp. 1407-1417.

[7] A. Abusoglu, S. Demir, M. Kanoglu, "Thermoeconomic assessment of a sustainable municipal wastewater treatment system," *Renewable Energy*, 48, 2012, pp. 424-435.

[8] M. Bianchi, L. Branchini, A. De Pascale, "Combining waste-to-energy steam cycle with gas turbine units," *Applied Energy*, 130, 2014, pp. 764-773.

[9] N. T. Raj, S. Iniyanb, R. Goicc, "A review of renewable energy based cogeneration technologies," *Renewable and Sustainable Energy Reviews*, 15, 2011, pp. 3640-3648.

[10] A. Verbruggen, "The merit of cogeneration: Measuring and rewarding performance," *Energy Policy*, 36, 2008, pp. 3069-3076.

[11] G. Xydis, E. Nanaki, C. Koroneos "Exergy analysis of biogas production from a municipal solid waste landfill, *Sustainable Energy Technologies and Assessments*, 4, 2013, pp. 20-28.

[12] A. Abusoglu, S. Demir, M. Kanoglu "Biyogaz beslemeli gaz motorlu bir kojenerasyon sisteminin termoekonomik analizi, *Isı Bilimi ve Tekniği Dergisi*, 33 (2), 2013, pp. 9-21.

[13] M. Kanoglu, S.K. Isik, A. Abusoglu, "Performance characteristics of a Diesel engine power plant, *Energy Conversion and Management*. 46, 2005, pp. 1692–1702.