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Off-design operation of ORC engines with different heat exchanger architectures in waste heat recovery applications

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Abstract

Organic Rankine cycle (ORC) engines in waste-heat recovery applications experience variable heat-source conditions (i.e. temperature and mass flow rate variations). Therefore maximising the ORC system performance under off-design conditions is of key importance, for the financial viability and wider adoption of these systems. In this paper, the off-design performance of an ORC engine with screw expander and two heat exchanger (HEXs) architectures is investigated, while recovering heat from an internal combustion engine (ICE). Firstly, nominal system sizing results indicate that the screw expander isentropic efficiency exceeds 80%, while the plate HEXs (PHEXs) heat transfer area requirements are 50% lower, than the respective ones for double pipe (DPHEX) design. Next, the ORC engine operation is optimised at part-load (PL) ICE conditions. Although, the HEXs heat transfer coefficients decrease with part-load, the total HEX effectiveness increases, due to higher temperature difference across the working fluids. Findings also reveal that the PHEX performance is less sensitive to the off-design operation. Off-design power output maps indicate that the optimised ORC engine PL reduces to 72%, for ICE PL of 60%, while ORC engines with PHEXs generate slightly more power, for the same heat source conditions. Overall, the modelling tool developed can predict ORC performance over an operating envelope and allows the selection of optimal designs and sizes of ORC HEXs and expanders.

Keywords: Energy efficiency; Heat exchanger model; Internal combustion engine; Off-design optimisation; Organic Rankine cycle; Screw expander.

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1. Introduction

Organic Rankine cycle (ORC) engines is a promising technology for recovering low to medium-grade waste heat or other forms of renewable heat streams for generating power [1]. There is a prolific literature on the design and sizing of ORC systems, where the engine performance is optimised for given (fixed) heat source conditions. However, in real applications, the ORC engines experience variable heat input; this may be the waste heat of industrial processes, or the exhaust-gas stream of internal combustion engines (ICE) or boilers, in combined heat and power (CHP) applications. Key for the wider adoption of the technology is maximising the system running hours once installed, to improve their economic proposition. This requires ORC engines that are able to follow the heat source variations, and maintain high efficiency not only at design conditions, but also during off-design operation.

The off-design ORC performance and thus the power output are influenced by: i) the ability of the evaporator heat exchanger (HEX) to extract heat from a time-varying heat source, and ii) the expander efficiency under varying operating conditions of the working fluid (temperature, pressure, mass flow rate etc.). In a typical ORC system design, the ORC is optimised thermodynamically based on the design (nominal) heat source conditions. The system components are then sized to deliver the design duty. At this stage, the ORC components size is fixed. To evaluate the ORC performance at off-design operation, predicting the performance of the various components is of paramount importance; i.e. being able to estimate the evaporator off-design heat transfer phenomena, and thus the resultant working fluids' conditions at the expander inlet, while also predicting the expander's new optimum operating point.

There is limited literature available on ORC performance evaluation under off-design conditions, with some studies focusing on the expander performance and others on the HEXs. Badescu [2] evaluated an ORC operating under off-design conditions for vehicles, focusing on the HEX performance, assuming a fixed expander efficiency. Uusitalo [3] evaluated experimentally the performance of ORC HEXs under varying heat input to the cycle. Lecompte [4] evaluated the off-design operation of a low-temperature ORC engine, including components sizing and costing. The most well-documented expander machines in ORC off-design studies are turbines [5–7]. Although volumetric expanders are a promising technology for small-medium scale ORC engines, there are only a few studies available on ORC off-design operation with volumetric machines. These include scroll expanders [8] or screw expanders [9,10], while piston expanders are the least documented in ORC engines off-design stationary applications [11]. By reviewing the literature, it is revealed that there are only limited efforts available investigating the combined HEXs and volumetric expander performance in an ORC off-design problem. In this context, the aim of this paper is twofold: i) to evaluate the off-design performance of ORC units that recover heat from an ICE-CHP system, with two candidate evaporator HEX architectures, double-pipe HEX (DPHEX) and plate HEX (PHEX); and ii) provide optimum ORC operation maps under varying heat source conditions, accounting for both the HEXs and screw expander performance variation.

