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Efficiency Improvement of a Biogas Engine-Driven CHP Plant

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Running title: **Trigeneration Plant with Biogas Engine**

Abstract

Farm scale biogas plants most often use internal combustion engine-based combined heat and power (CHP) plant. In some cases (during summer) the heat demand is reduced and therefore a solution to increase the CHP plant efficiency must be found. One way could be the integration of an organic Rankine cycle (ORC) system to produce electricity and heat using recovered heat from the exhaust gas leaving the engine and an absorption chiller to produce cold water using heat recovered from the engine cooling water. The energy analysis made by using the Cycle-Tempo software (for the integrated ORC system) and the SorpSim software (for the absorption chiller) of a CHP plant composed of two dual fuel engines with total electric power of 500 kW electric and total thermal power of 410 kW, shows that the overall efficiency of the plant may be increased in this way from 74.5% to 82.8% in winter and from 60.4% to 78.8% in summer. The investment costs of the ORC system and absorption chiller can be recovered in about 3 years by selling the extra electricity (100 kW) and by saving electricity required for cooling.

Practical applications

The organic Rankine cycle systems and absorption chillers may be implemented into internal combustion engine –based CHP plants running at farm-scale biogas plants to increase the plant efficiency during summer when the heat demand is lower. The cold water produced by the absorption chiller may be used for the air conditioning system of farm buildings. With the same fuel consumption it is produced a larger amount of heat, electric power is increased and additionally cold water is produced.

Key words: biogas plant, CHP with internal combustion engine, organic Rankine cycle, absorption chiller

Introduction

Production and use of biogas especially from animal manure spread more and more in Romania due to the implementation of the European Directive 91/67/EEC of 12 December 1991 Concerning the protection of waters against pollution caused by nitrates from agricultural sources, the promotion of Code of good agricultural practice to prevent the pollution of waters by nitrates from agricultural sources but also due to the law enforcement on the promotion of electricity from renewable energy sources (producers of energy from renewable sources benefit from a number of green certificates for electricity produced and delivered).

Typically the farm-scale biogas plants are operated with animal manure and other organic substances like energy crops and food wastes. The use of food wastes as co-substrate leads to increased biogas production. The biogas plant owner increases his earnings due to higher biogas production and also by picking up the food waste from their sources (Fischer T., 2014; Tamrat et al., 2013).

Around one third of the food produced globally is lost or stored as waste. European Commission assesses that only in the EU around 88 million tonnes of food are sent annually to the landfills. The food wastes (uneaten food and food preparation leftovers) are generated in the entire food chain, from food production (farming), manufacturing and processing to food retailing and consumption (residences, commercial establishments, institutional and industrial establishments).

Using multiple substrates requires finding the optimum mixture in order to obtain maximum biogas production. Biogas can be used in boilers for hot water production, in cogeneration plants with internal combustion engines, gas turbines, fuel cells, Stirling engines or in fuel driven absorption chillers to produce cold water. Generated electricity is delivered to the network, hot water is used to heat the digester content and for farm spaces heating, and cold water is used for air conditioning in farm buildings. In farm-scale biogas plants the internal combustion engines are most commonly used to generate heat and power.

The use of Otto engines is economically feasible for biogas plants with an electrical power of more than 150 to 200 kW (Fischer T., et al. 2015). The electrical efficiency is above 34%, and the investment cost is larger than for a dual fuel engine. The dual fuel engines can be operated with biogas but they have to use up to 2 to 10% diesel fuel of the overall energy input in order to facilitate the ignition of biogas (Yu G., 2013). The advantages of dual fuel engines are the following: they can be operated with diesel fuel during the initiation of anaerobic digestion when there is no production of biogas and hot water is required to heat the substrate; they can be operated with low-quality biogas with any given methane content. The commercial dual fuel engines have the electrical power output up to 250 kW because the consumption of diesel fuel increases and electrical efficiencies of gas engines are similar to those of dual fuel engines above this power (Fischer T., 2014).

