Proceedings of the 18th Annual North American Waste-to-Energy Conference
NAWTEC18
May 11-13, 2010, Orlando, Florida, USA

NAWTEC18-3563

ENERGY RECOVERY IMPROVEMENT USING ORGANIC RANKINE CYCLE AT COVANTA'S HAVERHILL FACILITY

Heping Cui
Covanta Energy Corporation, 40 Lane Rd. Fairfield, NJ 07004

Jim Lynch, David McQuillan, Joseph Becker
Covanta Haverhill Resource Recovery Facility, 100 Recovery Way, Haverhill, MA 01835

Tim Sundel
United Technologies Research Center, 411 Silver Lane, MS 129-13, East Hartford, CT 06108

ABSTRACT

Covanta Energy, in cooperation with United Technologies Corporation (UTC), has evaluated, designed, and is in the process of installing an Organic Rankine Cycle (ORC) system at its Haverhill Energy from Waste (EfW) Facility to improve heat recovery and energy efficiency, and to generate more clean renewable energy. ORC systems have been applied in geothermal applications and some other industrial processes to recover low grade and waste energy to generate electricity. This paper describes the design and integration of the ORC system into the Haverhill EfW steam cycle, and the landfill gas engine system, which also operates at the facility. The anticipated energy efficiency improvements and increased net power output have been analyzed and simulated. The results show that the integration of the ORC system could lead to a potential increase in the net power output by as much as 305 kWe in the summer and by 210 kWe in normal weather. It is also anticipated that with the ORC system the facility has the potential to improve the overall plant energy efficiency, as well as save city water.

1. INTRODUCTION

Covanta Energy owns and operates more than 40 EfW plants in North America. Covanta is committed to improving energy efficiency and generating more renewable energy from its EfW plants. One of the efforts is to effectively recover waste heat from those plants, such as vented and dumped steam, and energy lost with the stack gas. Covanta Energy, in cooperation with United Technologies Corporation, has evaluated, designed, and is in the process of installing an Organic Rankine Cycle (ORC) test system at its Haverhill Energy from Waste (EfW) Facility to improve heat recovery and energy efficiency, and to generate additional renewable energy. The installation will be completed in 2010.

The Haverhill facility operates two 825 TPD mass-burn EfW units that started up in 1989. Each boiler produces 865 psig (5.96 MPag) and 830 °F (443 °C) superheated steam, which is used to generate about 46 MW of gross power through a condensing turbine. The turbine has three bleeds for steam extraction. The 2 psig (13.8 kPag) extraction steam from the third bleed is used to heat the feedwater and is then merged with steam condensate in the air condenser collection tank. Intermediate pressure steam 50 psig (345 kPag) from the second bleed is directed to the deaerator for heating, temperature and pressure control. Energy in the steam turbine exhaust is rejected via an air-cooled condenser. Figure 1 shows a diagram of the main steam cycle system at the Haverhill facility. Due to limitations of the existing air-cooled condenser, some intermediate pressure steam from the 2nd turbine bleed has to be periodically vented to the atmosphere during hot weather (ambient conditions above 80 °F (26.7 °C)), while a given amount of MSW throughout is maintained, resulting in a decrease in both energy efficiency and net power output. This vented steam is a kind of high quality waste energy due to its latent heat, which the facility wants to recover. A secondary value of recovering this stream is the savings of clean, treated water which is lost with the vent.

The Haverhill facility also operates a landfill with a gas recovery system adjacent to the EfW facility. The landfill gas is used to run a 1.6 MW Caterpillar engine. The engine exhaust temperature is 900 - 950 °F (482 – 510 °C). The gas engine exhaust and jacket water coolant loop are sources of recoverable waste heat, which are currently lost to the atmosphere. It is estimated that this exhaust loses 1,158 kWt of recoverable thermal energy, while the jacket water circuit loses approximately 676 kWt of thermal energy, both of which can be recovered and converted into useful electricity by an ORC system.

This paper describes the design and integration of the ORC system into the Haverhill landfill gas engine and EfW steam cycle systems to recover waste heat and generate additional renewable energy (power). A detailed thermodynamic analysis and simulation was done to determine the expected energy efficiency improvements and impact on the plant operation. The results of this exercise are discussed in the following sections.

