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Design of Multi-pressure Organic Rankine Cycles for Waste Heat Recovery in Site Utility Systems

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Abstract

This work addresses the design of Organic Rankine Cycle (ORC) processes used for power generation from low-grade heat available in site utility systems. The Exergy Composite Curves approach is used within a systemic optimization framework to explore various complex ORC configurations. The method facilitates interconnectivity at several temperature and pressure levels, considering different types and numbers of turbines as design decision parameters simultaneously with other operating ORC features. It is employed to investigate the performance of two generic ORC configurations, namely one considering independent pressure loops with expansion turbines and the other considering pressure loops contacted through induction turbines. To optimize the number of pressure levels, ORC structural configuration, and operating parameters an inclusive objective function is used considering thermodynamic criteria. The application of the method is demonstrated by a case study on waste heat recovery and reuse in a utility plant.

Keywords: Organic Rankine cycle, Exergy analysis, Utility systems, Process design

1. Introduction

Utility systems are an essential part of process plants, supplying thermal energy in the form of steam which is generated at different pressure levels to satisfy heating demands for a wide range of temperatures. After utilization, the steam results in a saturated condensate often discharged into a lower pressure area where flash steam of low thermal content is generated. Process plants produce large amounts of flash steam often wasted in the environment, while instead it may be recovered for further utilization.

To this end, ORC systems are able to transform heat of low thermal content into useful power hence they have been identified as a very promising technology for waste heat recovery (Kapil et al., 2011). The ORC operation is based on the vaporization (*vap*) of a working fluid to drive a turbine (*turb*), followed by condensation (*cond*) into a liquid which is pumped (*pump*) back to the vaporizer to close the loop. Clearly, the ORC operating and economic performance depends on the way that different ORC equipment components are interconnected and integrated with the heat source. ORCs incorporating conventional heat extraction and expansion configurations are unsuitable for use with sources of varying heat content at different pressure levels; they result in increased entropy generation, leading to waste of thermal energy. More efficient configurations are necessary that are able to extract and transform heat into work at different pressures.

Process integration methods (Varbanov et al., 2012) provide a useful set of technologies for the analysis and design of similar systems. An increasing number of publications employ Pinch-based tools such as grand composite curve analysis (DiGenova et al., 2013) to investigate and improve the performance of pre-specified ORC configurations, or combine process integration principles with optimization methods to design efficient ORC flowsheets (Hipólito-Valencia et al., 2013). Despite obtaining promising results, improvements are mainly based on the design of heat-exchange networks around conventional ORC expansion operations using performance characteristics associated with energy analysis features (e.g. thermal efficiency etc.). The design of ORC flowsheets combining advances in both heat-exchange and expansion operations is clearly expected to result in considerable performance improvement. However, this requires the additional consideration of exergy ORC characteristics to identify configurations that better exploit the maximum useful work produced from heat sources of variable temperature and pressure. To date, few existing works have explored ORC design considering exergy analysis at different parts of the ORC flowsheet (Tchanche et al., 2010) or minimization of the exergy losses (Marechal and Kalitventzeff, 2004).

2. Proposed method

The consideration of exergy analysis in the investigation for promising ORC process configurations clearly deserves further attention in the context of systemic process integration methods. The presented work adopts the Exergy Composite Curves (ECCs) approach (Linhoff and Dhole, 1992) to explore the potential for ORC process improvements. The method is supported by a mathematical model representing a generic multi-pressure ORC cascade. The model facilitates interconnectivity at different temperature and pressure levels, also considering different types of turbines (e.g. expansion, induction turbines) to investigate the performance of different ORC configurations (e.g. independent pressure loops or pressure loops contacted through induction turbines). Such configurations are updated with new features within an iterative procedure supporting the systematic identification of the optimum number of pressure loops, together with several operating optimization parameters.

2.1. Model development

A major concern in the optimization of a standard ORC (Figure 1a) is the increase of the work extracted from a specific heat source or the reduction of exergy losses. This goal may be approached by modifications imposed on the ORC operating conditions which reflect on the shape of the ECCs, since the shaded area within the ECCs (Figure 1b) is directly associated with the observed exergy losses. Such modifications may be interpreted by different process configurations, as their practical implementation requires appropriate allocation of heat exchange and expansion equipment within the ORC flowsheet. In this context, different process configurations may be captured by a generic multi-pressure ORC cascade (Figure 2a) consisting of an arbitrary number of branches (*NLP*) to represent different pressure levels. The cascade considers two potential types of turbines, an expansion (*ET*) and an induction turbine (*IT*). The *ET* is used to generate work by expansion between any heat extraction and condenser pressure level, while the *IT* is used between successive pressure levels.

