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Greenhouse gas reduction potential by producing electricity from biogas engine waste heat using organic Rankine cycle

A. Uusitalo [a,*], V. Uusitalo [b], A. Grönman [a], M. Luoranen [b], A. Jaatinen-Värri [a]

[a] Lappeenranta University of Technology, School of Energy Systems, Laboratory of Fluid Dynamics, P.O. Box 20, 53851, Lappeenranta, Finland
[b] Lappeenranta University of Technology, School of Energy Systems, Laboratory of Environmental Technology, P.O. Box 20, 53851, Lappeenranta, Finland

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ABSTRACT

Organic Rankine cycles have been identified as a suitable technological option for converting low-grade heat into electricity with relatively high efficiency, and the organic Rankine cycle technology has been successfully implemented in different power production systems and in recovering heat in industrial processes. This paper studies the greenhouse gas emission reduction potential by using organic Rankine cycles for recovering exhaust gas heat of biogas engines. The study concentrates especially on the biogas engine power plants in Europe. Life cycle assessment methods are used and various waste heat utilization scenarios are compared. According to the results, greenhouse gas emissions can be reduced significantly if the thermal energy of the exhaust gases, otherwise lost in the process as waste heat, is utilized for additional electricity production by means of organic Rankine cycle. However, there may already be use for the exhaust gas heat in biogas plants in the form of heat power. In these cases, the use of organic Rankine cycle does not necessarily lead to greenhouse gas emission reductions. The results also indicate, that the working fluid leakages and production as well as the organic Rankine cycle construction materials and production have only marginal effects on the results from greenhouse gas perspective.

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1. Introduction

Global warming due to increasing greenhouse gas (GHG) emissions is one of the greatest challenges humankind is facing. Approximately 60% of GHG emissions from human activities are related to energy production (World Resource Institute, 2009). This has led to the search for more environmentally friendly energy production methods. The dominant energy production method globally is combustion, which usually leads to relatively low electricity production efficiency. For example, the electrical efficiency is 30–40% for reciprocating engine power plants (ASUE, 2011) and 20–40% for gas turbines (ASUE, 2006). The remaining heat is only utilized in some applications. Thus, if the waste heat could be converted into additional electricity the primary energy needs of the electricity production can be reduced significantly. In general, several aspects should be considered while choosing the method for waste heat utilization. Walsh and Thornley (2012a) have concluded that the main barriers in utilizing low grade heat in the process industry are the cost, return on investment, and technology performance. They recommended that the energy, life-cycle and techno-economic analysis could be combined in order to identify the most promising options for waste heat recovery in different process industries.

This paper investigates the waste heat utilization in biogas engine power plants by means of the organic Rankine cycle (ORC). ORC technology is suitable for converting low grade heat into electricity, and commercial ORC power plants are available for different power scales and applications (Tchanche et al., 2011; Colonna et al., 2015). The conventional steam Rankine power plants are widely used technology in large-scale power production. The use of water as the working fluid in the cycle is an optimal solution in many cases since water is widely available, entails high thermal and chemical stability, and is non-flammable. However, if the power output of the cycle is low ($\approx P < 1$ MW) or the temperature level of the process is low ($\approx T < 300$ °C) an ORC is often

Abbreviations: CO_2, carbon dioxide; CH_4, methane; CHP, combined heat and power; GHG, greenhouse gas; ISO, International Organization for Standardization; LCA, life cycle assessment; LUT, Lappeenranta University of Technology; NG, natural gas; N_2O, nitrous oxide; ORC, organic Rankine cycle.

* Corresponding author. Present address: Lappeenranta University of Technology, P.O. Box 20, 53851, Lappeenranta, Finland. Tel.: +358 40 583 7741.
E-mail address: antti.uusitalo@lut.fi (A. Uusitalo).

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favored instead of a steam Rankine due to the technical difficulties related to the low boiling pressure level of steam at low temperature levels and difficulties in the expander design with steam (Colonna et al., 2015). ORC processes are based on the use of organic working fluids with a relatively low boiling temperature at reasonable pressure. The relatively low boiling point of organic fluids and the freedom in the working fluid selection enables the utilization of low-grade heat sources which would otherwise be technically or economically very difficult to utilize for electricity production. Another unique feature of ORC power systems is that the technology is in principle applicable for any external heat source (Colonna et al. 2015). Therefore, there is significant potential for ORC use globally in different heat recovery applications (Colonna et al., 2015).

In ORC processes the working fluid circulates in a closed system and the power production is based on the phase change of the working fluid from liquid to vapor. A process flow diagram and the main components of a simple ORC are illustrated in Fig. 1. The ORC process can be generally divided in the following stages: 1) increasing the pressure of the liquid working fluid in the feed pump, 2) preheating the working fluid in the recuperator, 3) preheating, evaporating and superheating the fluid in the evaporator, 4) working fluid vapor expansion in the turbine from high pressure to low pressure, 5) removal of superheating in the recuperator and in the condenser, and 6) condensation of the low pressure vapor to liquid form in the condenser.

