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Optimal Integration of Organic Rankine Cycles into Process Heat Exchanger Networks

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This paper presents a mathematical programming model for the synthesis of an optimal heat exchanger network (HEN) in a process incorporating an organic Rankine cycle (ORC), which is used for improved heat recovery. The model is based on a modified stage-wise superstructure, where the process and ORC streams can exchange heat in all the stages. In addition, the evaporation and condensation temperatures of the ORC working fluid are treated as variables, and its thermodynamic properties (e.g. enthalpies and temperatures) are correlated as functions of evaporation and condensation temperatures. This allows the ORC operating conditions and the HEN to be optimised simultaneously, with the objective of maximising net power output or minimising overall energy cost. A literature example is presented to demonstrate the application of the proposed model. Results show that, besides producing shaft work, the ORC can further reduce the cold utility requirement. Furthermore, the overall energy cost can be minimised by increasing ORC power production, at the expense of increased hot and cold utility requirements. The proposed approach is thus useful in assessing the benefits from optimal ORC integration in the background process.

1. Introduction

The organic Rankine cycle (ORC) is a Rankine cycle using organic fluid as the working medium. Compared with traditional Rankine cycles using water as the working fluid, ORCs have the advantage of being able to effectively produce shaft work from various low-to-medium temperature heat sources. ORCs have been applied to power generation from industrial waste heat as well as renewables such as solar thermal energy, geothermal energy and biomass.

For process waste heat recovery, Desai and Bandyopadhyay (2009) proposed a pinch-based methodology for the integration and optimisation of an ORC with the background process to generate shaft work/power. Hipólito-Valencia et al. (2013) presented a superstructure-based mixed integer nonlinear programming (MINLP) model for optimal integration of a regenerative ORC with the process. Chen et al. (2014) presented a superstructure-based mathematical model with a two-step solution approach for the synthesis of a heat exchanger network (HEN) with ORC integration. Chen et al. (2020) presented a multi-objective MINLP model to address the trade-off between improved heat recovery and economic feasibility in the ORC-HEN integration. Dong et al. (2020) proposed a simultaneous approach to the optimisation of an ORC-integrated HEN.

Most previous works on process waste heat recovery through ORC integration used sequential approaches, in which not all the variables are optimised at the same time, thus resulting in suboptimal solutions. Also, most of these works utilised only low-temperature heat below the process pinch. However, allowing the ORC to absorb higher-temperature heat may generate more profit. In some works (e.g. Dong et al., 2020), ORC streams for evaporation and condensation are divided into separate sensible heat and latent heat sections, with the latter approximated by a non-isothermal stream with a minimal temperature change and a large heat capacity. This approximation simplifies the formulation but requires a larger number of heat exchangers. All the above issues are addressed in this paper, where a simultaneous optimisation approach is developed for the synthesis of ORC-integrated HENs. Based on a modified stage-wise superstructure, the mathematical model deals with the

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phase change of the ORC working fluid and treats its evaporation and condensation temperatures (and hence thermodynamic properties) as variables. This allows the ORC operating conditions and the HEN to be optimised simultaneously. A literature example is solved to illustrate the proposed approach.

2. Problem statement

The problem addressed in this paper can be stated as follows. Given:

- A process with a set of hot process streams $i \in \mathbf{I}^{\mathrm{P}}$ and a set of cold process streams $j \in \mathbf{J}^{\mathrm{P}}$. The supply and target temperatures and the heat capacity flowrates of these streams are known parameters.
- An ORC to be integrated with the process. The ORC working fluid acts as a cold stream $j \in \mathbf{J}^{\mathrm{ORC}}$ in the evaporator, and as a hot stream $i \in \mathbf{I}^{\mathrm{ORC}}$ in the condenser. The evaporation and condensation temperatures of the working fluid and its flowrate are to be optimised. Therefore, the thermodynamic properties (such as temperatures and enthalpies) of the ORC streams are treated as variables.

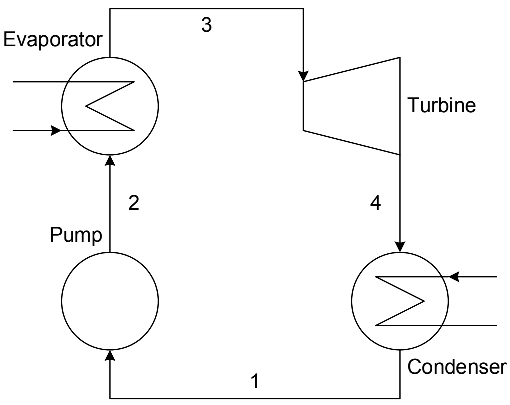
In the present work, the objective is to synthesise an optimal HEN of the process and ORC streams for maximum work production or minimum overall energy cost.

3. Model formulation

The overall model for the synthesis of an ORC-integrated HEN consists of an ORC model and a HEN model. The notation used in the formulations is given in the Nomenclature.

3.1 ORC model

Figure 1a shows a schematic diagram of a basic ORC. The working fluid, preferably a dry fluid, is pressurised (1→2), evaporated (2→3), expanded (3→4) and condensed (4→1). It is assumed that the inlet stream of the pump is saturated liquid, and that the inlet stream of the turbine is saturated vapour, as shown in Figure 1b. Based on the basic ORC configuration, the ORC model is formulated as follows.



