An adapted organic Rankine cycle - ORC in Gaziantep Municipal Solid Waste Power Plant

Emrah Özahi, Alperen Tozlu, and Ayşegül Abuşoğlu

Abstract**—** In recent years, municipal solid waste (MSW) management has drawn an attention due to the increasing risk of its environmental pollution and becoming energy source potential. Municipal solid waste can be reused efficiently in an energy recovery systems if a proper method is selected in a power plant. Up to now, the typical disposal and energy recovery method of MSW is sanitary landfill and currently there are some developments on MSW incineration systems. As an energy recovery system, an organic Rankine cycle (ORC) can be an alternative technique in order to increase an overall energetic efficiency of a MSW power plant using excessive energy of exhaust gas sent to atmosphere. In this respect, a proper fluid that operates in ORC should be determined for satisfying maximum amount of energy recovery. In this study, a model in which ORC system is used for energy production from the exhaust gas is proposed for an existing MSW power plant located in Gaziantep city. The thermodynamic analyses were carried out for the adapted ORC system using pentafluoropropane, R245fa as a working considering the energetic and exergetic efficiencies of the system.

Keywords**—**Municipal solid waste, Organic Rankine cycle, Power plant, Waste to energy.

I. INTRODUCTION

INCREASE in industrial facilities, economic development and rapid urbanization in Gaziantep city have caused an increase in the amount of municipal solid waste (MSW). Until the end of 1990s, there was only one unsanitary landfill that had serious environmental problems because of uncontrolled gas emissions and air pollution. In this study, a theoretically adapted ORC system to the existing MSW power plant will be investigated in the frame of energy recovery.

Organic Rankine cycle (ORC) is an important low grade thermal energy recovery technology because of its small scale feature. ORC can be used to all kinds of low-temperature heat sources including geothermal energy, solar energy, biomass energy, and especially waste heat energy. Drescher and Bruggemann [1] presented a procedure to calculate ORC efficiency with sufficient accuracy based on the DIPPR database and the Peng–Robinson–EOS. They aimed to find thermodynamic suitable fluids for ORC in biomass power plants. They resulted that efficiency correlates with a low minimum temperature, high vaporization temperature and a high amount of vaporization enthalpy to input enthalpy and if these parameters are optimal, low maximum and minimum process pressure leads to a slight improvement of efficiency. The conclusion of their study showed that the best operating values for a biomass plant is a maximum process temperature of 573 K, a maximum pressure between 0.9 and 1.5 MPa. They also concluded that the family of alkyl benzenes gives highest efficiencies.

Hung et al. [2] investigated Rankine cycles using organic fluids as working fluids in converting low-grade energy with the main purpose of describing suitable working fluids which may yield high system efficiencies in an ORC system. They calculated the efficiencies of ORC systems using such parameters which are turbine inlet temperature, turbine inlet pressure, condenser exit temperature, turbine exit quality, overall irrversibility, and system efficiency regarding to an assumption that the inlet condition of the working fluid entering turbine is in saturated vapor phase. They indicated that wet fluids with very steep saturated vapor curves in T-s diagram have a better overall performance in energy conversion efficiencies than that of dry fluids. Also they suggested that all the working fluids have a similar behavior of the efficiency-condenser exit temperature relationship. Finally they concluded that an appropriate combination of solar energy and an ORC system with a higher turbine inlet temperature and a lower condenser temperature may provide an economically feasible and environment-friendly renewable energy conversion system.

Bao and Zhao [3] reviewed that the selections of working fluids and expanders for organic Rankine cycle, including an analysis of the influence of working fluids category and their thermodynamic and physical properties on the organic Rankine cycle's performance. They also presented a summary of pure and mixed working fluids screening researches for organic Rankine cycle, a comparison of pure and mixture working fluids applications and a discussion of all types of expansion machines operating characteristics. They resulted

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that it would be beneficial to select the optimal working fluid and suitable expansion machine for an effective organic Rankine cycle system.

Kaska [4] carried out an energy and exergy analysis of a waste heat driven ORC and determined performance of the cycle and pinpoint sites of primary exergy destruction using actual operational plant data. In addition to this, he has tabulated variations of energy and exergy efficiencies of the system with evaporator/condenser pressures, superheating and subcooling. It was concluded that the components which are evaporator, turbine, condenser and pump have greater exergy destructions to lower, respectively.

Tchanche et al. [5] presented various Rankine cycle architectures for single fluids and other improved versions operating with ammonia/water mixture. They sketched the waste heat resources and their potential for driving ORC. They claimed that the nature state and temperature of the heat source significantly influenced the choice of the type of ORC machine and also the temperature appeared as a critical parameter during the selection process. They considered characteristics of a module: heat source temperature, power output, thermal efficiency. They calculated the maximum thermal efficiency of module is 25 %. They concluded that the selection of a module primarily based upon application, heat source temperature and desired power output.