2. Methodology

2.1. Organic Rankine cycle (ORC) engine model

A subcritical non-recuperative ORC system is considered in this study, composed of: the evaporator HEX, the expander, the condenser HEX and a pump. The ORC engine recovers heat from the exhaust-gas stream of an ICE-CHP unit. For detailed description of the ORC thermodynamic model, the reader is referred to previous work of the authors [11]. Two types of HEX units were investigated for their off-design performance: the double-pipe HEX (DPHEX) and the plate HEX (PHEX). For the nominal sizing exercise, the optimum thermodynamic cycle points, defined in the ORC optimisation stage (refer to Section 2.2), are used to size the various components. At this stage, the HEX area requirements, geometry etc. are defined, aiming to maintain a maximum pressure drop across the HEX of 50 kPa. The sizing is achieved by discretising the HEX in space into N-sections, and by calculating for each i-section the corresponding local heat transfer coefficient (HTC_i). The logarithmic mean temperature difference (LMTD) method is then used to obtain the area requirements for each section (A_i).

For the off-design performance evaluation, the exhaust-gas temperature and mass flow rate vary, following the ICE-CHP unit part-load (PL) operation, and the ORC engine operating points are optimised, to adjust to the new heat source conditions. During this process, the moving boundaries method for HEXs is used. With the changes in temperature and flow rate, the phase boundaries as defined in the nominal sizing exercise change, but the overall heat transfer area available is fixed. The optimiser predicts the revised HEX performance at each section by calculating the new HTC_i. For the single phase zone *HTC* calculation of the PHEX, the Chisolm [12] correlation has been used. For the evaporating zone, the correlation of Han [13] was used, while for the condensing zone the correlation of Han [14] is used. The details of the DPHEX *HTC* and pressure drop correlations, are presented in previous work of the authors [11]. Equations are omitted here for brevity.

A screw machine is selected as the ORC expander. The advantages of screw expanders are the balanced loading of the main screw, their durability, the efficient operation at volume ratios of up to 8 and pressure ratios of up to 10, low noise, low vibration and compact configuration [15]. Screw expanders typically are reversed screw compressors and are capable of dry gas expansion or wet vapour. In this study, the correlation provided by Astolfi [16] has been used to predict the screw expander isentropic efficiency at design and off-design operation. The correlation is based on available efficiency data of screw compressors in the market. Finally, the pump is a centrifugal unit with relatively flat curve, which can maintain a constant pressure head across a range of flows. This feature is important, since for the off-design operation analysis that follows, the pressure head of the system is maintained at the nominal design levels, while the flow rates/temperatures are allowed to alter.

2.2. Design and off-design optimisation

The ORC engine is first optimised thermodynamically for maximum power output ($\dot{W}_{\mathrm{net}}$). The decision variables include the evaporator and condenser pressure ($P_{\mathrm{evap,}}\, P_{\mathrm{con,}}$), the mass flow rate of the working fluid ($\dot{m}_{\mathrm{wf,}}$), the superheating degree (*SHD*), the evaporator pinch point ($PP_{\mathrm{evap,}}$) and the expansion stages (x_{exp}). For the off-design optimisation the evaporating/condensing pressure are assumed fixed, and the decision variables include: the working fluid *SHD*, and mass flow rate ($\dot{m}_{\mathrm{wf}}{}'$), the heat source mass flow rate and leaving temperature ($\dot{m}_{\mathrm{hs}}'$, $T_{\mathrm{hs,out}}'$) and the expansion stages ($x_{\mathrm{exp}}{}'$). The objective functions of the optimisation study are presented in Eqs. 1-2. A number of constraints during the nominal optimisation ensure that: i) the cycle is subcritical; ii) the minimum PP is not violated; iii) there is no two-phase expansion; and iv) the maximum working fluid temperature in the evaporator does not exceed the maximum recommended temperature for the specific fluid, to avoid decomposition problems of the working fluid. During the off-design optimisation, apart from the thermodynamic constraints, the HEXs available area is also fixed, and forms an additional constraint. Finally, a number of working fluids have been selected for the optimisation study, including conventional refrigerants, new low ODP/GWP compounds, along with some hydrocarbons.