The fuel combustion energy is converted into mechanical energy in proportion of (25-28)% in spark ignition engines and of (30-42)% in diesel engines, the remaining being lost in exhaust and coolant systems. The flue gas generated by internal combustion engines are evacuated with high temperature (450-510)°C, containing (30-35)% from total fuel combustion energy. The heat available in the jacket cooling water (outlet temperature of 90-95°C and return temperature of 70 – 85°C) represents (15-25)% from total fuel combustion energy (Office of Industrial Technologies, Office of Energy Efficiency and Renewable Energy, 1999). The waste heat can be recovered by using different technologies (boiler, absorption chiller, steam Rankine cycle, organic Rankine cycle, thermoelectric generators, turbo-compounding, Kalina cycle, Stirling cycle) and converted into hot water, electrical power or cold water depending on the requirements (Binev I. et al. 2015; I. Iliev, S. Andreev, I. Hristoskov 2011; Hung T.C. et al. 1997; Iliev I. et al. 2012; Iliev I. et al. 2014; Iliev I. (2013); Srinivasan K.K. et al. 2010; Tchanche B.F., et al. 2011; Wang T. et al. 2011).

The most energy favourable technology used to convert waste heat into power is the organic Rankine cycle (ORC). The organic Rankine cycle is similar to traditional Rankine cycle but it uses organic working fluid instead of water. There is a wide variety of organic fluids which can be used in ORC systems. Selection of the working fluid for ORC cycles depends on the application, source and heat level. The organic working fluid should be economical, nontoxic, non-flammable, environmentally friendly and should allow high utilization of the available energy from the heat source (Vélez F., et al. 2012).

Mainly organic fluids, like refrigerants, toluene, (cyclo) pentane or silicone oils are used in ORC systems. These fluids are characterized as dry fluids which mean they have positive slope of saturation vapour curves in the T-S diagram. They do not need superheating to avoid expansion in the wet vapour domain which is dangerous for expander. Refrigerants are used with a low grade heat source and toluene or silicone oils are used with high temperature heat source like exhaust gases of combustion engines (Vanslambrouck B., 2011).

The heat recovered from the internal combustion engines may be used also to drive absorption chiller to produce cold water. An absorption chiller consists of a condenser, an evaporator, a lamination valve like mechanically driven chiller and an absorber, a regenerative heat exchanger, a vapour generator and a pump in which the vapour compression is carried out. An absorption chiller uses as working fluid a solution with two components: liquid absorbent and refrigerant. The most common refrigerant–absorbent pairs are water/lithium bromide and ammonia/water. Absorption chillers are classified as single, double, or triple effect. Multi-effect cycles have higher coefficient of performance (COP) but they have more components and work with higher temperature waste heat (Keith E. H., A. K. Sanford (1996).

In this paper a study on the integration of an organic Rankine cycle system and an absorption chiller in a CHP plant based on internal combustion engine is presented.

Description of system considered in the investigation

The biogas plant of a poultry farm uses as a substrate a mixture of own poultry litter, manure from the neighbouring farms, food waste collected from neighbouring towns and food manufacturing facilities and corn silage. The average production of biogas is 210 Nm^3/h. The biogas average composition is given in Table 1. The lower calorific value of biogas is 21000 kJ/Nm^3. It is used in a combined heat and power (CHP) plant driven by two dual-fuel engines. The electric power of each engine is 250 kWe. The diesel engines use additional ignition diesel oil in a proportion of 10% of the power generated by the fuel combustion in the engine. Part of the residual heat contained in the exhaust gas and jacket cooling water is recovered to produce hot water to be used for heating the substrate of biogas plant (238 kWt), farm related activities and for space heating in winter. The generated electricity is fed into the network. The poultry farm needs cold water during summer which is produced by electrically driven cooling plant. The dual fuel engine is an inline six-cylinder turbocharged engine with constant speed of 1500 rpm. The main engine characteristics are given in Table 2.