2. ORGANIC RANKINE CYCLE (ORC) AND HEAT RECOVERY SYSTEM INTEGRATION

An ORC unit manufactured by Pratt & Whitney Power Systems, and furnished by Carrier Corporation, both divisions of United Technologies Corporation, will be installed to recover the waste energy sources outlined above at the Haverhill facility. The major components of an ORC unit are a pump, an evaporator, a turbine generator, a condenser and a cooling system, as shown in Figure 2. It uses refrigerant R-245fa as the working fluid, which has a much lower boiling point (59 °F, or 15 °C) than water. The working fluid is vaporized in the evaporator under a well-controlled pressure and is then used to drive the ORC turbine. Afterwards, the refrigerant is condensed and pumped back to the evaporator to complete the cycle. Similar to traditional Rankine steam turbine generation systems, the efficiency of the ORC generation system is dependent upon the heat sources, condensing system and atmosphere conditions.

This ORC system is rated at 280 kWe gross, and will be powered by a combination of waste heat recovered from the landfill gas engine and the extraction steam from the turbine 3rd bleed, as shown in Figures 1 and 3. For the purposes of the testing program at Haverhill, it was decided to employ standard, commercially available ORC equipment, and utilize a 30% propylene glycol solution as the heat transfer media in the heat recovery system. The cool glycol fluid will first recover waste heat from the 230 °F (110 °C) engine jacket water through a heat exchanger. The glycol will then be further heated by a portion of the 3rd extraction steam. Finally, the warm glycol will be heated through a third heat exchanger to recover waste heat from the 900 °F (482 °C) exhaust of the gas engine.

3. THERMODYNAMIC ANALYSIS

The ORC unit is designed with an efficiency of 8.67 % for the normal ambient conditions in Haverhill, but fluctuates with the temperature of the heat recovery fluid entering the ORC unit and atmospheric temperature, as shown in the Table 1. Either higher heat recovery fluid temperature or lower cooling tower returning water temperature can lead to higher ORC efficiencies. Alternatively, when the heat recovery fluid temperature decreases, or the cooling tower returning water temperature increases in summer, the ORC efficiency drops. For example, the ORC efficiency drops to 8.27% at an ORC cooling tower returning water temperature of 85 °F (29.4 °C). In this case, more thermal energy input to the ORC unit is needed to maintain a constant ORC power output. During summer, we expect to provide an additional about 500 pounds (226.8 kg) per hour of 2 psig (13.8 kPag) steam to compensate for hot day ambient conditions. This has the added benefit of both keeping the steam in the process and by-passing the under-surfaced main steam turbine air condenser.

As shown in Table 1, the total thermal energy input needed for the ORC unit at 8.67 % efficiency under normal ambient conditions 55 °F (12.8 °C) is 3230 kWt, which increases to 3386 kWt when the efficiency drops to 8.27 % in summer. The total recoverable thermal energy from the landfill gas engine is 1834 kWt, including 1158 kWt from the exhaust and 676 kWt from the jacket water. Thus, the heat input demanded from the low pressure 3rd extraction steam (1092.8 btu/lb or 2541.9 kJ/kg) is 1396 kWt and 1552 kWt for the normal ambient conditions (55 °F, or 12.8 °C) and summer conditions (85 °F, or 29.4 °C), respectively. These demands correspond to steam flow requirements from the 3rd extraction of 4359 and 4846 lbs/hr (1977 and 2198 kg/hr), respectively. Figure 3 presents a simulated case of the temperature distribution along the glycol fluid route for the normal weather condition, where the glycol fluid enters the ORC unit at 226 °F (107.8 °C) and exits at 178 °F (81.1 °C).

A power plant simulation and analysis software was employed to further analyze and optimize the integration of the ORC system into the EfW plant, and predict its impact on the whole plant operation and performance. The following discusses the results of this analysis for normal ambient conditions and hot summer conditions at the Haverhill facility.

3.1 Summer Conditions

The thermodynamics analysis shows that under the conditions which require venting steam, benefits are particularly evident, consisting not only of the additional power output from both the ORC system and the existing turbine, but also recovery of hot condensate water.

The current steam cycle and whole plant efficiencies are obviously lower in summer compared to the normal weather conditions (Table 2). With the same rate of MSW processing, the EfW facility may lose net power output by 2500 kWe or more in summer, as a result of venting a large amount of the intermediate pressure steam and increasing in the turbine exhaust pressure due to the limitations of the existing air condenser. This unwanted situation will be improved with the integration of the ORC heat recovery system. A part of the intermediate pressure steam which is periodically vented from the 2nd turbine bleed, can continue do work in the turbine section between the 2nd and 3rd bleeds, generating additional power, which is then supplied to the ORC system through the 3rd turbine bleed.

