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Thermoeconomic analyses of an actual power plant

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ABSTRACT **A municipal solid waste power plant located in Malatya, Turkey has been analyzed thermodynamically and thermoeconomically in this study. The sanitary landfill plant was constructed with an installed power capacity of 2.4 MW for both disposals of municipal solid waste and energy production from produced landfill gas (LFG) of 9425 m^3, corresponding to the 2.86 % of total power demand of the city. As a result of the thermodynamic analyses throughout the power plant, the exergetic efficiencies of the compressor and the turbine of the turbocharger are found to be 83.02 % and 65.41 %, respectively; which means that there is a considerable amount of exergetic losses in the turbocharger. Moreover, the overall exergetic efficiency of the power plant is found to be 50.97 %. On the other hand, the thermal efficiency of the gas engine is obtained as 37.30 %. In terms of thermoeconomic analyses, the payback period of the plant is found to be 7.70 years which is an acceptable period for such a power plant.**

Keywords: Municipal Solid Waste, Landfill Gas, Thermodynamic Analysis, Thermoeconomic Analysis, Exergetic Efficiency

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1. INTRODUCTION

Thermodynamic and thermoeconomic analyses of Malatya Municipal Solid Waste Power Plant (MMSWPP) using actual operation data was performed to evaluate the potential increase in electricity production. Herein, the main motivation is to reveal the unexpected losses in the actual power plant during the electricity generation. Therefore, the thermoeconomic analysis of the system is required.

Municipal solid waste (MSW) is a vitally important issue from the point of the environmental aspect. Besides, the huge amount of MSW in all over the world is seen to be a potential for power production in recent years. The literature is abundant on the MSW management in different countries and their MSW policies as well as economic effects. The literature of this field can be classified into 4 groups which are solid waste management, waste disposal processes, landfill gas (LFG) and energy generation, thermodynamic and thermoeconomic analyses.

Solid wastes collected by municipalities are composed of household food waste, paper, plastic, glass, textile, metal, wood, leather, sanitary products and so on. With the increasing population, solid waste management is becoming an increasing concern. Disposal of solid wastes is a major challenge in the every country in terms of both for infrastructure and for environmental reasons. Therefore, a significant number of studies have been performed to address this in the literature. Most of those investigations deal with choosing a proper disposal system, and investigating an acceptable energy cost, a convenient investment cost and a desirable environmental benefit [1-12].

The waste-to-energy (WTE) methodologies in use can be classified under three headings, fundamentally as thermal conversion methods (incineration, pyrolysis, and gasification), biochemical conversion and landfill. Every country resort to manners of disposing solid wastes to the extent of its capabilities, even though the methods of MSW disposal differ concerning the development level of countries. As a result of these developments, there are

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many ongoing trials to determine the more advantageous and environmentally friendly procedures [13-20].

LFG based energy production is another important research subject. The existing studies mainly focus on waste conversion, MSW burning, gas engines, and cogeneration technologies. The ultimate goal is to improve the total system performance by utilizing abovementioned factors [21-28].

There are many variables that need to considered in power plants for improved efficiency. Improving efficiency from both technical and economical points of view might be challenging sometimes for companies as. For this reason, thermodynamic and thermoeconomic analyses are vitally important to evaluate the efficiency of a thermal system. Thermoeconomic performance of the various thermal systems are analyzed in literature [29-40]. The common conclusion from those is that the thermoeconomic analysis is an obligation for all thermal systems in order to evaluate the overall system performance. Therefore, the thermoeconomic analyses were performed for the case in current study.

2. MATERIAL AND METHOD

In MMSWPP, the LFG is created during the anaerobic decomposition of organic substances in MSW, industrial and medical wastes. All wastes collected in the landfill area are subjected to mechanical segregation of inorganic materials then the rest of the wastes are sent to the sanitary landfilling site for the production of gas. Solid wastes, which are buried underground in landfilling site, are led to produce gas for months. The produced gas from the storage area is collected, and then it is transferred to gas collection stations. The LFG is sucked into two identical TCG MWM 2020 V12 type gas engines coupled with a generator.

