Scroll expander Organic Rankine Cycle (ORC) efficiency boost of biogas engines

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ABSTRACT: The most common energy application for biogas is on-site power generation using gas engine units. The introduction of a bottoming cycle based on Scroll expander Organic Rankine Cycle (ORC) technology within a biogas plant is of high interest since the excess heat produced by biogas engines can be used to produce additional power. This paper describes the retrofit of a plant consisting of a digester fed with green municipal wastes and two biogas engine units (200kWe each). The waste heat from the cooling jacket of the first biogas unit is used in cogeneration for the fermentation process and also for heating the buildings of the facility. The objective of the retrofit project is, in a first step, to convert the excess heat from the cooling jacket of the second biogas unit by means of Organic Rankine cycles. Onsite preliminary tests from the operation of the 7 kWe unit have been done, allowing performances to be measured over a broad range of conditions. Those tests confirmed a reasonable behavior of the ORC scroll expander and the interest of the concept. The measured efficiency of the ORC is about 7% with a heat source at around 90°C (i.e. 40% exergy efficiency).

Keywords: Scroll Expander, Organic Rankine Cycle, Bottoming Cycle application, Biogas Engine Cogeneration unit

NOMENCLATURE

ORC = Organic Rankine Cycle
$\dot{E}_T$ = Electrical power of the turbine [kW]
$\dot{E}_C$ = Electrical power of the pump and others components [kW]
$\dot{M}$ = Mass flow rate [kg/s]
h = Specific enthalpy [MJ/kg]
P = Pressure [Pa]
T = Temperature [K]
v = Specific volume [m^3/kg]
s = Superheat vapor
ε = First Law efficiency
Δh_{ho} = Specific enthalpy difference of the heating source

1. INTRODUCTION

The valorization of biogas from landfills, waste water treatment plants or digestors of green biomass is usually done by internal combustion engines with or without cogeneration of heat and power. The efficiency of these engines is, in some countries like Switzerland, penalized by tough constraints of emissions (CO, NOx). Given the fact that catalysts are often unreliable because of various contaminants in the biogas itself, the widespread solution is to use uncatalyzed lean burn engines with a low compression ratio and therefore a rather low efficiency. Work is underway to improve combustion using unscavenged prechambers allowing an increase of compression ratio and an efficiency level close to that of natural gas engines [1]. However the next promising step is to better use of the exergy potential of the available heat from the combustion gas and jacket cooling. This can be done by using Organic Rankine Cycles (ORC). Figure 1 shows the efficiency of a broad range of gas engines installed in Europe [2] together with the range of improvements, which can be achieved using unscavenged prechambers and bottoming ORCs. The latter is the object of the present paper.

Electricity generation from low-temperature heat sources (<300 °C) generally implies the use of Rankine cycles equipped with turbines or expanders. Considering gas or biogas engines of a few hundreds of kW with a jacket cooling heat available of the same order of magnitude, the bottoming ORCs have to be in a range of electric power of a few tens of kW.

This is typically a power range for volumetric machines like scroll expanders [3]. Even if steam is not to be completely excluded in the future [4], working fluids mainly considered today are non flammable organic fluids like HCFC123, HFC134a or HFC245. Other fluids like toluene, isobutene, mixtures of siloxane, are also implemented for geothermal or biomass fired systems but mainly with dynamic machines and powers of several hundred of kW [5]. Smaller systems have not been economically feasible due to the lack of turbines in that size range with adequate efficiencies (particularly when having to cope with high expansion ratios and variable operating conditions) and high specific costs associated with low initial production quantities. These limitations led to the innovation of the "ORC scroll turbine" concept, a feasibility of which has already been demonstrated in previous studies [3,6]. These turbines are based on the modification of hermetic scroll compressors widely used in refrigeration and air-conditioning applications.

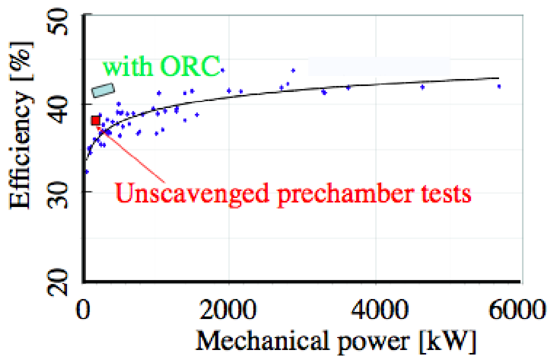

Figure 1 Efficiencies of some installed gas cogeneration motors in Europe and perspective for biogas with improved combustion and ORC.