The simulation and analysis shows that in hot summer, the actual power benefit by the ORC system will be more than the net ORC power output, with a potential increase of 380 kWe (gross) and 305 kWe (net). Consequently, both the steam cycle efficiency and the whole plant electric efficiency are expected to increase with the integration of the ORC system during the summer, as shown in the Table 2. In addition, the warm ORC condensate will be pumped back to the feedwater system, which will save about 50 TPD of city water usage for the facility.

3.2 Normal Conditions

It is anticipated that the integration of the ORC system into the Haverhill EfW facility will provide a potential increase in boiler efficiency, in addition to the waste energy recovery and energy efficiency improvements.

The Haverhill boiler efficiency is currently about 68.6 %, with an excess air ratio of about 100 %. The design temperature of flue gas exiting the economizer is 430 °F (221 °C), and is also a waste heat source which is worthy of future consideration for energy recovery. With the integration of the ORC heat recovery system, there will be potential gains for the facility to improve the boiler efficiency, while maintaining no change for other factors except the benefit of additional power output.

As shown in Table 3, in normal weather there will be at least two ways to arrange that part of the 3rd extraction steam needed for the ORC system, depending on the actual demand of the facility. One way is to extract additional steam from the 3rd bleed to supply the ORC system, which will lead to slightly lower steam flows through the last section of the turbine. This will result in slightly less power generation from the existing turbine generator, however it will also slightly reduce the load on the air condenser, yielding slightly higher main turbine-generator efficiency due to a lower turbine exhaust/condenser pressure. The ORC system will return the warm condensate (195 °F, or 90.6 °C) back to the feedwater, recovering 75 kWt thermal energy. The total increase in the net power output in the facility will be anticipated to be about 130 kWe with the ORC system. This is a simple operating mode, which however, does not take the full advantage of the ORC system installation in the facility.

Alternatively, a second strategy is to maintain the same 3rd extraction in the normal condition, with no affect and no change in the steam turbine operation. The 3rd extraction steam flow will then be split into the two streams, with a certain amount going to the ORC system and the remaining flow going to the low pressure feedwater heater. In this case, the current turbine generator has the same power output as usual, while the feedwater temperature in the deaerator will be anticipated to drop to 240.3 °F (115.7 °C) from 250 °F (121.1 °C) because of the reduced steam flow into the feedwater heater. Similar to the first strategy mentioned above, the ORC system will return the warm condensate back to the feedwater. In addition, the resulting lower feedwater temperature will result in added heat recovery in the existing economizer and improve the boiler efficiency. Such integration of the ORC test system has the potential to enable the facility to generate an additional net power of 210 kWe under the normal weather conditions.

Furthermore, to compensate for the reduction in the thermal energy in the feedwater and produce the same amount of superheated steam, the excess air to the boilers can be reduced slightly, leading to a small increase in boiler efficiency. This will also lead to a higher overall plant electric efficiency compared to the current operation, as shown in the Table 3.

4. CONCLUSIONS

This paper describes the design and integration of an ORC system to recover waste energy and improve the energy efficiency of the Covanta Haverhill EfW steam cycle and landfill gas engine system. The expected energy efficiency improvements and the net power output have been analyzed and simulated. The results of this study show that the integration of the test ORC system could lead to a potential increase in the net power output by as much as 305 kWe during hot summer weather conditions when steam is vented, and 210 kWe under normal weather conditions. It is also anticipated that with the ORC system there is a potential that the facility can improve the overall plant efficiency. The waste energy recovery system will also help the facility to save city water.

ACKNOWLEDGMENT

The authors are very grateful for the support and assistance from other team members in Covanta and UTC, particularly to Steve Goff for his help in enhancing this paper.