The electrical power production process in MMSWPP (Figure 1) can be summarized as follows: the produced gas is transferred to the two identical gas engines with a mass flow rate of 0.30 kg/s. The gas, which has an averagely 55% methane combined with air in an air-fuel tank is then delivered to the compressor coupled with the turbine which are components of the turbocharger unit. The mixture is transmitted to the gas engine after its temperature is decreased to the 55-60 ˚C by using intercooler and heat exchanger (HE 1). In the gas engine part, two pumps and two heat exchangers (HE 2 and HE 3) are used to cool the gas engine. The exhaust gas which has a temperature of roughly 490-500 ˚C is discharged to the atmosphere after the turbocharger unit.

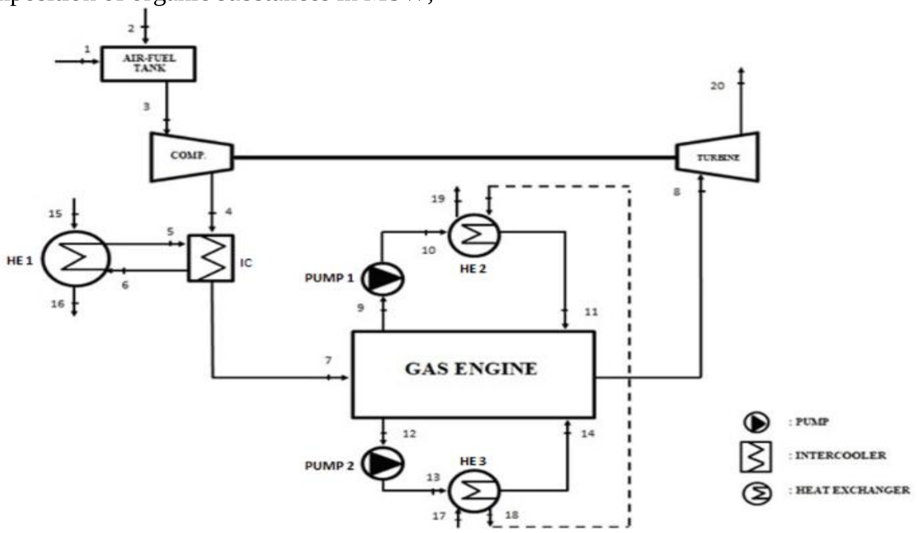

Fig. 1. Schematic layout of energy production in Malatya Municipal Solid Waste Power Plant [31].

Thermoeconomic analysis of a typical power plant is actually based on the second law of thermodynamics. The thermoeconomic analysis is an effective solution for the consideration of the costs of a power plant in view of thermodynamic aspects. Cost analysis lonely is not an effective and adequate solution to demonstrate the economical view of a power plant. In this manner, Tsatsaronis and Moran proposed a new methodology in 1997, which is called the exergoeconomy [1]. The specific exergy costing (SPECO) method is chosen and utilized for the thermoeconomic analysis of the power plant in this study. In the SPECO method, at first, all exergetic and energetic flows in the system are labeled by considering exergy interaction taking place in each sub-components. All exergy inputs and outputs to a sub-component are named as the fuel (F) and product (P), respectively. Then, the auxiliary equations for thermoeconomic analysis of each sub-component are carried out [33].

3. RESULTS

Thermodynamic analyses of MMSWPP were performed by using the equations given in Table 1. The details on the thermodynamic analyses can also be seen in the related literature [33].

Energy and exergy analyses of the power plant are carried out by using actual operational data. Exergy rates of flow streams in the power plant are calculated. Thermodynamic properties and exergy rates of flow streams are provided in Table 2.

Table 1. Thermodynamic equations used in analyses.