2. SCROLL EXPANDER ORGANIC RANKINE CYCLE TECHNOLOGY

Scroll compressors are characterized by good reliability and high efficiency, with low specific costs. The concept is basically simple and was the subject of a patent in 1905 by the French engineer Léon Creux. The technology only became available from the eighties, however, due to the previous lack of high-precision machine tools capable of achieving the very high tolerances required for fabrication. Since scroll compressors offer a number of advantages in terms of function, operation and efficiency that far exceed those of reciprocating machines, their development represents a technological breakthrough, and hermetic scroll units are produced worldwide in large quantities for refrigeration and air-conditioning applications.

The scroll turbine consists of expansion chambers delimited by two involute scrolls (one fixed and one mobile) positioned such that they form a series of crescent shaped pockets (Figure 2). The mobile scroll is mounted on an eccentric drive shaft, which induces an orbital movement rather than a simple rotary motion. During expansion, high-pressure refrigerant gas is introduced into the center and moves progressively towards the periphery by increasing the volume of the pockets. When the pockets reach the periphery, the gas expands to its discharge pressure and leaves the expander through one or two large diameter ports on the opposite flanks.

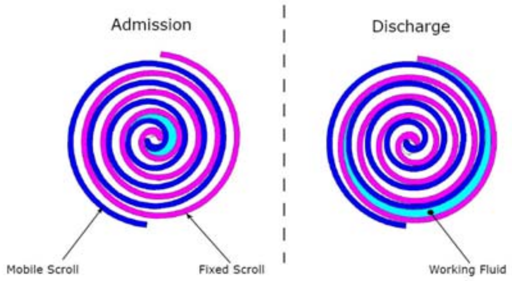

Figure 2: Scroll expander expansion process

The main advantages of this type of turbine compared to conventional volumetric turbines are: a low number of components (no suction and discharge valves), few moving parts, resulting in a high level of reliability, an ability to successfully work with a two-phase flow, low mechanical vibrations and pulsations implying a quasi-steady mechanical torque, and a quasi continuous expansion process with an excellent volumetric efficiency.

The feasibility of the Scroll expander ORC system has been demonstrated in previous work for different types of scroll units [3,5], including a 12-kWe prototype designed to work at around 150 °C. The latter has been tested both in the laboratory, using heat from a thermal oil boiler, and in the field test using heat from a solar concentrator system complemented with waste heat from a 13-kWe reciprocating diesel engine. For this specific application, two superposed ORCs were used, each working with a different fluid, so that they could be operated independently if required due to fluctuations in solar conditions and heat demand requirements. The working fluids chosen were HCFC 123 for the topping cycle and HFC 134a for the bottoming cycle.

In the literature a number of Organic Rankine Cycles are reported, in particular in liaison with solar thermal energy conversion [7,12] but generally not with scroll expanders.

3. BOTTOMING CYCLE APPLICATION TO BOOST EFFICIENCY FOR BIOGAS ENGINES

The production of biogas is an energy-intensive process that often requires both electricity and heat. The most common use of the biogas product is on-site power generation using conventional gas engines to provide the energy needed to the process. A typical plant like in *Nant de Chatillon* (Geneva, Switzerland) consists of a digester fed with green municipal wastes and producing biogas which is converted in two biogas engine units (200 kWe each). Originally the waste heat from the cooling jacket of the first biogas unit has been used in cogeneration mode to satisfy the power needs of the plant as well as the thermal needs of the fermentation process and of the heating the buildings of the facility. A retrofit project of the plant has been considered by introducing Scroll expander ORC systems as a Bottoming Cycle application to boost the efficiency of the second gas engine unit. The design of the bottoming cycle concept is a tradeoff between the efficiency, the expander characteristics and the control complexity (reliability, robustness, cost, training requirements, etc.).While both the heat from the combustion gas and from the jacket cooling could be used, in a first and conservative step, it was decided to only convert the low-temperature (90°C) excess heat from the cooling jacket to produce additional power. Available hermetic scroll expander-generators are limited in size because they are based on the modified standard scroll compressor units. Therefore the proposed concept includes two parallel ORC units (ORC1-7kWe and ORC2-13 kWe) with the advantage of better load control by shutting down one of the unit to match the fluctuations of the available heat. The present paper discusses the preliminary operation and tests of the 7 kWe ORC unit (ORC1). A detailed single-line drawing of this system is given in figure 3.