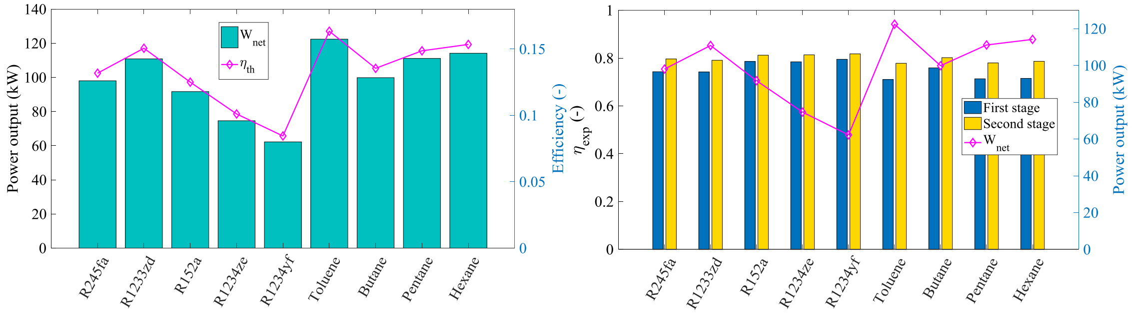
$$\text{Nominal operation: Maximise } \frac{\{\dot{W}_{\mathrm{net}}\}}{P_{\mathrm{evap}},\, P_{\mathrm{con}},\, \dot{m}_{\mathrm{wf}},\, SHD,\, PP_{\mathrm{evap}},\, x_{\mathrm{exp}}} \tag{1}$$

$$\text{Off-design operation: Maximise } \frac{\{\dot{W}_{\mathrm{net}}{}'\}}{T_6{}',\, T_{\mathrm{hs,out}}',\, \dot{m}_{wf}{}',\, \dot{m}_{\mathrm{hs}}{}',\, x_{\mathrm{exp}}{}'} \tag{2}$$

3. Results and discussion

3.1. Nominal ORC engine power output and components sizing

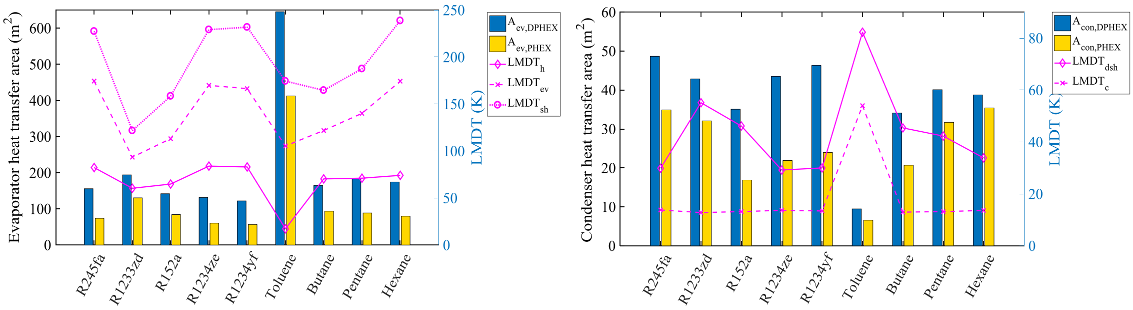
The exhaust-gas conditions of an ICE-CHP 1500 kW unit provided by EnerG has been used, as the heat source input profile to the ORC. The ORC engine is first optimised and sized for 100% loaded ICE operation, and then off-design performance maps are obtained, based on the ICE PL operation from 100% to 60%. It is noted that the exhaust-gas temperature increases, while the ICE PL decreases (682 K-727 K for 100%-60% ICE PL), while the mass flow rate reduces (2.16-1.29 kg/s for 100%-60% PL). The power output of the optimum ORC engines is presented in Fig.1a for ICE-CHP 100% operation. The best performing ORC generates 122 kW of power output with Toluene, followed by R1233zd with 110 kW. The screw expander performance is presented in Fig. 1b for the different expansion stages. All optimum cycles have a double stage expansion, aiming to keep the volume ratio (VR) of the expanders between 4 and 5. It is noted that the fluids with the highest power output do not have the highest screw expander efficiency (η_{exp}). Although more power is generated from fluids such as R1233zd or Toluene (η_{exp} = 0.71-0.79), the expander efficiency is best for fluids such as R1234yf and R1234ze (η_{exp} = 0.8-0.83). These findings highlight that cycles with the former fluids can tolerate lower specification on the expander design, while still generating more power at the design point.