About 35% of the fuel energy is contained in exhaust gas and 20% in jacket cooling water. The exhaust gas can be cooled up to 120°C because below this temperature the SO_2 present in flue gas may form a corrosive condensate.

The CHP plant delivers 500 kW of electricity to the network, produces 238 kW of heat during summer and 410 kW of heat during winter. The overall efficiency of CHP plant is 74.5% in winter and 60.4% in summer (not all generated heat is used). To increase the overall efficiency of the CHP plant especially during summer it was analysed the integration of an ORC system that uses the residual heat contained in flue gas to produce electricity and hot water and of an absorption chiller that uses heat from the engine cooling water to produce cold water in summer. In winter the heat from engine cooling water is recovered to be used for space heating. As working fluid for ORC system was selected the toluene which is one of the common working fluids in commercial ORC installations (Quoilin S., 2013). The ORC system includes an evaporator, a turbine which drives an electric generator, a recuperator, a condenser and a circulating pump. The absorption chiller is a single-effect unit which uses lithium bromide - water as working fluid. The scheme of CHP plant with integrated ORC system and absorption chiller is shown in Figure 1.

System modelling and simulation

In order to perform the thermal modelling the first law of thermodynamic in the steady state is applied. The mass and energy balance equations for the system components are considered to determine the flow rates and energy transfer rates. The flow through each component is considered to be accompanied by pressure drops.

The steady-state process simulation of the ORC system was performed by using the Cycle-Tempo Release 5.1.5 software in combination with the FluidProp software package, both developed by the Delft University of Technology and by TNO, the Dutch Institute for Applied Research (Colonna P. & T.P. van der Stelt 2004; http://www.asimptote.nl/software/cycle-tempo/).

After the system was drawn and part of the input has already been determined, such as connection points between apparatuses, apparatus types, connection types and independent cycles, other input data like: data of apparatuses (isentropic efficiency, mean temperature difference, pressure loss), data of pipes, compositions of working fluids, environment definition and production functions are introduced (Figure 2).

The design parameters of absorption chiller were predicted by using the Sorption Simulation (SorpSim) software developed by the Oak Ridge National Laboratory (Grossman, G., 1995). The SorpSim software contains the working fluid properties, the governing equations of standard absorption components and a solver package imported from the ABSIM, a program initially developed by the Oak Ridge National Laboratory. It has a modular program structure and allows investigation of various cycle configurations of absorption systems. The absorption chiller integrated in the CHP plant was firstly configured and then the components and the working fluids were selected (Figure 3). The required input were the following: the units' interconnections, size or transfer characteristics and values of the parameters set fixed at specific state points.

Results

The simulation result indicates that the ORC system generates 100 kW of electricity and 238 kW of heat by cooling the exhaust gas from 450°C to 120°C. The overall efficiency of ORC system is 94.5% (30% of incoming thermal power is transformed into electric energy and 64.5% into heat). The circulating pump consumes 1.68 kWe.

The simulated absorption chiller produces 123kW of cooling power (covering the demand for about 760m^2 of poultry house) with an efficiency of 66.8% by cooling the jacket cooling water from 92°C to 70°C. The chilled water inlet temperature is 20°C and the outlet temperature is 3.5°C and the mass flow rate is 1.58 kg/s.

Integration of the ORC system and absoption chiller in the CHP plant leads to the increase of plant overall efficiency from 74.5% to 82.8% in winter and from 60.4% to 78.8% in summer, by generating more electricity (100 kW) all year and by generating cold water in summer from the excess heat (123 kW$_c$).

The investment costs of commercial high temperature ORC systems vary from 1000 €/kWe for a 2 MW unit, to 2000 €/kWe for a 500 kW unit and up to 3000 €/kWe for a 150 kW unit. The installation costs of ORC systems used for waste heat recovery applications can vary from 50% (higher power range) to 100% (lower power range) of the ORC unit cost (Vanslambrouck B. et al. 2011).