The working fluid chosen for the system is HCFC134a working between 0.6 to 2.2 MPa. The vapor produced in the (plate) evaporator is either bypassed (during warm-up) or expanded in the scroll unit. The discharged vapor is cooled and condensed in a condenser (plate) heat exchanger. Liquid HCFC134a is then returned to feed the evaporator of the cycle by a membrane-piston pump. The nominal capacity of the scroll-expander generator is 7 kWe. The hot source temperature (from the engine water cooling system) ranged between 80°C and 90°C. A wet cooling tower (not represented in the drawing) is used to cool the ORC within an intermediate close-loop water network of about 20°C to 30ºC depending on the seasons. This circuit includes a three way valve regulator that allows the adaptation of the condensation pressure. The lubricant oil required by the expander circulates with the working fluid, and the separation is made at the end of evaporation allowing to directly lubricate the bearings using the available pressure difference. A sub-cooler component has been added in order to also level the working fluid fluctuations. A flexible and robust command system has been made in place for the purpose of controlling the working-fluid mass flow by controlling the frequency of the pump. Figure 4 shows a picture of the installation in Chatillon (Genève, Switzerland). The system has been built and developed taking into account the implementation of all safety and technical requirements. This includes: safety procedures and automation (operating procedures, security system and measurement).

4. ON-SITE TESTING AND RESULTS

A series of tests have been made on-site to demonstrate the performances of the scroll expander ORC unit by using a thermal oil heat source to supply heat to the evaporator. Onsite preliminary tests from the operation of the 7 kWe unit have been done, allowing performances to be measured over a broad range of conditions.

The objective is to measure the performances of the cycle for different conditions and therefore to determine the operational feasible range of heat supply to the ORC cycle. The supply temperature as well as the heat rate from the biogas engine are directly related to the working conditions of the biogas engine. The mass flow rate of the ORC cycle can be adjustable to change the conditions (pressures and temperatures) of the working cycle. Moreover, the ORC cooling water circuit can be also used to adapt the condensation pressure of the cycle. The measured data includes the temperatures and pressures at the inlet and outlet of the main components (turbines, pump, heat-exchangers) and the net electricity output. In addition, flow-meters and temperature measurements on the hot and cold streams have been used for the determination of the energy balance of the cycles. Figures 5 and 6 show the variations of the ORC efficiency as well as the net power output in function of the heat recovered from the biogas engine.