(a) (b)

Fig. 1. ORC engine: a) power output, and b) screw expander performance, at design conditions (ICE-CHP 100% load)

The HEX requirements for the evaporator and the condenser are presented in Fig. 2, with two different architectures. For all working fluids investigated the area requirements of DPHEXs are almost double the respective ones for PHEXs. These findings highlight the compactness of PHEXs in comparison to DPHEX, being able to transfer an equivalent amount of heat, over smaller heat transfer areas. Thus, they are suitable for applications where the physical size of the system is important. In terms of the relative heat transfer area requirements of the different fluids, the trend observed in the PHEX and the DPHEX design is the same. It is noted that lower *PP* (low LMDT) result in higher area requirements. Therefore, even fluids with similar power output have completely different heat transfer area requirements. This will have significant implications on the cost of such engines.



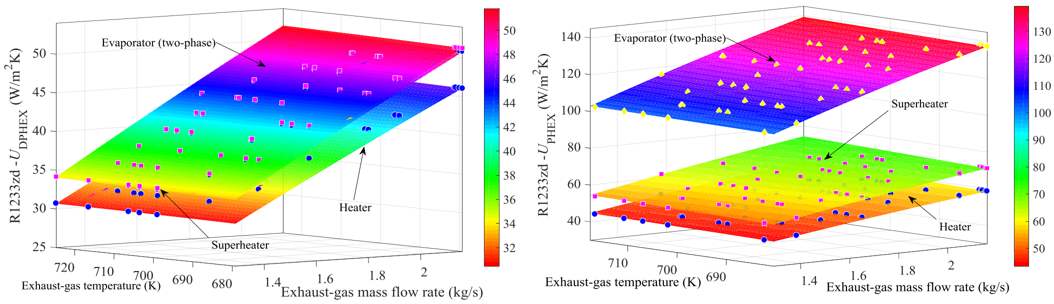
(a) (b)

Fig. 2. Heat transfer area for: a) evaporator, and b) condenser, with DPHEX and PHEX, for ORC design conditions (ICE-CHP 100% load)

3.2. ORC engine off-design performance maps

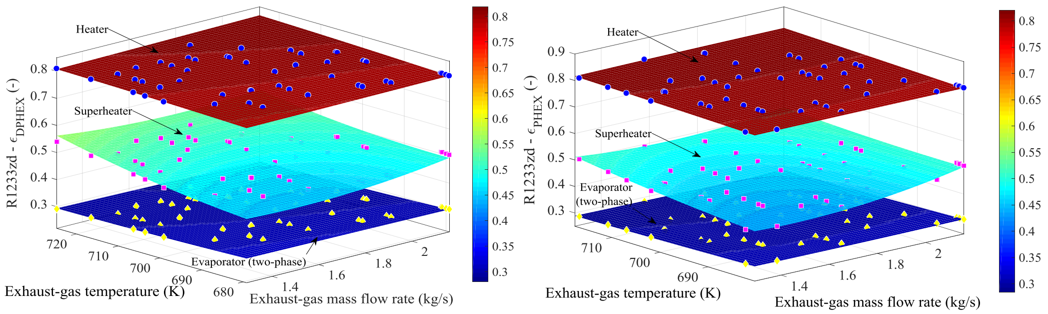
In this section the optimum ORC engine off-design performance maps with R1233zd are presented, since this is the best performing refrigerant with low ODP/GWP as identified during the nominal optimisation analysis. The off-design map of the evaporator overall heat transfer coefficient (*U*-value) is shown in Fig. 3, for the two HEX architectures investigated. While the ICE-CHP load reduces from 100% to 60%, the *U*-value reduces significantly by up to 30% (DPHEX) and 25% (PHEX). The PHEX system has higher *U*-values than the DPHEX, which is in line with the lower heat transfer area requirements of the former. It is also observed that the PHEX *U*-values are less sensitive to the PL conditions. Although, the *U*-value decreases, the overall evaporator effectiveness is either improving or stays constant while operating at off-design (Fig. 4). This is attributed to the increase of the temperature difference between the heat source and the working fluid at ICE-CHP PL. The exhaust-gas temperature increases from 680 K to 720 K, while the mass flow rate also reduces, making the heat transfer more effective, over the same available heat transfer area. For both architectures, the heater zone has the highest effectiveness, because this is where the minimum PP is recorded, followed by the superheater and the evaporator.