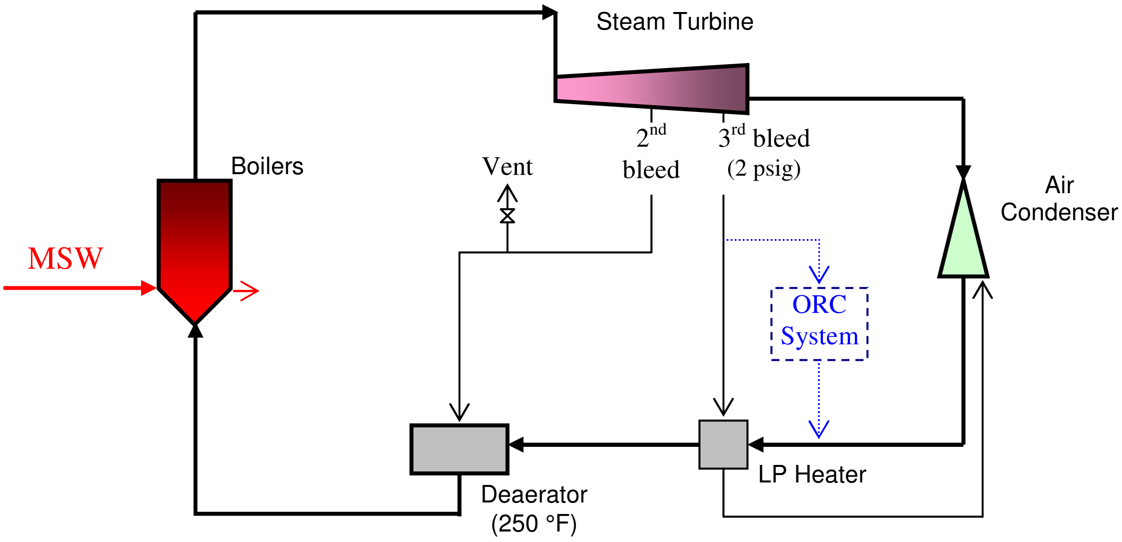

Fig. 1 Diagram of steam cycle system in Covanta's Haverhill EfW plant

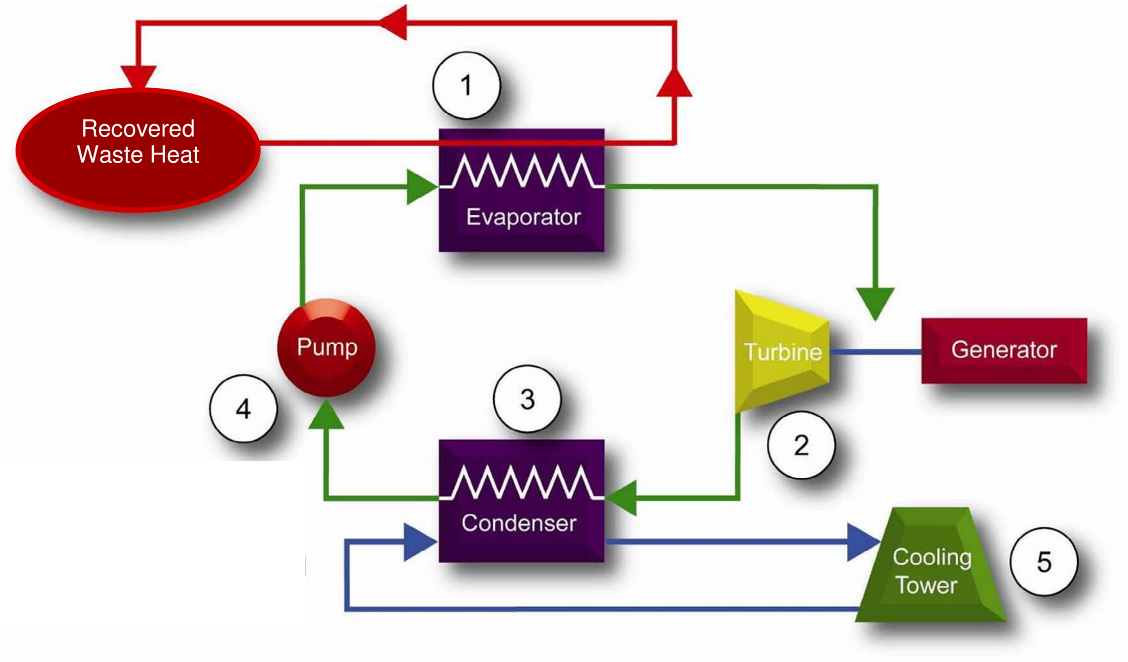

Fig. 2 Principle of Organic Rankine Cycle (ORC) system and its main components (1. Recovered waste heat is circulated through the ORC Evaporator vaporizing refrigerant which enters the expansion turbine; 2. Expanded refrigerant turns the generator and exits the turbine, entering the condenser; 3. Low pressure refrigerant vapor is liquefied in the condenser; 4. Liquid refrigerant (working fluid) is pumped into the evaporator for vaporization by recovered waste heat; 5. Condenser water circulates through the ORC via a cooling tower)