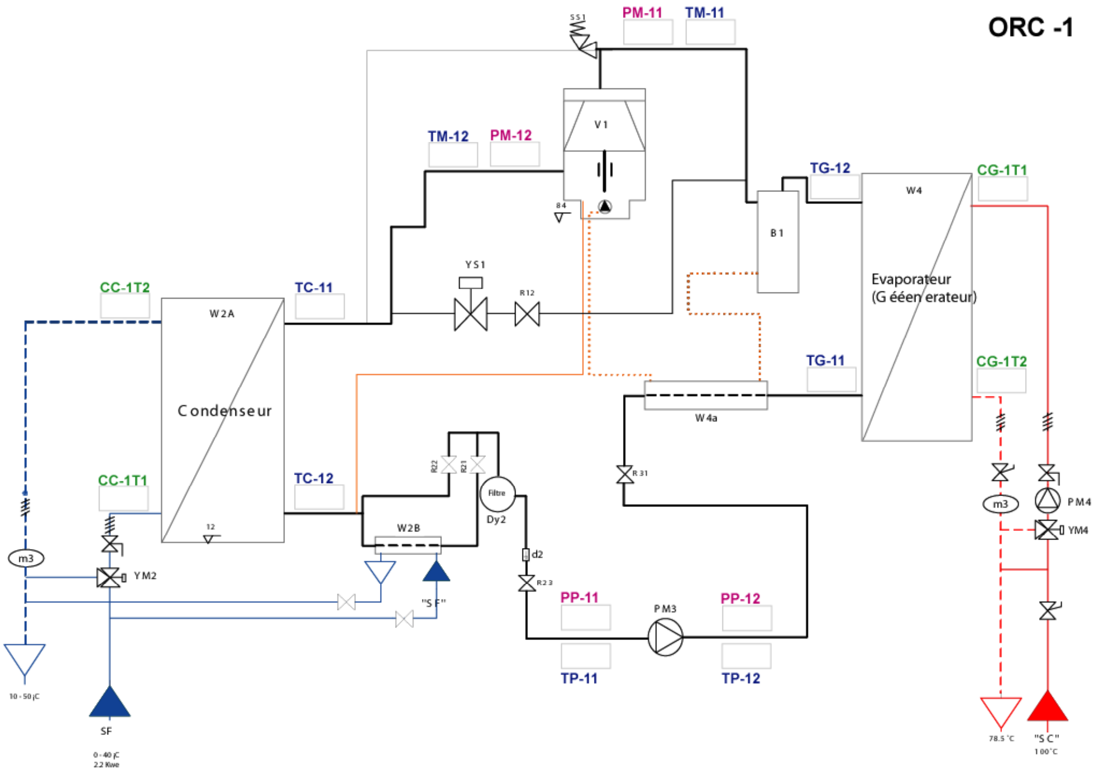

Figure 3: Schematic drawing of the 7 kWe Scroll expander ORC unit

Figure 4: ORC1 installed in Nant de chatillon

The ORC net electric output is the difference between the output of the expander and the electric power consumed by the others components like pump, fans and valves, fans divided by the heat recovered from the engine (*equation 1*)

$$\varepsilon_{ORC} = \frac{\dot{E}_T - \dot{E}_C}{\dot{M}\,\Delta h_{ho}} \qquad (1)$$

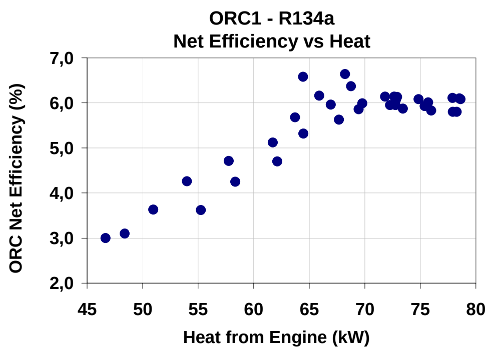

Figure 5: ORC net energy efficiency for various recovered heat rate from the engine

Results show that the ORC system can be operated even at very low power output, below 20% of its nominal design value. The cycle efficiency up to 7% was expected for this low temperature application (up to 90°C).

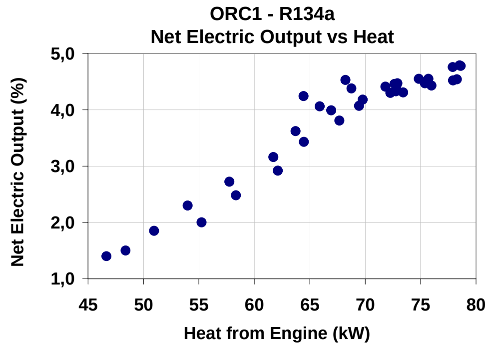

Figure 6: ORC net electric output for various heat rate from the engine

All these tests have been realized in summer when the ORC cooling network temperature achieved 30°C. The corresponding Carnot efficiency is of the order of 18%. Figure 7 shows the variations of the ORC exergetic efficiency in function of the heat recovered from the biogas engine. A net exergetic efficiency of about 40% is achieved for this application.

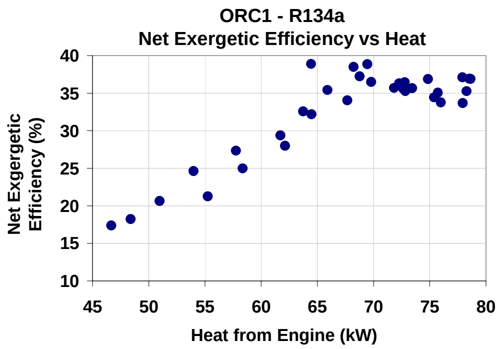

Figure 7: Net exergetic efficiencies of the ORC for various heat rates from the engine

Note that the efficiency decrease at low heat rates can be explained by the losses linked to the pressure ratio which is then too low at the expander of the working cycle. As shown in figure 8 it can be pointed out that the expander is used at very part load (operation with a pressure ratio down to **1.8**). This turbine was in fact designed to work at a pressure ratio of about **3.67** (corresponding to evaporation pressure of 2.2 MPa and a condensation pressure of 0.6 MPa). But in summer operation, as mentioned above, the ORC cooling network is at around 30°C and imposes a high condensation pressure between 0.8 and 1 MPa, which is detrimental to the efficiency. An alternative is to introduce a variable speed expander to better adjust the load. For simplicity of operation and a cheaper approach for this demonstration project, the generator is directly connected to the grid without any inverter.