Commercial ORC power systems implement different technical solutions for the expander and cycle configuration and use different types of organic working fluids e.g. hydrocarbons, siloxanes, or fluorocarbons (Tchanche et al., 2011; Colonna et al., 2015). The most important applications for ORC power systems, cycle configuration options, and important design aspects are generally presented and discussed by Colonna et al. (2015). The number of ORC power systems suitable for different power levels and different applications has been increasing significantly in recent years, mainly due to the flexibility and high conversion efficiency in low power range applications (Colonna et al., 2015). ORC has been considered applicable to waste heat recovery especially with non-centralized

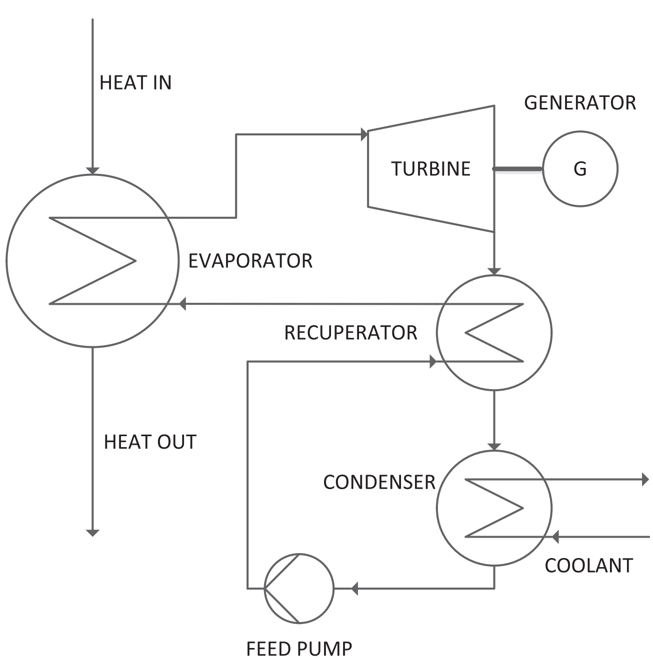

Fig. 1. Process flow diagram and the main components of an ORC process.

electricity production plants such as in reciprocating engine power plants and marine diesel engines (e.g. Bombarda et al., 2010; Uusitalo et al., 2014a) and in heat recovery from gas turbine applications (e.g. Invernizzi et al., 2007; Chacartegui et al., 2009). A recent patent landscape analysis for different technologies for recovering waste heat from internal combustion engines highlighted that there has been a rapid growth in the number of patent filings related to ORC in the past 5–10 years, which indicates a strong interest towards the ORC technology in the industrial sector (Karvonen et al., 2015).

Gas engines and gas turbines are developed to produce electricity from gaseous fuels, such as natural gas (NG), landfill gas and biogas. They are commonly located next to or at landfills, waste water treatment plants and biogas plants where in some cases the utilization of waste heat as heat power is not feasible or there simply is no use for heat. In these applications, ORC could be an attractive technical option for utilizing waste heat of the engines in additional electricity production and thus increasing the overall performance of engine power plants and lowering the emissions. The results of previous numerical studies (e.g. Bombarda et al., 2010; Vaja and Gambarotta, 2010; Uusitalo et al., 2014a) have indicated that by using ORCs in recovering heat of different types of large-scale reciprocating engines, the power output can be increased about 9–12% depending on the type of the engine, operating conditions, and power scale.

Despite the large number of thermodynamic studies on using ORCs in different waste heat applications, there is very little detailed research available related to the environmental advantages of using ORC to produce electricity from waste heat. Poeschl et al. (2010, 2012) have studied the efficiency and environmental impacts in various biogas production and utilization pathways, including a combined heat and power (CHP) power plant having an ORC as a bottoming cycle for recovering waste heat. Their results highlighted that the efficiency and the produced emissions in biogas utilization are highly dependent on the efficiency of the energy conversion system as well as on the potential substitution of the usage of different fossil fuels. Liu et al. (2013) have conducted detailed research on the environmental impacts of electricity production from low temperature waste heat using an ORC process. They have concentrated on emissions from the construction, utilization and decommissioning phases. In their study, seven different working fluids were considered and the effects of the working fluid on the emissions were analyzed. According to their life cycle assessment (LCA) results, the construction phase is the most important when GHG emissions are considered and the payback time for GHG emissions varies from three to six years, depending on the reference electricity production method. Yang and Yeh (2015) have concentrated on the thermodynamics and economics of the ORC process utilizing waste heat in large marine diesel engines. According to their study, the production of electricity with an ORC from the diesel engine exhaust gas instead of using diesel fuel led to a 76% reduction in CO_2 emissions. Walsh and Thornley (2012b) have studied the environmental impacts of using low grade heat for electricity production via ORC in the production of metallurgical coke. Their results showed the installation of ORC could offset 1–3% of the CO_2 emitted directly through the production of coke. Furthermore, they concluded that the life-cycle environmental impacts of coke production would be reduced less than 1%.

Despite the earlier studies, there is still lack knowledge related to the environmental impacts of using ORC in recovering exhaust gas heat of biogas engines. In addition to calculating GHG emissions for ORC, the electricity reference scenarios have to be carefully considered. There may be already heat utilization for gas engine exhaust gas, such as recovering the heat to the digester in biogas

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