The investment cost of commercial single-effect absorption chillers is about 250€/kW$_c$ and the operation and maintenance cost about 7.56 €/kW$_c$ and year (Morvay Z.K., 2008).

Considering the average costs for the ORC system and absorption chiller and taking into account the earned money by selling the extra power energy (83€/MWh), by using the chilled water generated by waste heat recovery instead of electricity consumption and due to the national support of green certificates (about 10 €/MWh) results a payback period of about 3 years.

Conclusions

Integration of an ORC system with toluene as working fluid and of a single-effect absorption chiller working with lithium bromide – water into a CHP plant driven by two dual-fuel engines of 250kWe each fuelled with biogas lead to the increase of plant overall efficiency from 74.5% to 82.8% in winter and from 60.4% to 78.8% in summer. The total investment cost of integrated systems reaches 509620 € and after 3 years this cost is equalled by the cumulative returns.

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Table 1. Biogas average composition (% vol).

Methane, CH_4	60
Carbon dioxide, CO_2	38.2

Hydrogen, H_2	1.0
Nitrogen, N_2	0.5
Carbon monoxide, CO	0.1
Oxygen, O_2	0.1
Hydrogen sulphide, H_2S	0.1

Table 2. Characteristics of dual fuel engine

Capacity, litre	12.0
Cylinder arrangement	6 inline
Speed, rpm	1500
Electric generator	370 kVA
Electrical power output, kW	250
Thermal power output, kW	205
Biogas consumption, Nm^3/h	92.6
Ignition oil (diesel oil) consumption, kg/h	2.2
Temperature of exhaust gas, °C	450
Mass flow rate of exhaust gas, kg/s	0.415
Jacket cooling water temperatures, °C	92/70
Mass flow of jacket cooling water, kg/s	2.25
Electrical efficiency, %	43
Thermal efficiency, %	34
Excess air ratio	1.5
Full load hours per day, h	22

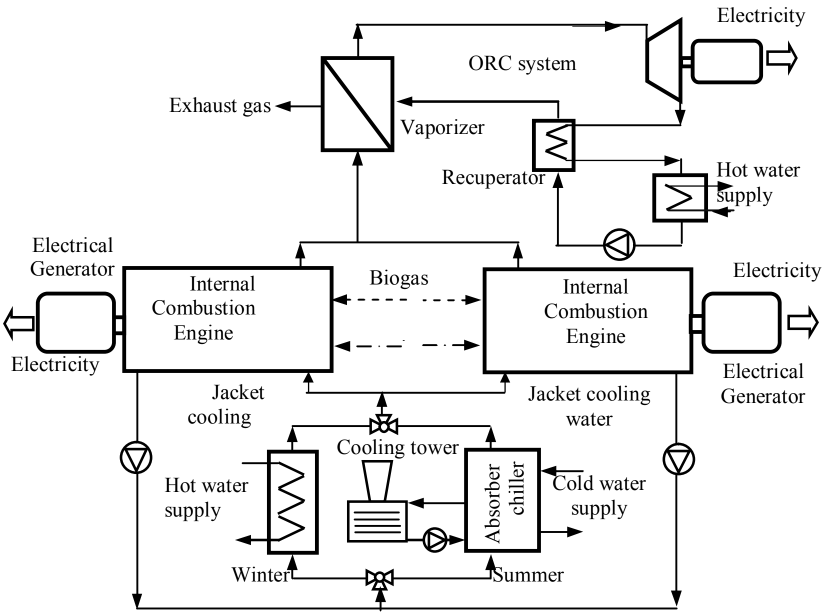

Figure 1. Biogas engine based CHP plant with integrated ORC system and absorption chiller