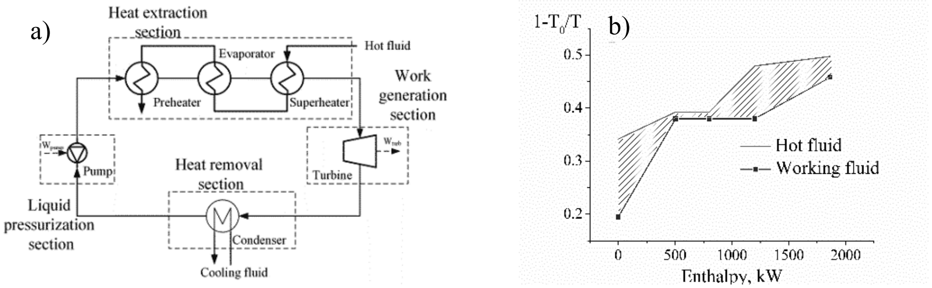

Figure 1. a) Scheme of a standard ORC, b) Exergy Composite Curves of heat extraction

The operating features of the cascade may be represented in a composite curve diagram (Figure 2b). The enthalpy intervals (*NWI*) for the working fluid (*wf*) curve follow a sequential, recursive pattern until the last interval where superheating of the *wf* takes place only at the highest pressure level. The system pressure levels are represented in the *wf* curve using three isothermal profiles (i.e. T_2-T_3, T_5-T_6, T_{3NLP-1}-T_{3NLP}). The hot fluid (*hf*) curve may also be composed of *NHI* temperature intervals (Θ_1-Θ_{NHI}). As the shaded area of Figure 1b corresponds to the observed exergy losses, the difference between the exergy contents of the hot fluid (Ex^{hf}) and the working fluid (Ex^{wf}) needs to be minimized whilst considering the minimum temperature driving force to ensure realistic heat transfer rate and exchange area. This is represented by Eq.(1), as follows:

$$\Delta E_{loss} = \sum_{l=1}^{NHI} \frac{\left(1-T_0/\theta_{l+1}\right)+\left(1-T_0/\theta_l\right)}{2}\Delta H_l^{hf} - \sum_{j=1}^{NWI} \frac{\left(1-T_0/T_{j+1}\right)+\left(1-T_0/T_j\right)}{2}\Delta H_j^{wf} \tag{1}$$

Based on the *wf* and *hf* curves the enthalpy (ΔH-kW) in each interval is calculated as:

$$\begin{aligned}
\Delta H_{3i-2}^{wf} &= \left(\sum_{i}^{NLP} F_i^{wf} \cdot C_{P_{liq},i}^{wf}\right)\left(T_{3i-1}-T_{3i-2}\right), i \in [1, NLP] \\
\Delta H_{3i-1}^{wf} &= F_i^{wf} \cdot \Delta H_{vap}\left(T_{3i-1}\right), i \in [1, NLP] \\
\Delta H_{3i}^{wf} &= F_i^{wf} C_{P_{vap},i}^{wf}\left(T_{3i+1}-T_{3i}\right) + \left(\sum_{i+1}^{NLP} F_i^{wf} \cdot C_{P_{liq},i}^{wf}\right)\left(T_{3i+1}-T_{3i}\right), i \in [1, NLP-1] \\
\Delta H_{3i}^{wf} &= F_i^{wf} C_{P_{vap},i}^{wf}\left(T_{3i+1}-T_{3i}\right),\ i = NPL \\
\Delta H_l^{hf} &= F_l^{hf} C_{P_{liq},l}^{hf}\left(\theta_{l+1}-\theta_l\right), l \in [1, NHI]
\end{aligned} \tag{2}$$

