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Abstract

The performance of Organic Rankine Cycles (ORC) plants is subject to uncertainties deriving from several factors. Such uncertainties are unavoidably propagated through the model to the outputs, affecting predictions of the commercial-scale performance and cost of this technology. The aim of this work is to analyse how the uncertainties associated with the performance of the expander, one of the main ORC components, propagate to the relevant thermodynamic and economic outputs and affect their final value. The analysis was performed for three different expander options (a single-stage turbine, a twin screw and a two-stage turbine) to generate a full spectrum of possible outputs rather than exact figures. Overall, a considerable variability of the output metrics was highlighted compared to the results from the deterministic analysis.

Keywords: Monte Carlo simulation, stochastic analysis, mini Organic Rankine Cycle, techno-economic modelling and analysis.

1. Introduction

Organic Rankine Cycle (ORC) plants are a promising technical solution for recovering and converting low-to-medium grade waste heat into electricity, as they present several advantages compared to other technologies in terms of improved thermal performance, flexibility and maintainability (Tchanche et al., 2011). However, the introduction of this advanced solution at a small scale, although technically interesting, is not always economically attractive. As a matter of fact, the small-scale application of ORCs is hindered by their uncompetitive specific cost, which is too high compared to other existing technologies. For this reason, a core issue for the development of the small-scale ORC systems is the assessment and optimization of their techno-economic feasibility. More specifically, considerable research efforts have been channelled into the technical performance optimization of different cycle layouts (including selection of the most appropriate organic fluids) and improvement of the performance of the individual components, with the ultimate aim of maximizing the power production of ORC plants while keeping their specific total capital requirement as low as possible. (Tocci et al., 2017). In all of the existing studies and analyses, however, the models devised and applied are essentially deterministic (i.e., they use best estimates of model input parameters, without inclusion of any uncertainties, and generate exact figures for the output parameters). This is a concern because the input values characterizing such process models can have significant uncertainties, stemming from several factors (e.g., material properties, variable operating conditions, design factors, low technological readiness level). Such uncertainties will be unavoidably propagated through the model to the
outputs, thus affecting predictions of the commercial-scale performance and cost of this technology. Combining the techno-economic evaluation of energy conversion systems with a stochastic analysis has proved helpful in dealing with such uncertainties and thus providing a more comprehensive understanding of their technical and economic feasibility and their operation (Di Lorenzo et al., 2012; Maccapani et al., 2014). The aim of this study is to evaluate, by means of a stochastic approach, the impact of uncertainties in model input parameters on the performance of the ORC power plants. In particular, the stochastic method has been used in this work to systematically and explicitly analyse how the uncertainties related to the expander performance propagate to the relevant thermodynamic and economic outputs and affect their final value. The proper selection of the expander for small-scale ORC systems remains an outstanding issue (Tocci et al., 2017), as can be deduced from the existing literature. For small-scale applications different expander options are available, each with its own advantages and disadvantages. The selection process is complicated further by the fact that, among all of the ORC components, the expander is the one whose performance is most negatively affected when downscaling to kW (Tocci et al., 2017). The analysis in this work has been performed on three different expander options that were previously comparatively studied by the authors (Di Lorenzo et al., 2019). By including uncertainties in the techno-economic evaluation, a full spectrum of possible outputs is made available rather than exact figures, thus quantifying the confidence in the results from the previous work.

2. Description of the ORC Plant

The plant considered in this analysis is an ORC plant for Waste Heat Recovery (WHR) applications with a power output of less than 100 kWe based on a subcritical cycle. Three different expanders have been considered, i.e. a one-stage radial turbine (Case A), a twin-screw expander (Case B) and a two-stage radial turbine (Case C). On one hand, the twin-screw expanders display lower speed and higher nominal pressure ratios compared to a single-stage turbomachine, which theoretically fits well ORC requirements. However, the performance of twin-screw expanders for small-scale applications is considerably reduced by under- or over-expansions in off-design conditions, leakage and clearance gap losses, and lubrication issues. On the other hand, radial-inflow turbomachines are robust and reliable machines and could provide higher performances in a wide range of operating conditions, though high rotational speeds, low pressure ratio per stage, clearance and windage losses, and choking conditions hinder the design of an efficient turbine for ORC applications.