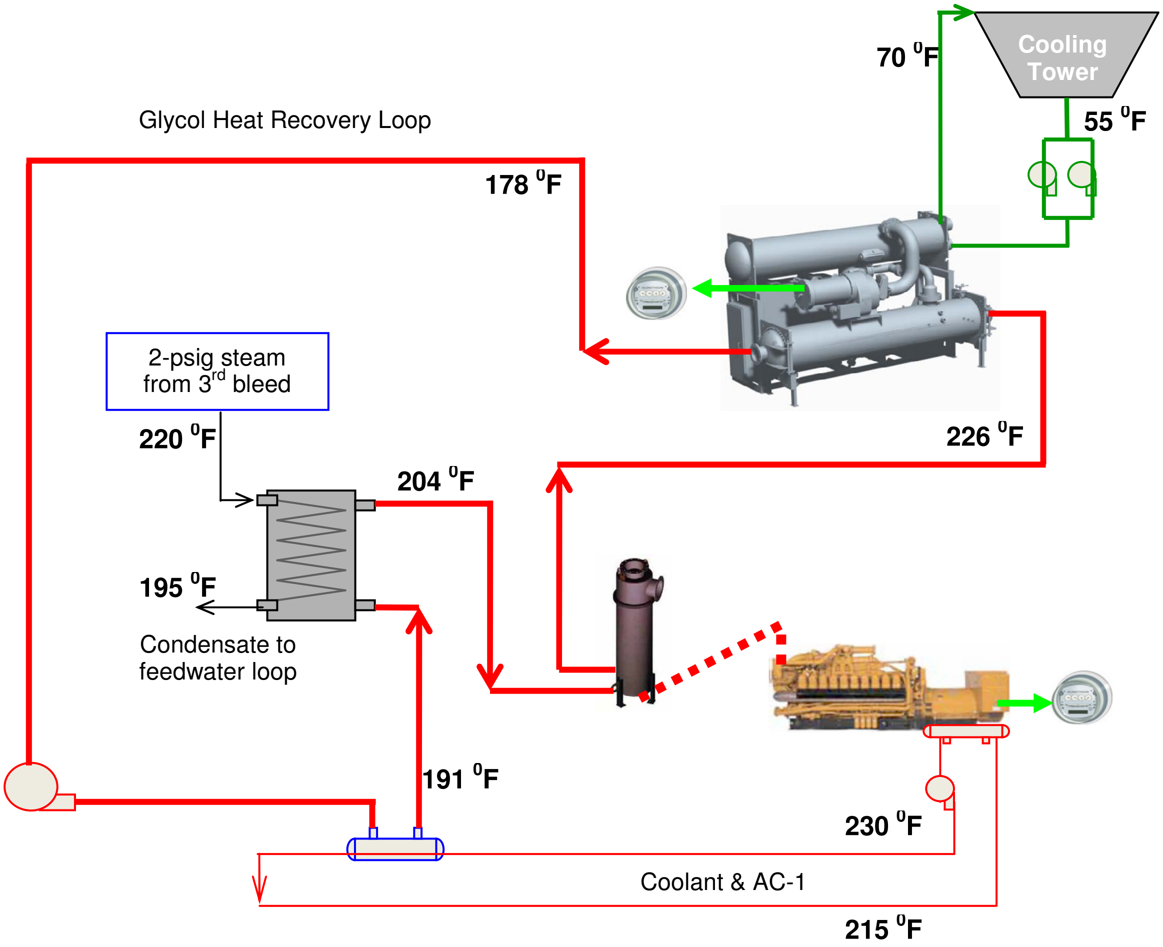

Fig. 3 Diagram of ORC heat recovery system design for landfill gas engine and low pressure steam

Table 1 Thermal input of ORC system (280 kWe, gross) under normal and summer conditions

Condition	ORC Cooling Water Inlet Temperature, °F	ORC Efficiency, %	Total ORC Heat Input, kWt	Heat from Gas Engine, kWt		Steam Heat, kWt	Steam Flow Rate Lbs/hr
				Exhaust	Jacket		
Normal	55	8.67	3230	1158	676	1396	4359
Summer	85	8.27	3386	1158	676	1552	4846

Table 2 Efficiencies of steam cycle and whole EfW plant under different conditions

Condition	Boiler Efficiency, %	Steam Cycle Efficiency, %, gross	Whole Electricity Efficiency, %, gross	Whole Electricity Efficiency, %, net
Normal (current)	68.6	32.17	22.08	19.10
Summer (current)	68.6	30.25	20.76	17.78
Summer with ORC	68.6	30.53	20.95	17.93

Table 3 Comparison of EfW facility performance with ORC system under normal conditions

Condition		Boiler Efficiency, %	Steam Cycle Efficiency, %, gross	Whole Electricity Efficiency, %, gross	Whole Electricity Efficiency, %, net	Additional Net Power Output, KWe
Current (normal)		68.6	32.17	22.08	19.10	
Normal, with ORC	A. Additional 3rd extraction	68.6	32.30	22.16	19.17	130
	B. No additional 3rd extraction, with Boiler efficiency improvement	69.2	32.11	22.22	19.21	210