He et al. [6] categorized the low-grade heat sources coupled by ORC (organic Rankine cycle) into two groups. They presented these groups as the inlet temperature and the mass flow rate are known, and the working mass of the heat source was directly discharged after being used and the heat release was specific and the working mass of the heat source was usually recycled after releasing heat. They claimed that the selection of working fluids for subcritical ORC should couple with the types of low-grade heat sources. For the first heat source, they resulted that the working fluids with high liquid specific heat and low latent heat of evaporation should be selected as the working fluids using theoretical analysis and numerical simulation. On the other hand, they also concluded that the working fluids with low liquid specific heat and the high latent heat of evaporation were better for the second heat source.

Di Maria et al. [7] analyzed the energetic performance of an ORC system fueled by the heat generated from the integrated aerobic/anaerobic treatment of organic waste. They increased the temperature and heat content of the exhaust air arising from the aerobic treatment by the combustion of the biogas produced by the anaerobic digestion of a fraction of the same waste. After the investigation, they claimed that the best energetic utilization of the biogas was achieved for ORC compression ratios from 1.5 to 2 and for maximum air temperatures from 335 to 340 K and in these conditions, by using a micro-ORC system, it was possible to convert about 20 % of the energy content of the biogas into electrical energy.

Di Maria and Michale [8] performed the amount of heat rejected by the exhaust air generated by the aerobic treatment of organic waste (OW) with the aim of evaluating the amount of electrical energy recoverable by a micro organic Rankine cycle. They carried out energetic and exergetic analysis along with an evaluation of the investment costs for a full scale facility processing 32,000 ton/year of OW and resulted that the average exhaust air rate was of about 4,000 Nm3/h with a temperature of 341 K and a relative humidity of 100%. They determined the net power output of the micro-ORC ranged from about 2 kW to about 20 kW and the net electrical efficiency decreased from 5% to about 2% also the exergetic efficiency increased from 11% to 1%. Finally they calculated that the specific investment ranged from about 2,800 €/kW to about 3,900 €/kW and the cost of the electrical energy resulted of about 0.1 €/kWh to about 0,13 €/kWh.

Galloni et al. [9] investigated the prototype of a small ORC power plant using R245fa as working fluid at the Energy Systems Laboratory of Cassino University. The aim of their study was to assess the feasibility of small-scale ORC plants. During their investigation hot source and cold sink temperature and R245fa vapor maximum pressure were in the range of 75-95 °C, 20-33 °C, and 6-10 bar, respectively. In this operating range, they resulted that the best option as: electric power equal to 1.2 kW, specific work about 20 kJ/kg and cycle efficiency slightly greater than 9 %.

Andreasen et al. [10] presented a novel organic Rankine cycle layout, named the organic split-cycle, designed for utilization of low grade heat. They developed this by implementing a simplified version of the split evaporation concept from the Kalina split-cycle in the organic Rankine cycle in order to improve the boiling process. They carried out for eight hydrocarbon mixtures for hot fluid inlet temperatures at 120 °C and 90 °C, using a genetic algorithm to determine the cycle conditions for which the net power output was maximized using optimizations. They resulted that the most promising mixture was an isobutene/pentane mixture which, for the 90 °C hot fluid inlet temperature case, achieved a 14.5 % higher net power output than an optimized organic Rankine cycle using the same mixture.

Desai and Bandyopadhyay [11] carried out thermo-economic comparisons of organic Rankine and steam Rankine cycles powered by line focusing concentrating solar collectors. They proposed a simple selection methodology, based on thermoeconomic analysis, and a comparison diagram for working fluids of power generating cycles. They concluded that concentrating solar power plants with any collector technology and any power generating cycle could be compared using the proposed methodology.

Muhammad et al. [12] performed an experimental investigation of a small scale (1 kW range) organic Rankine cycle system with R245fa as working fluid for net electrical power output ability, using low-grade waste heat from steam. They designed a system for waste steam in the range of 1–3 bar then they carried out thermodynamic simulation, equipment selection and construction of test rig. They produced a maximum electrical power output of 1.016 kW with 0.838 kW of net electrical power output and determined the thermal efficiency of the system, net efficiency, and expander isentropic efficiency 5.64 %, 4.66 %, and 58.3 %, respectively at maximum power output operation point. They resulted that the measured electric power output and enthalpy determined power output showed a change by 40 %. They concluded that expander and screw pump were losing power in electric and mechanical losses presenting a need of further development of these components for better efficiency.