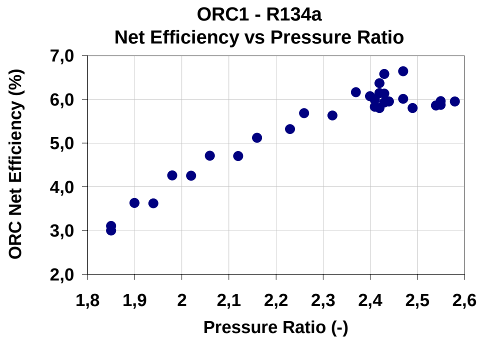

Figure 8: Net efficiency of the ORC vs pressure ratio

Others sources of losses that can influence the efficiency are related to the oil mixed with the evaporating working fluid (HFC134a), whose boiling temperature strongly increases in the dryout region of the evaporator. This phenomenon is well known in heat pumps and is accompanied by a significant drop in heat transfer coefficient with a corresponding drop of the evaporation pressure. One solution would be to introduce a falling film shell in tube evaporator instead of the plate evaporator with an accurate and fine control of the liquid pump.

Fluctuations of both the amount of heat recovered from the biogas engine and/or outside ambient temperature can be coped with the adaptation of the mass flow rates of the ORC working fluids and operational feasible ranges of vapor superheating and liquid sub-cooling can be maintained. Figures 9 and 10 show the variations of the ORC net efficiency in function of superheating and sub-cooling temperatures.

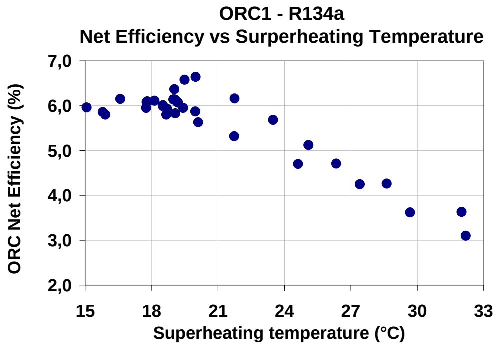

Figure 9: Net efficiencies of the ORC for various vapor superheating

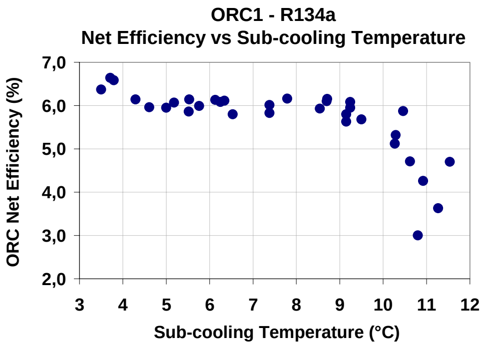

Figure 10: Net efficiencies of the ORC for various liquid sub-cooling

The results show that there is no advantage to work at relatively high difference of temperature (superheating above 20°C and sub-cooling above 10°C). A high difference of temperature corresponds in fact to a low mass flow rate that is accompanied by a significant drop of the evaporation pressure. This makes the cycles work at part load, which is detrimental for the efficiency. A low difference of temperature (for example superheating temperature below 15°C or sub-cooling temperature below 3°C) corresponding to a high mass flow is not feasible because of the possibility of refrigerant flow disturbances at the pump that makes the cycle non-stable. The limiting range is influenced by the quantity of refrigerant charged in the circuit.

4. CONCLUSIONS

The concept of bottoming cycle based on Scroll expander Organic Rankine Cycle (ORC) system has been applied to boost the electrical efficiency of a 200kWe biogas engine in a green waste fermentation plant in Nant-De-Chatillon (Geneva, Switzerland). For the retrofit project, two ORC single cycles (ORC1-7kWe and ORC2-13kWe) have been built and installed to convert only the engine cooling energy in a first approach. The design was optimized to demonstrate the system taking account of all safety requirements (safety procedures and automation). Onsite preliminary tests of the 7 kWe ORC unit have been conducted allowing the performances to be measured for a broad range of conditions. Results show that the ORC system can be operated even at very low power output, below 20% of his nominal design value and a cycle net efficiency of 7% can be achieved for a low temperature application (90°C). The field experience gained is being used to improve the automatic control of such plants which is currently underway.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support provided by OCEN and the contribution of the Swiss Federal Office of Energy. The authors also thank the companies who contributed to the construction and installation on-site.

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