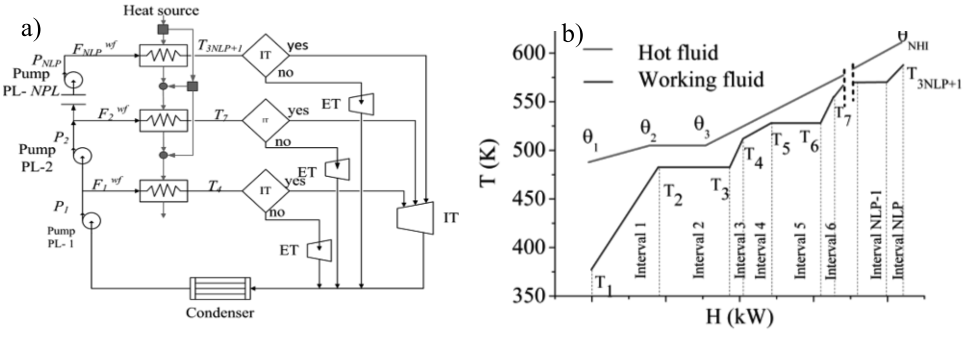

Figure 2. Generic a) multi-pressure ORC cascade, and b) corresponding ECCs

For the work generation (*turb*), heat removal (*cond*) and liquid pressurization (*pump*) sections of the cycle the following equations hold:

$$
\begin{aligned}
&W_{turb,i} = -\int_{T_{turbout,i}}^{T_{3i+1}} C_{p,vap}(T)\cdot dT \\
&W_{cond} = \lambda\left(Q^{hf} - \sum_{i=1}^{NLP} W_{turb,i}\right) \\
&W_{pump,i} = F_i^{wf}\cdot \upsilon^{sat}\left[P^{sat}(T_{3i-1}) - P^{sat}(T_1)\right]\big/\eta_{pump},\ i\in[1,NLP]
\end{aligned}
\tag{3}
$$

where λ is a coefficient of the power input necessary to remove 100 kW of condenser heat, $C_{p,vap}$ and $C_{p,liq}$ are the vapor and liquid heat capacities (kJ/kmol.K), P^{sat} is the saturation pressure (Pa), υ^{sat} is the saturated liquid molar volume (m^3/kmol), F is the flowrate (kmol/s), W is the work (kW), Q is the heat transferred (kW) and η is the efficiency.

2.2. Optimization problem formulation and design approach

The minimization of exergy loss improves (i.e. maximizes) the quality of the extracted heat. The quantity of the work produced from the available exergy depends on the behaviour of the *wf* during the expansion process because it is a strong function of the fluid thermo-physical properties (Stijepovic et al., 2012).Therefore, the work generation in the expansion should be part of the objective function employed in optimization. Power requirements for liquid pressurization and condensation affect the overall power output. Higher operating pressures which are beneficial for exergy loss minimization require more power during the liquid pressurization process. Due to this trade – off the power requirement for pressurization should also be part of the objective function. The power requirement for the condensation process decreases as the quantity of the generated work increases. This affects the overall power output balance, therefore the power requirement for condensation should also be considered in the objective function. Hence the optimization problem can be defined as follows:

$$\min \Phi = \Delta Ex_{loss} - (|W_{turb}| - W_{pump} - W_{cond}) \tag{4}$$

Subject to:

$$T_{j+1} - T_j \geq 0,\ j\in[1,3NWI] \tag{5}$$

$$\theta\left(\sum_{j=1}^{m}\Delta H_j^{\,c}\right) - T\left(\sum_{j=1}^{m}\Delta H_j^{\,c}\right) - \Delta T_{\min} \geq 0,\ j\in[1,m], m = NWI \vee NHI, c = wf \vee hf \tag{6}$$

$$C_{P_{liq},i}(T_{3i-1} - T_0) + \Delta H_{vap}(T_{3i-1}) - C_{P_{vap},i}(T_{turbout,i} - T_0) \leq 0,\ i\in[1,NPL] \tag{7}$$

$$T_{turbout,i+1} - T_{3i+1} = 0, i\in[1,NLP-1] \tag{8}$$

where Eq.(8) represents a case of an induction turbine where the outlet of a particular turbine stage has to be equal to the temperature of the stream with which it is mixed before entering the next turbine stage.

A systemic design approach is proposed consisting of the following stages: i) the quantity of the available heat is first determined based on the available hot stream (e.g. inlet temperature etc.), ii) an initial process configuration is then setup serving as a reference point to measure potential subsequent improvements, iii) the optimization problem is solved for this process, iv) a new process configuration is generated by adding a new pressure level, v) the new configuration becomes the reference process, hence steps (ii), (iii) and (iv) are repeated until no significant improvement is observed when adding new pressure levels (i.e. changing the process configuration).