$\sum \dot{m}_i = \sum \dot{m}_e$	(1)
$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i$	(2)
$\dot{E}x_{heat} - \dot{W} = \sum \dot{m}_e \psi_e - \sum \dot{m}_i \psi_i + \dot{E}x_d$	(3)
$\dot{E}x_d = T_0 \dot{S}_{gen}$	(4)
$\dot{E}x_{heat} = \sum \left(1 - \frac{T_0}{T}\right) \dot{Q}$	(5)
$\psi = (h - h_0) - T_0 (s - s_0)$	(6)
$\dot{E}x = \dot{m} \psi$	(7)
$\eta_t = \frac{w_a}{w_s} = \frac{h_i - h_e}{h_i - h_{es}}$	(8)
$\eta_{comp} = \frac{w_s}{w_a} = \frac{h_{es} - h_i}{h_e - h_i}$	(9)
$\eta_{th} = \dot{W}_{net} / \dot{m}_f Q_{LHV}$	(10)
$\varepsilon_t = \frac{w_a}{w_{rev}} = \frac{h_i - h_e}{h_i - h_e - T_0 (s_i - s_e)}$	(11)
$\varepsilon_{comp} = \frac{w_{rev}}{w_a} = \frac{h_e - h_i - T_0 (s_e - s_i)}{h_e - h_i}$	(12)
$\varepsilon_{he} = \frac{(\dot{E}x_e - \dot{E}x_i)_{cold}}{(\dot{E}x_i - \dot{E}x_e)_{hot}} = \frac{\dot{m}_{cold} [h_e - h_i - T_0 (s_e - s_i)]_{cold}}{\dot{m}_{hot} [h_i - h_e - T_0 (s_i - s_e)]_{hot}}$	(13)

Table 2. Thermodynamic properties of MMSWPP

#	Fluid	P (bar)	T (°C)	$\dot{m}$ (kg/s)	h (kJ/kg)	s (kJ/kg.K)	Energy Rate (kW)	Exergy Rate (kW)
1	LFG	0.1	24.8	0.15	-5656.7	7.27	0.9	2654.0
2	Air	1.0	28.2	2.61	303.2	5.68	25.0	28.8
3	LFG-Air	0.9	28.0	2.76	-5656.7	7.29	48.3	8.2
4	LFG-Air	20.0	300.0	2.76	-5608.7	7.61	180.9	-118.3
5	Water	2.1	37.5	30.00	157.1	0.54	2196.9	74.7
6	Water	1.5	50.0	30.00	209.3	0.70	3763.3	194.5
7	LFG-Air	20.0	56.5	2.76	-5616.7	7.38	158.8	45.8
8	Exhaust	18.0	546.0	2.76	819.1	6.57	1451.5	732.5
9	Lub-oil	4.3	98.0	0.17	223.5	0.78	23.8	0.4
10	Lub-oil	5.0	98.0	0.17	304.9	0.79	37.7	13.7
11	Lub-oil	5.0	95.0	0.17	233.1	0.76	25.4	2.9
12	Water	1.5	88.1	3.52	370.4	1.18	1008.3	96.3
13	Water	2.1	90.0	3.52	377.8	1.19	1034.6	110.2
14	Water	2.1	72.2	3.52	302.3	0.98	768.7	64.1
15	Air	1.0	28.2	1.40	301.3	5.68	10.8	12.9
16	Air	1.0	40.0	1.40	313.1	5.69	27.3	25.3
17	Air	1.0	28.2	0.51	301.3	5.68	3.9	4.7
18	Air	1.0	75.0	0.51	348.1	5.71	27.8	23.6
19	Air	1.0	96.0	0.51	369.1	5.74	38.5	29.8
20	Exhaust	1.0	490.0	2.76	763.1	6.67	1296.9	496.1

In all calculations, the air and the exhaust gases are assumed as ideal gases [31]. The heat transfer rates $(\dot{Q})$, the work $(\dot{W})$, the exergy rate of fuel $(\dot{E}x_f)$ and the product $(\dot{E}x_p)$, the exergy destructions $(\dot{E}x_d)$ and the exergetic efficiencies (ε) are calculated using the governing equations given above for the components. The energetic and exergetic analyses of all subcomponents are given in Table 3.