Ozdil et al. [13] presented thermodynamic analysis of an ORC in a local power plant that was located southern of Turkey and analyzed system components separately using actual plant data and performance cycle taking into account the relationship between pinch point and exergy efficiency. They resulted that when the pinch point temperature decreased, the exergy efficiency increased because of the low exergy destruction rate. They calculated energy and exergy efficiencies of the ORC as 9.96 % and 47.22 %, respectively. They also calculated exergy efficiency of the ORC for different water phases as 41.04 % for water mixture form which had quality 0.3, 40.29 % for water mixture form which had quality 0.7, 39.95 % for saturated vapor form. Then they resulted that exergy destruction rates of the system were 520.01 kW for saturated liquid form, 598.39 kW for water mixture form which had quality 0.3, 609.5 kW for water mixture form which had quality 0.7 and 614.63 kW for saturated vapor form. Finally they concluded that evaporator had important effect on the system efficiency in terms of exergy rate.

Safarian and Aramoun [14] presented a theoretical framework for the energy and exergy evaluation of a basic as well as three modified ORCs which were considered incorporating turbine bleeding, regeneration. They resulted that evaporator had major contribution in the exergy destruction which was improved by increase in its pressure and the integrated ORC with turbine bleeding and regeneration had the highest thermal and exergy efficiencies and the lowest exergy loss due to decrease in cold utility demand and high power generation.

Li et al. [15] performed simulations based on the engineering equation solver (EES) software programme to determine the suitable working fluid for the simple ORC system in different temperature ranges. They considered the influence of different organic working fluids on the efficiency of the subcritical ORC power generation system under the condition of various temperatures and a constant thermal power of the flue gas and also compared its efficiency and other parameters with those of the regenerator system. They showed that the efficiency of the subcritical ORC system was the best option when the parameters of the working fluid in the expander inlet were in the saturation state. They also resulted that the R245fa was better than other working fluids when the flammability, the toxicity, the ozone depletion, the greenhouse effect and other factors of the working fluids were considered for the ORC. They suggested that the R601a working fluid might be preferred for the high-temperature heat source because of its high flammability.

Li [16] investigated many working fluid candidates for various ORC applications based on the heat source temperature domain for the thermal efficiency, exegry destruction rate and mass flow rate under different ORC configurations. It was found that the thermal efficiency could be increased when the critical temperature of the working fluid was increased and the condensing temperature and evaporating pressure are fixed. He also resulted that the ORC within heat exchanger had a higher thermal efficiency than the baseline ORC, the reheat ORC thermal efficiency was close to the baseline ORC, and the regenerative ORC could achieve higher thermal efficiency than the baseline by reducing the addition of heat from the evaporator heat source.

Pu et al. [17] carried out a small scale ORC system, which was built for an experimental study, capable of generating electric power using a low temperature heat source. They used a single stage axial turbine expander and selected R245fa and the new environmentally friendly HFE7100 as the working fluids in the experimental system. Then they resulted the influences of the evaporating pressure, pressure drop and mass flow rate on overall system performance. It was concluded that the maximum electric output generated by the turbine expander was 1979 W for R245fa, while the maximum electric power output was 1027 W for HFE7100.

II. THERMODYNAMIC ANALYSES

Mass, energy and exergy balances for any control volume at steady state with negligible kinetic and potential energy changes can be expressed, respectively, by [18]

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{1}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \, h_e - \sum \dot{m}_i \, h_i \tag{2}$$

$$\dot{Ex}_{heat} - \dot{W} = \sum \dot{m}_e \, \psi_e - \sum \dot{m}_i \, \psi_i + \dot{Ex}_d \tag{3}$$

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, $\dot{Ex}_d$ is exergy destruction and $\dot{Ex}_{heat}$ is the net exergy transfer by heat at temperature T, which are given by:

$$\dot{Ex}_d = T_0 \, \dot{S}_{gen} \tag{4}$$

$$\dot{Ex}_{heat} = \sum \left(1 - \frac{T_0}{T} \right) \dot{Q} \tag{5}$$

The specific flow exergy is given by

$$\psi = (h - h_0) - T_0(s - s_0) \tag{6}$$

$$\dot{Ex} = \dot{m}\psi \tag{7}$$

where the subscript 0 stands for the restricted dead state. Isentropic efficiencies of turbine and compressor can be defined as [19]:

$$\eta_t = \frac{w_a}{w_s} = \frac{h_i - h_e}{h_i - h_{es}} \tag{8}$$

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

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 [19]:

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

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:

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

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

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.

