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Design and Off-Design Analysis of an ORC Coupled with a Micro-Gas Turbine

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Abstract

In the recent years, the possibility of recovering heat from gas turbine (GT) exhaust gases using Organic Rankine Cycles (ORC) have been largely explored. However, it is difficult to identify working fluids properly matching with micro-GT exhaust gases. For this reason, in the present work, the fluid selection and the plant layout optimization of an ORC which recovers the exhaust gases heat content of a 65 kW micro-gas turbine is presented. During the optimization process different plant configurations are considered: simple or regenerative and subcritical or transcritical. Exergy and economic analyses are also performed to estimate the exergy destruction rate and evaluate the economic feasibility of the optimized solutions. In order to find out the most suitable ORC unit and its behaviour, an off-design analysis is also performed using the commercial software Aspen Plus. Adopting a management strategy that maintains the turbine inlet temperature constant the best off-design performance is reached with Cyclopentane as working fluid.

Keywords: Waste heat recovery, Organic Rankine Cycle, Fluid selection, Design analysis, Off-design analysis

1. Introduction

In the last decades, the consumption of energy from all sources has increased due to the rapid growth of population. But, concerns about energy security and effects of fossil fuel emissions on the environment supported the use of renewable energy sources and natural gas (which is the least carbon-intensive fossil fuel) as well as the development of waste heat recovery units able to convert medium and low temperature heat sources into electricity.

The Organic Rankine Cycle (ORC) technology is one of the most promising methods to convert medium and low temperature heat into electricity because cycles using water as working fluid fail for technical and economic reasons in this temperature range [1,2].

The design of an ORC is a complicated task because the type and temperature of the heat source significantly influences the choice of the working fluid which in turn determines the configuration, the performance and the economy of the plant [2].

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For these reasons, several researchers worked on the ORC fluid selection and plant layout optimization using high, medium and low temperature heat sources. As an example, Delgado-Torres and Garcia-Rodriguez[3] performed an analysis and optimization of a low-temperature solar Organic Rankine Cycle while Astolfi et al.[4] performed a thermodynamic and techno-economic optimization of an ORC which recovers the geothermal fluid heat at a temperature of 120–180 °C. Tańczuk and Ulbrich[5] implemented a biomass-fired cogeneration plant in which the ORC is used as heat source for a small scale heat distribution system while investigations on the use of ORCs which recover waste hear from industrial processes, medium size gas turbine and biogas engine have been presented in, e.g., [6–9].

Despite the large variety of available works, only few of them are focused on recovering micro-gas turbine waste heat. As an example, Invernizzi et al.[10] and Clemente et al.[11] designed ORCs which recover the heat from the flue gases of a 100 kW_{el} commercially available small gas turbine fed by natural gas.

In the above mentioned researches, the Authors focused their attention on the ORC fluid selection and plant layout optimization at design point condition but, during the real operation, the temperature of the heat source may be different from the value assumed in the design phase. This aspect greatly affects the ORC output power. For this reason, an off-design analysis needs to be performed in order to select the ORC working medium, the plant layout and the management strategy which guarantees the highest ORC performance during the entire year of operation. As for fluid selection and plant configuration design, several works are available in the scientific literature. For example, Hu et al.[12], Cao and Dai[13] and Song et al.[14] analysed the ORC off-design behaviour under different operating conditions and management strategies.

However, despite the large number of published works, as far as the Authors know, no one has investigated the possibility of improving the performance of a 65 kW_{el} micro gas turbine (m-GT) by adding an ORC which recovers the exhaust gases heat considering both the design and off-design operation. For these reasons, in the present work, the Authors propose the ORC fluid selection and plant layout optimization at design point condition using an “in-house” optimization tool called “ORC-Plant Designer” while the ORC off-design behaviour is predicted using the software ASPEN Plus. The rest of the paper is organised as follow: in Section 2 the case study and the method adopted to perform the design and off-design analysis are described while, in Section 3, the optimization results and the plant off-design behaviour are presented and discussed. Finally, conclusions remarks are given in Section 4.

2. Case study and methodology

The case study is the power generation system of a small manufacturing industry. At the time of writing, a boiler is used to produce both the process heat and that for space heating while the electric load is partially covered with a photovoltaic system installed on the industry roofs. The photovoltaic plant and the boiler design power are 50 kW_{el} and 250 kW_{th}, respectively. Based on an electricity and heat consumption analysis, the industry owner has decided to install a micro gas turbine with a design power of 65 kW to self produce electrical energy. The m-GT is a Capstone C65 non-cogenerative turbine fed by natural gas with the design characteristics listed in Table 1.

Table 1. Micro-gas turbine characteristics.

Parameter	
Ambient Temperature [°C]	15
Relative Humidity [%]	60
Ambient Pressure [bar]	1
Net Power [kW]	65
Net Efficiency [%]	29
Exhaust Gases Mass Flow Rate [kg/s]	0.49
Exhaust Gases Temperature [°C]	309

Being the exhaust gases temperature relatively high, the industry owner wants to explore the possibility of adding a waste heat recovery unit to additionally improve the self production. To this purpose, the ORC is, firstly, designed and, then, its off-design behaviour analysed. The methodology adopted to perform the design and off-design analysis is briefly summarized in the following.