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Robust optimization of an Organic Rankine Cycle for heavy duty engine waste heat recovery

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Abstract

A robust parametric optimization of Organic Rankine Cycles (ORC) is carried out by taking into account uncertainties in the cycle input parameters. A typical engine driving duty cycle is considered and sampled in order to construct a suitable probability distribution describing the variability of the exhaust gases mass-flow and temperature. Besides, the environmental and condensing temperatures, specific heat ratio of the waste gases, turbine and pump efficiencies are also considered as uncertain. The parameter combination that maximizes the mean cycle efficiency and minimizes its variance is sought as optimal. Six organic fluids have been taken into account, namely R245fa, R245ca, R134a, R11, R113 and Novec649, with the best results provided by R11 and R113.

Keywords: optimization; uncertainty quantification; heavy duty; heat recovery

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1. Introduction

In recent years, the Organic Rankine Cycle (ORC) technology has received great interest from the scientific and technical community because of its capability to recover energy from low- grade heat sources. In some applications, as waste heat recovery (WHR) in the automotive field, ORC plants need to be as compact as possible because of geometrical and weight constraints. Effective solutions have been proposed by Honda [1] and BMW [2] for passenger cars and Cummins [3] for long-haul trucks. The performances of recently developed prototypes of ORC for automotive applications seem to be promising [4], with reduction of fuel consumption up to 12% and engine thermal efficiency improvements of 10%. However, currently no commercial ORC solutions in the automotive field are available. Indeed, the large range of operating conditions on typical duty driving cycles may lead to difficulties in the design of the ORC plant, resulting in hesitancy of the investors towards this applications and leading to a system performance improvement that is too low to justify the corresponding economic effort. In this work, a robust optimization approach is proposed in order to overcome these issues for a real-world application, namely the recovery of residual energy from the waste gases of a heavy duty diesel engine. The robust optimization approach has been applied in the past by Persky et al. [5] to the design of a power block and turbine of a supercritical CO_2 solar Brayton cycle, in order to account for

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the day-night cycle and seasonal variations, whereas Wang et al. [6] provided a deterministic parametric optimization by means of genetic algorithms of an ORC using a low grade heat source considering both thermodynamic and economic factors simultaneously. The effect of the key thermodynamic parameters on the net power output and the resulting surface of heat exchangers was examined. Here, a robust parametric optimization of the ORC is carried out by taking into account uncertainties in the cycle input parameters. The focus of the present work is to explore a way of accounting for the uncertainty about various input parameters and give a general approach for preliminary ORC component design. Robust optimization (RO) was initially introduced by Taguchi in the 1960s, with the introduction of a new paradigm for the design of an industrial product. By citing Marczyk [7], ”optimization is actually just the opposite of robustness”. This statement means that classical and robust optimizations lead to different solutions which are sensitive or insensitive to uncertain conditions, respectively. A typical engine driving duty cycle is considered and sampled in order to construct a suitable probability distribution describing the variability of the exhaust gases mass-flow and temperature. Besides, the ambient and condensing temperatures, the specific heat ratio of the waste gases, turbine and pump efficiencies are also considered as uncertain. An importance analysis based on the ANalysis Of VAriance (ANOVA) of the cycle performance is carried out in order to identify the most influential variables. Six working fluids of interest for WHR application have been analysed, namely: R245fa, R245ca, R11, R113, R134a and Novec649. The ORC parameters are optimized by means of a Non-dominated Sorted Genetic Algorithm (NSGA) [8] coupled with an uncertainty quantification method, based on a Monte-Carlo simulation of the thermodynamic cycle, with the objective to maximise the cycle thermal efficiency while minimising its variance. Constraints on the minimal efficiency are also explicitly accounted for. The outcomes of this process are the ORC parameters that ensure the best trade-off between high efficiency and a stable behaviour of the system, as well as confidence intervals on these parameters.

2. Thermodynamic cycle and parameters for WHR

2.1. Cycle configuration

In this work, the waste gases discharged from a four-stroke heavy-duty Diesel engine (338 kW) are used as the low-grade heat source of ORC. The residual energy is converted to supply the auxiliary electric devices of the vehicle. A sketch of the ORC layout is shown in Fig. 1a, along with a representation of the cycle in the temperature-entropy diagram for R245fa working fluid (Fig. 1b), for a baseline configuration with: $p_{ev} = 0.545 p_{cr}$, $\Delta T_{pp} = 8\ K$ and $\Delta T_{TIT} = 5\ K$, where p_{ev}, ΔT_{pp} and ΔT_{TIT} are the evaporating pressure, pinch point temperature difference and turbine-inlet/evaporation temperature difference, respectively. The working fluid is compressed and pumped into the evaporator by the feed pump. After evaporation and a slight super-heating, the enthalpy drop is converted into electric energy by means of an expander coupled with a generator. In order to minimize the system size, no regenerations and thermal oil loops are considered. The pre-heating and evaporation energy is totally provided by the waste gases, and a turbo-expander provides the work output. Despite the wide-spread use of positive-displacement expanders for ORC applications, due to their low cost and manufacturing simplicity, their performance for small-scale applications as automotive WHR is rather poor, due to volumetric expander intrinsic problems as low adaptivity to volumetric ratios different from the nominal ones, resulting in losses for under- or over-expansions, internal leakages and lubricating issues [9]. On the other hand, turbo-expanders could provide higher performances in a wide range of operating conditions, but the high rotational velocities, high pressure ratios, complexity of the working fluids and the need for a compact geometry make the design of an efficient ORC turbine challenging. About this, some authors have proposed some design solutions in the past [10–13]. After the expansion, the fluid is cooled in the condenser in order to close the thermodynamic cycle. In this study, no sub-cooling is considered during the condensation and the heat exchanger between the source and the working fluid is modelled as perfect. The attention is focused on the main cycle outcomes which could be affected by the variability of the waste gases mass-flow ($\dot{m}_w$) and temperature ($T_{w,in}$), namely: the cycle thermal and exergy (2nd law) efficiencies ($\eta_I = W_{net}/Q_{in}$, $\eta_{II} = W_{net}/[Q_{in}(1 - \frac{T_0}{T_m})]$, with W_{net} the net work of the cycle, given the energy input Q_{in}, T_0 and T_m the ambient and log mean temperature, respectively), representing the energy conversion efficiency and the maximum amount of extractable work, the volumetric expansion ratio (V_r) and the turbine size parameter ($S_T = \frac{\dot{V}_{t,out}^{0.5}}{\Delta H_t^{0.25}}$, with $\dot{V}_{t,out}$, ΔH_t the turbine exit volumetric flow rate and enthalpy drop, respectively). Other variables of interest for the cycle analysis are: the condensing and ambient pressures (p_{cond}, p_{amb}), waste gas specific heat (c_w), pump and turbine efficiencies (η_P, η_T).