$$\varepsilon_{he} = \frac{(\dot{Ex}_e - \dot{Ex}_i)_{cold}}{(\dot{Ex}_i - \dot{Ex}_e)_{hot}} = \frac{\dot{m}_{cold}\left[h_e - h_i - T_0(s_e - s_i\right]_{cold}}{\dot{m}_{hot}\left[h_i - h_e - T_0(s_i - s_e\right]_{hot}} \tag{13}$$

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

III. RESULTS AND DISCUSSIONS

Gaziantep Municipal Solid Waste Power Plant (GMSWPP) was installed in 1996, in Gaziantep, Turkey. In GMSWPP, landfill gas (LFG) is created during the anaerobic decomposition of organic substances in municipal solid waste (MSW), industrial and medical wastes. This plant which has 5.66 MW installed power produces a portion of 1.25% of total power demand of Gaziantep. However, there are many deficiencies in the existing plant such that the exhaust gas with a temperature of approximately 567 °C is sent to atmosphere without any energy recovery.

In this respect, an ORC system which is given in Fig. 1 is modelled and adapted theoretically to the existing GMSWPP using an organic fluid, pentafluoropropane, R245fa due to its potential use in low-grade energy source. In this frame, an ORC system is modelled in Aspen Plus software program and then the thermodynamic analyses are performed in Engineering Equation Solver (EES).

In order to transfer the energy of the exhaust gas with a temperature of 567 °C at 1.9 bar to the organic fluid, water is used as an intermediate working fluid in a heat exchanger. Because the energy with this high temperature is not suitable to transfer directly to an organic fluid. Thus, not only the temperature of exhaust gas is decreased before discharging to the atmosphere but also a heat source is obtained for ORC system. The inlet exhaust gas with a temperature of 567 °C increases the water temperature to 101 °C at 1 bar in the heat exchanger and leaves with the temperature of 190 °C. Then the saturated mixture water at 101 °C delivers the energy to R245fa in the evaporator so that the temperature of R245fa is increased to 93.4 °C at 9 bar. Throughout the turbine, 234.5 kW power is produced, which is about 3.92 % of total power production at GMSWPP. A small portion of the produced power in turbine, which is 12.29 kW, is used for pump operation. The remaining part of energy, 2196 kW, is rejected through the condenser to the water which increases the temperature of water to approximately 36 °C. This water supply at 36 °C can be utilized for general purpose in the plant.

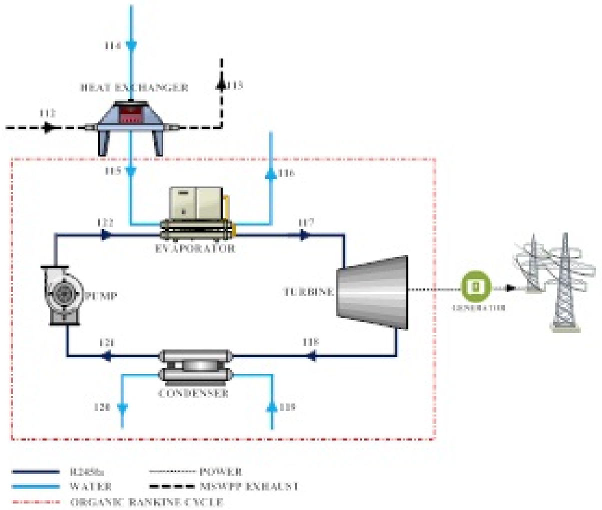

Fig. 1 Organic Rankine cycle model adapted to the existing municipal solid waste power plant

Energy and exergy analyses of the ORC system are carried out by using actual operational data taken from GMSWPP and the results are tabulated in Table I.

Table I. The results of thermodynamic analyses of the ORC system

Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{E}_F$ (kW)	$\dot{E}_P$ (kW)	$\dot{E}_D$ (kW)	ε (%)
Heat Ex.1	6409	0	3596	1176	2420	33
Evaporator	2716	0	657	484	173	74
Turbine	0	235	277	235	42	85
Condenser	2196	0	214	158	56	74
Pump	0	12	12	7	5	53
Energetic Efficiency						8.2 %

IV. CONCLUSION

This study provides a knowledge about energy recovery systems that can be adapted to any power plant in order to profit from waste energy of exhaust gas. One of the most suitable energy recovery systems is a typical organic Rankine cycle with a proper organic working fluid. In this study, it is found that 3.92 % of total power production at GMSWPP can be reproduced by coupling an ORC system to the existing power plant with an energetic efficiency of about 8.2 %. In future studies, it is suggested that different organic working fluids should be examined for such power plants at different operating conditions. The effects of mass flow rate, temperature and pressure of working fluid and auxiliary fluids in heat exchangers, type of heat exchanger, etc. on energetic and exergetic efficiencies of energy recovery systems should be investigated.

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