In the ORC system considered in this work, a feed pump compresses and pumps the working fluid up to 17.5 bar into the Primary Heat Exchanger (PHE), where the waste heat is transferred to the working fluid, which is pre-heated, evaporated and then superheated. An expander is connected to a generator, so that the thermal energy of the working fluid is converted into useful work and then into electricity. After the expansion (down to 6 bar for Case A, 4 bar for Case B and 2.2 bar for Case C, according to the expander’s features), the thermodynamic cycle is closed by condensing the fluid in the condenser. The resulting three power plants were designed for the same reference waste heat source with the same refrigerant used as the working fluid. They were compared from a thermodynamic and economic performance viewpoint in a previous study by the same authors (Di Lorenzo et al., 2019), using only a deterministic approach and delivering the following key results. Case C, with a two-stage turbine, resulted in efficiency (11.6%) and power output (87.4 kWe) well above those achieved by the plants with a one-stage turbine (7% and 45kWe) and a twin-screw expander (8.5% and 58.5 kWe). The plant
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A specific cost figure for the two-stage turbine plant is also considerably below those for the other two plants ($6188 USD\text{2016}$ against $9889 USD\text{2016}$ and $8221 USD\text{2016}$). These results were obtained assuming exact figures for the input variables with no consideration of their stochasticity. Among these input variables is the efficiency of the expander (Case A: $\eta_{is}=75\%$; Case B: $\eta_{is}=72\%$; Case C: $\eta_{is}=75\%$ for the first stage, $\eta_{is}=72\%$ for the second stage), which has a strong impact on the cycle performance.

3. Methodology

In this analysis, the approach adopted was the Monte Carlo method, an established stochastic approach that has been used extensively to model and study uncertainty in engineering system behaviour evaluation. In a Monte Carlo simulation a sufficiently large number of samples of the uncertain input variables are randomly generated based on the defined probability distributions. The samples are input into the model of the system being considered and the resulting output variables chosen as indices of the performance of the system are collected and stored. The analysis of these results ultimately produces a quantitative estimate of the impact of the uncertainty of the input variables on the system behaviour. The three ORC plant variants were modelled with a simulation routine developed in-house (Di Lorenzo et al., 2019), estimating their design-point performance. The thermodynamic and transport properties of the organic fluid were determined using the RefProp database (Lemmon et al., 2002). The stochastic analysis was performed assuming as a stochastic input the isentropic efficiency of the expander. The uncertainty of this input parameter was described by means of triangular and normal distributions with the features presented in Table I. The deterministic on-design value was assumed to be the central value of the distribution, while the standard deviation stemmed from information and data collected from the open literature and critically reviewed: for the single stage turbine the values suggested by (Costall et al., 2015; Kang, 2012; Han et al., 2014; Sung et al., 2016; Wong et al., 2013; Shao et al., 2017; Giovannelli et al., 2019) were examined, while for the twin-screw expander, the figures proposed by (Hsu et al., 2014; Stošić et al., 1997; Lee et al., 2017; Platell, 1993; Astolfi, 2015) were evaluated. For the two-stage turbine, in contrast, not many values are currently available in the literature, apart from the one resulting from the work by Kang (2016). A summary of the other main assumptions used for the calculation of the heat and mass balances of the ORC systems is reported elsewhere (Di Lorenzo et al., 2019). The performance metric that was monitored to evaluate the effect of the uncertainty in the expander performance on the ORC system was the thermal efficiency.

### Table I - Probability distributions for the expander efficiency

<table>
<thead>
<tr>
<th>Case – Expander Type</th>
<th>Distribution</th>
<th>Min and Max Values</th>
</tr>
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<tbody>
<tr>
<td>Case A – Single Stage Turbine</td>
<td>Triangular</td>
<td>68% - 83%</td>
</tr>
<tr>
<td>Case B – Twin Screw</td>
<td>Triangular</td>
<td>70% - 85%</td>
</tr>
<tr>
<td>Case – Two Stage Turbine (second stage)</td>
<td>Normal</td>
<td>65% - 79%</td>
</tr>
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</table>