3. Case study

3.1. Implementation details

The waste heat consists of water condensate with saturation temperature of 250 °C with mass flowrate of 267 t/h. The outlet temperature of the condensate should be decreased to 120 °C to recover part of the desired energy with an ORC. Dibromomethane is the *wf*, which is assumed to be appropriate for the specified hot fluid inlet temperature (Tchanche et al., 2011). A standard ORC process (Figure 1a) is optimized first using as decision variables the F^{wf}, the saturation temperature (T_2) and the outlet temperature at the heat extraction section (T_4). After determining the optimal values structural improvements are explored by introduction of a new pressure level (PL). Two alternative configurations are considered including (a) independent pressure loops with expansion turbines (PLET)and (b) pressure loops contacted trough an induction turbine (PLIT). For the 2ndPL the type of optimization variables are the same but their number is doubled (one set for each level). Following the proposed optimization approach, the resulting 2-PLconfiguration will become the reference point for a 3-PL process if a significant performance improvement is achieved compared to the standard ORC process. The procedure is repeated fo 3PLs and so forth.

3.2. Results and discussion

Figure 3 shows the dependence of the net work output on the type of configuration and number of PLs. Configurations with 2-PLs have higher power output compared with a standard ORC with 1 PL (Figure 3a). This is because multi-PL processes are able to closely match the ECCs of the wf and hf, hence decreasing the exergy losses.

The recovered exergy loss is partially converted to power; this is why power production is increased with a multi-PL cascade compared to a standard process. The 3-PL configurations present slightly higher power output compared to the 2-PL ones. The 3-

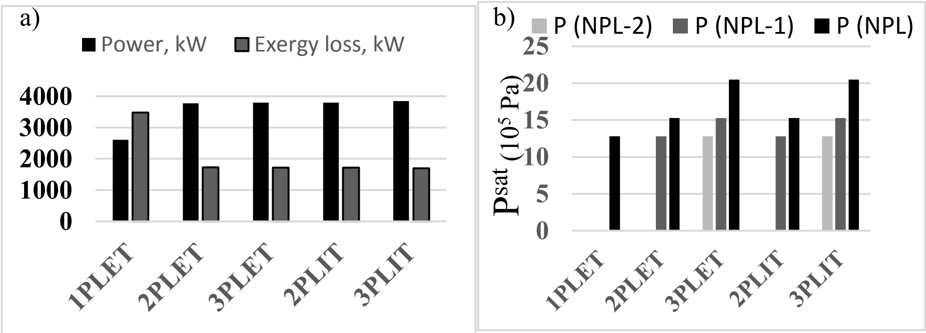

Figure 3. Type of ORC configuration vs. a) power output and exergy loss, b)saturation pressure distribution per pressure level

PL configuration matches the ECCs even more closely than the 2-PL case, but the improvement is not as significant. The induction turbine (e.g. 2-PLIT etc.) systems have higher power output than systems with expansion turbines (e.g. 1-PLET). In fact, a 3-PL with 3 expansion turbines (3-PLET) has the same power output as a 2-PL with 1 induction turbine (2-PLIT), while the 3-PLIT power output (3-PL, 1 induction turbine) is even higher (this is not clearly visible due to space restrictions). Figure 3a shows that the power output in multi-PLs is 44.5% higher than in a standard ORC.

Optimal values of pressure levels for each ORC configuration are given in Figure 3b. Figure 3b shows that the optimal value of pressure for each additional level is higher. This is because the working fluid operating parameters are limited by the pinch temperature. By adding new pressure levels the limitations introduced by the pinch point are reduced, and the system produces more power, reducing exergy losses if the new pressure level is higher. As a result exergy loss reduction is key for design of ORCs with improved performance. Future work should focus on the employment of mixtures in multi-pressure systems.

4. Conclusions

This work proposes an efficient approach for exploring potential ORC process improvements by introducing multi-pressure configurations. The consideration of exergy analysis in this investigation shows high potential to identify and reduce losses that occur due to process irreversibility. The method is used to explore different ORC configurations, which are updated with new features within an iterative procedure supporting the systematic identification of the optimum number of pressure loops together with several operating parameters. The optimization is performed using an inclusive objective function. The case study indicates significant improvements in power output from the introduction of multiple pressure loops.

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