Being able to predict the HEX and screw expander performance under varying heat input conditions, allows us to generate optimum ORC off-design power output maps. Optimum ORC system power output maps are presented in Fig. 5 for both HEX designs. It is noted that the ORC with PHEXs generates slightly higher power output than the engine with DPHEX. Finally, the power output is mostly sensitive to the heat source mass flow rate variation. For fixed heat source entering temperature, power output decreases by up to 30%, while the exhaust-gas mass flow rate drops in ICE-CHP part-load operation. In contrast, for fixed mass flow rate, decreasing the exhaust-gas stream temperature reduces the ORC engine power output by less than 10%.



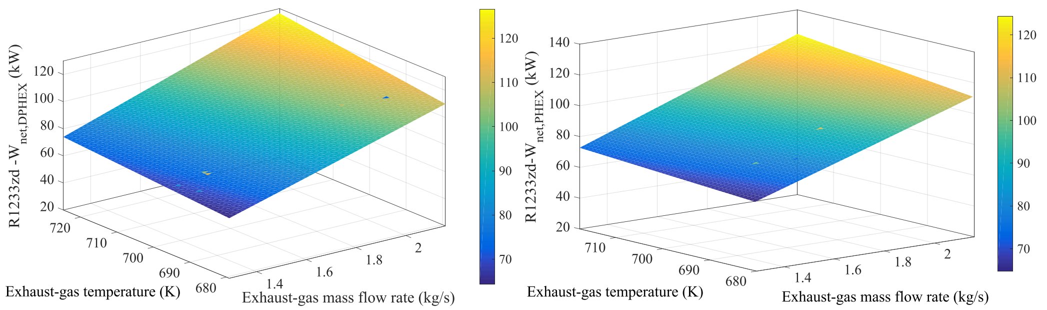
(a) (b)

Fig. 3. Evaporator heat exchanger heat transfer coefficient for ORC off-design conditions: a) DPHEX and b) PHEX



(a) (b)

Fig. 4. Evaporator heat exchanger effectiveness for ORC off-design conditions: a) DPHEX and b) PHEX



(a) (b)

Fig. 5. ORC off-design power output performance map for: a) DPHEX and b) PHEX

4. Conclusions

ORC engines in real applications, operate under time-varying heat source conditions. In this work, ORC optimum off-design performance maps are generated, to predict the engine power output, using screw expanders, and two HEX architectures. Results indicate that the PHEX design has 50% lower heat transfer area requirements than the DPHEX, while the PHEX evaporator performance is less sensitive to changes during off-design operation. By accounting for the components time-varying operating characteristics, the ORC PL power output reduction is lower than the respective one for the ICE-CHP unit. Specifically, with the ICE at 60% PL, the ORC engine operated at 72% PL. Present results are based on maintaining the evaporator pressure at the design level. An alternative control strategy would allow the optimiser to choose the new optimum pressure level at every PL point. Preliminary results of the latter approach indicate that power output can increase further. Overall, this work has proven that the time-varying HEX and expander performance should be incorporated in the off-design modelling of ORC engines.

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