Table 3. Thermodynamic results of MMSWPP

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}x_f$ (kW)	$\dot{E}x_p$ (kW)	$\dot{E}x_d$ (kW)	ε (%)
Compressor	-	132.59	132.59	110.08	22.51	83.02
Intercooler	1566.45	-	164.13	119.75	44.38	72.96
HE 1	1566.45	-	119.75	12.42	107.34	10.37
Pump 1	-	13.84	13.84	13.33	0.51	96.33
HE 2	12.21	-	10.82	6.22	4.59	57.54
HE 3	265.84	-	46.05	18.93	27.11	41.12
Pump 2	-	26.22	26.22	13.84	12.38	52.78
Turbine	-	154.67	236.45	154.67	81.78	65.41
Energetic Efficiency						**37.30**
Exergetic Efficiency						**50.97**

Table 4 shows the actual investment costs and other related equipment costs which are provided by the power plant management. The operating cost of each component is also considered as 20 % of the capital investment cost according to the statement of the contractor municipality.

Table 4. Total capital investment of the MMSWPP

I. Fixed Capital Investment	x 10^3 $
A. Direct Costs	
1. Onsite Costs	
Total Purchased Equipment Cost (PEC)	**926.54**
Purchased equipment installation	520.63
Piping	488.1
Instrumentation and controls	569.44
Electrical equipment and materials	488.1
Total Onsite Costs	**2066.27**
2. Offsite Costs	
Civil, structural, and architectural work	162.7
Service facilities	455.56
Total Offsite Costs	**618.26**
TOTAL DIRECT COSTS	**3611.07**
B. Indirect Costs	
Engineering and supervision	146.43
Construction costs	244.05
Total Indirect Costs	**390.48**
FIXED CAPITAL INVESTMENT	**4001.55**
II. Other Outlays	**146.43**
TOTAL CAPITAL INVESTMENT	**4147.98**

It is predicted by the authorized engineers in power plant that the process with a full load is carried out at approximately 8040 h per year for 20 years. The total purchased equipment costs (PEC) of all sub-components in the plant are presented in Table 5 evaluating the link between first capital investment (CI) cost and operating & maintenance (OM) costs using operation time. Here $\dot{Z}_k^T$ in represents the total capital cost rate. The exergy flow rate $\dot{E}x$, cost flow rate $\dot{C}$ and the unit exergy cost c of each stream in the plant are also evaluated utilizing the exergy cost rate balance and by the corresponding auxiliary equations.

Table 5. Total cost rate of components of MMSWPP

Component	PEC (x 10^3 \$)	$\dot{Z}_k^{CI}$ (\$/h)	$\dot{Z}_k^{OM}$ (\$/h)	$\dot{Z}_k^{T}$ (\$/h)
Chiller	83.89	10.43	2.09	12.52
Blower	31.18	3.88	0.78	4.65
$DeSO_x$	97.62	12.14	2.43	14.57
Compressor	50.67	6.30	1.26	7.56
Intercooler	43.79	5.45	1.09	6.54
HE 1	46.25	5.75	1.15	6.90
Pump 1	35.27	4.39	0.88	5.26
HE 2	46.25	5.75	1.15	6.90
HE 3	46.25	5.75	1.15	6.90
Pump 2	35.27	4.39	0.88	5.26
Turbine	58.67	7.30	1.46	8.76
Other plant equipment	351.43	43.71	8.74	52.45
Total Purchased Equipment Cost (PEC)	926.54	115.24	23.05	138.29

The unit exergy cost of fuels and products, the relative exergy cost difference, the exergoeconomic factor, the cost rate of exergy destruction and the total investment cost rate of the sub-components in the plant are tabulated in Table 6 considering fuel (F) and product (P) costs of each sub-component.