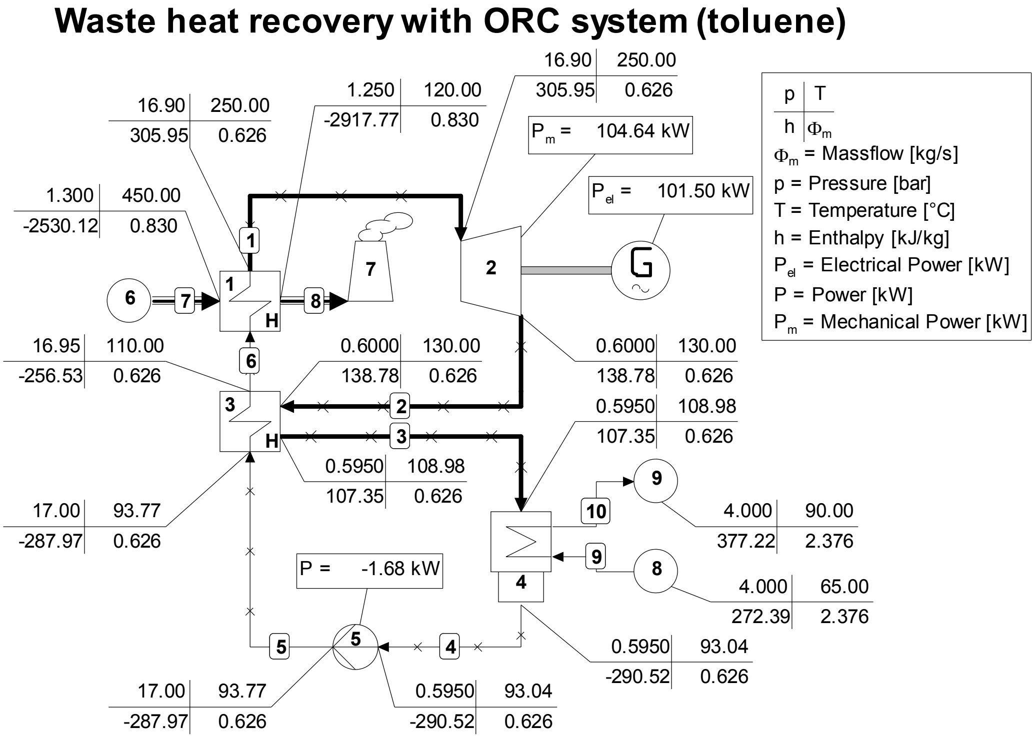

Figure 2. Results of CycleTempo simulation of ORC system

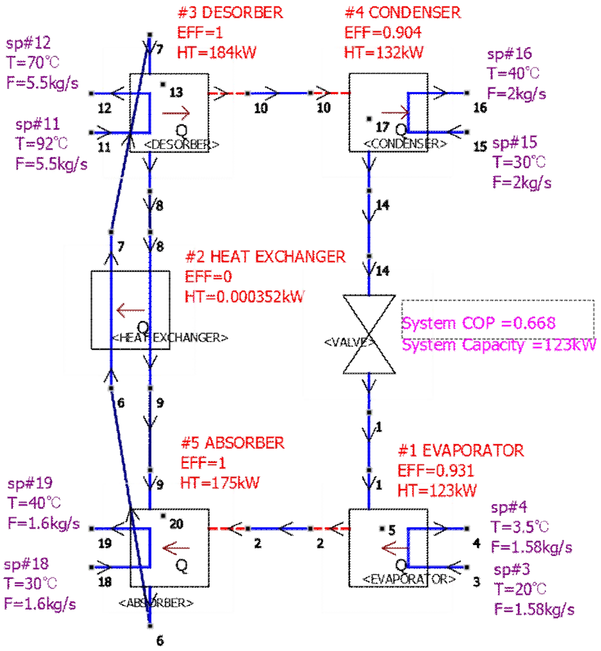

Figure 3. Design parameters of the single-effect absorption chiller obtained through simulation using the SorpSim software