*For the first stage the probability distribution adopted for the single stage case was used.*

Furthermore, the uncertainty in the expander performance was propagated through economic parameters. The Specific Unit Cost ($\text{USD}/\text{kW}$) was used as an indicator representative of the economic performances of the power plants being investigated. The work aimed primarily to assess the propagation of uncertainty from the expander to the
economic parameters. For this reason, the impacts that the variability of expander $\eta_0$ can have on the sizing and design of the other components (e.g., the condenser) were not taken into account, but rather, all of the other components were assumed to be as estimated in the previous work and unchanging. Nevertheless, the final results are yet informative, as they reflect changes in economic expectations based on expander performance variability.

4. Key Results
The results are presented as cumulative probability distributions (Figures 1-3), which provide the analyst with the likelihood of random variable $X$, evaluated at $\bar{x}$, being equal to or less than the specified value $x$; the complement (one minus the cumulative probability) is the probability that the variable will exceed the specified value $\bar{x}$. The deterministic evaluation is represented in the same figures by a vertical dotted line.

According to the simulation results, the probability that the thermal efficiency for Case A could be less than the deterministic value of 7.1% is approximately 50%. It could range between 6.3% and 7.9% with a standard deviation of 0.003 and a relative standard deviation of 0.045. The median value was equal to 7.1% in line with the deterministic prediction. For Case B, the resulting efficiency displays a median value of 8.9% close to the deterministic value of 8.5%. It could vary within a range of 8.2% to 10.1%, with a standard deviation of 0.004 and a relative standard deviation of 0.048. The probability that the final figure of plant efficiency could exceed the deterministic value is quite high (85%). The results indicate that a considerable level of uncertainty is also associated with the variation of the expander performance in Case C. The likelihood that the forecast efficiency value can exceed the deterministic value is approx. 52%, with a remaining 48% probability that the final value could be lower than the deterministic one. The variation in
the expander efficiency in Case C causes the plant efficiency to vary between 10.6% and 12.6%, with a median value of 11.6% (well aligned with the deterministic result), a standard deviation of 0.003 and a relative standard deviation of 0.025. It is of paramount importance to highlight that these results (like the results of any Monte Carlo simulation analysis) rely on the initial assumptions, especially the statistical distributions selected and assigned to the uncertain input variables. A deterministic analysis only provides the decision maker with information on deterministic efficiencies, with no suggestion of the above-mentioned likelihood of a higher (or lower) value. Figure 4 shows the cumulative probability distributions of the plant efficiency for the three cases. It is evident that there are not any intersection points among the three curves; therefore, Case C (the two stage turbine) should be selected, as its probability distribution curve spreads further to the right (higher values of efficiency), although the results (i.e., same chance of observing a lower or higher value compared to the deterministic one) suggest that additional research should be undertaken in order to reduce uncertainty in the expander performance.

Figure 5 - Cumulative probability distribution for the three cases for the economic results

Figure 5 reports the cumulative probability distributions for the Specific Unit Cost for the three cases. Like the plant efficiency results, the three cumulative probability distributions do not intersect at any point, confirming the superior economic performance of Case C already highlighted by the deterministic analysis.

5. Conclusions
The research effort presented in this paper focuses on the inclusion of uncertainties in the techno-economic evaluation of ORC power plants. The Monte Carlo simulation technique was employed to quantify the impact of uncertainties associated with three different expanders on key techno-economic performance outputs (plant efficiency and specific unit cost). By including uncertainties in the techno-economic evaluation of the three plant options, it was found that the plant efficiency was equally likely to be lower or higher than the deterministic value for Cases A and C, while it could exceed the forecasted value with an 85% probability in Case B. The economic results are indicative of how the probability distribution of specific unit cost is affected by the uncertainty in the expander performance and confirm that the two-stage turbine outperforms the other
two cases. Overall, a considerable variability of the output metrics was highlighted compared to the results from the deterministic analysis. A full spectrum of possible outputs was made available, rather than exact figures. This type of analysis allows the decision-maker to make more informed decisions on the evaluation of the ORC technology and, in particular, on what options to pursue for further R&D activities by establishing the least expensive and the best-performing solution among those analysed.

References