Table 6. Thermoeconomic results of MMSWPP

Component	$c_{f,k}$ (\$/GJ)	$c_{p,k}$ (\$/GJ)	r (%)	f (%)	$\dot{D}_D$ (\$/h)	$\dot{Z}^T$ (\$/h)
COMP	12.54	44.79	72.01	99.77	0.02	7.56
IC	44.79	171.56	73.89	98.73	0.08	6.54
HE1	1.40	8.30	83.13	96.41	0.26	6.90
PUMP1	9.44	119.47	92.10	86.54	0.82	5.26
HE2	29.48	37.25	20.85	7.93	80.12	6.90
HE3	0.03	29.48	99.89	99.86	0.01	6.90
PUMP2	16.14	136.22	88.15	6.73	72.98	5.26
TURBINE	15.48	39.39	60.70	96.41	0.33	8.76

4. CONCLUSION

An increase in the waste amount which is produced by inhabitants and industrial facilities can be a vital problem for municipalities and this waste should be annihilated to preserve our environment. On the other hand, it is also possible to produce power using the waste as fuel to the power plants. Due to this reason, waste disposal technologies have been continuously improved in Turkey as well as in all other countries. Under the light of this knowledge, the energy and exergy analyses of the Malatya Municipal Solid Waste Power Plant were carried out to reveal the losses in the plant in this study. The main conclusions of this study can be summarized as follows:

- The exergetic efficiencies of the compressor and turbine of the turbocharger were calculated as 63.36% and 65.41%, respectively. This represents that a huge exergetic loss from the turbocharger.
- The exergetic efficiencies of the heat exchangers (1-2-3) were calculated as 10.37%, 57.54%, and 41.12%, respectively.
- The worst and best exergetic performances are evaluated for the heat exchanger 1 (10.37%) and pump 1 (96.33%), respectively.
- By means of thermodynamic analyses of all subcomponents, the exergetic efficiency of the power plant was found to be 46.34%.
- Moreover, the thermal efficiency of the gas engine was evaluated as 33.91% which is compatible with the technical specifications of the MWM TCG 2020 type gas engine.
- The net electrical output of the MWM TCG 2020 type gas engine is 1000 kW. The total cost rate of the power plant is found to be 74.66 \$/h.
- The marketing price of electricity for 1 kWh is set to 13.3 ¢ throughout the economic system life of 20 years regarding agreements. The price of 1 kWh electricity production in a power plant is found to be 6.601 ¢.
- 2 identical gas engines in power plants can produce power of 2000 kWh. As a result of thermoeconomic analyses, the total investment cost and an annual gain of MMSWPP are found to be 8,295,960 \$ and 1,077,189 \$, respectively.
- The payback period of the Malatya Municipal Solid Waste Power Plant is found to be 7.70 years as a result of thermoeconomic analyses, which is rational for energy production power plants. However, if the plant is to be operated with an installed capacity of 2.2 MW of electricity generation capacity, this period will be reduced considerably.

Nomenclature

A	heat transfer area, m^2
c	cost per exergy unit, \$/GJ
c_f	unit exergy cost of fuel, \$/GJ
c_p	unit exergy cost of a product, \$/GJ
$\dot{C}$	cost rate, \$/h
$\dot{D}$	cost rate of exergy destruction, \$/h
$\dot{E}x$	exergy rate, kW
f	exergoeconomic factor
h	specific enthalpy, kJ/kg
i	interest rate
$\dot{m}$	mass flow rate, kg/s
n	total lifetime
N	annual operation time
P	pressure, bar
PR	pressure ratio
$\dot{Q}$	heat addition, kW
r	relative cost difference

s specific entropy, kJ/kg-K
T temperature, °C
U heat transfer coefficient, kW/m^2-K
$\dot{W}$ workflow rate-power, kW
$\dot{Z}$ capital cost rate, $/h

Greek symbols

ε exergy efficiency
εf effectiveness
η energy efficiency
η_C compressor isentropic efficiency
η_{GT} turbine isentropic efficiency
ϕ maintenance factor
ψ specific flow exergy, kJ/kg

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Biographies

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