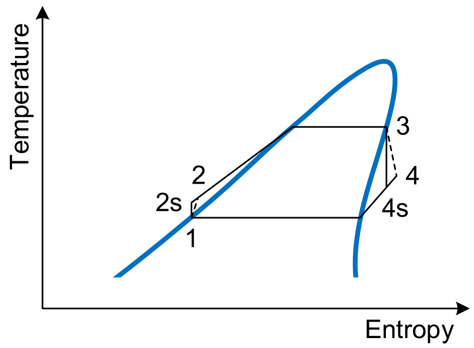


Figure 1: Basic ORC configuration (a) and the corresponding temperature-entropy diagram (b)

The work required for the pump (w_{pump}) is calculated using Eq(1).

$$w_{\mathrm{pump}} = m(h_2 - h_1) \tag{1}$$

where h_1 is a function of the condensation temperature (t^{cond}); h_2 is a function of t^{cond} and the evaporation temperature (t^{evap}). The work produced by the turbine (w_{turb}) is calculated using Eq(2).

$$w_{\mathrm{turb}} = m(h_3 - h_4) \tag{2}$$

where h_3 is a function of t^{evap}; h_4 is a function of t^{evap} and t^{cond}. The outlet temperatures of the pump (t_2) and the turbine (t_4) can also be calculated as functions of both t^{cond} and t^{evap}. Expressions for h_1, h_2, h_3, h_4, t_2 and t_4 can be obtained from regression analysis within the specified ranges of t^{cond} and t^{evap}. In this work, the fluid properties were calculated using REFPROP, and regressions were performed in Microsoft Excel.

3.2 HEN model

Figure 2 shows a modified stage-wise superstructure for a HEN of process and ORC streams. After integrating the ORC with the process, the working fluid is condensed by heat exchange with cold process/utility streams, and evaporated by heat exchange with hot process streams. The cold ORC stream is not allowed to use a hot utility, because the ORC is integrated for improved heat recovery. Therefore, the hot process streams are the only source of heat for the ORC. The possibility of heat exchange between the ORC hot and cold streams is also excluded, although the possible heat exchange in the ORC can be considered by incorporating an internal heat exchanger. Based on the modified HEN superstructure, the HEN model can be formulated.

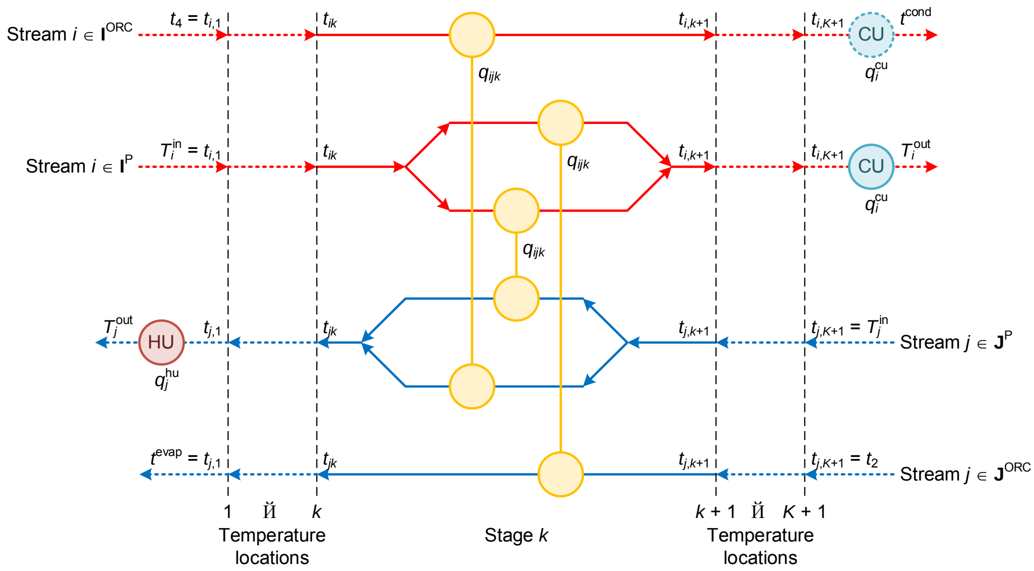


Figure 2: Stage-wise superstructure for an ORC-integrated HEN

In the proposed model, constraints included for heat balances, temperature assignment and feasibility, upper limits on heat loads, and feasible temperature driving forces are much the same as those presented by Ponce-Ortega et al. (2009). The main difference is that, the flowrates, inlet and outlet temperatures, and the heat of vaporisation of the ORC streams are variables. Due to space limitations, these constraints are omitted.
Eqs(3)-(6) ensure feasible latent heat exchange for the ORC streams during condensation and evaporation, which take place when the saturation temperature is reached. Eq(3) compares the temperature of the hot ORC stream at the outlet of stage *k* ($t_{i,k+1}$) with t^{cond}. When $t_{i,k+1} \le t^{\mathrm{cond}}$, $y_{ik} = 1$, meaning that the hot ORC stream is saturated and there may be condensation in stage *k*. When $t_{i,k+1} > t^{\mathrm{cond}}$ ($t_{i,k+1} \ge t^{\mathrm{cond}} + \epsilon$), $y_{ik} = 0$, in which case q_{ik}^{Λ} is forced to zero by Eq(4) – no condensation of the hot ORC stream in stage *k*. Eq(5) compares the outlet temperature of the cold ORC stream at stage *k* (t_{jk}) with t^{evap}. When $t_{jk} \ge t^{\mathrm{evap}}$, $y_{jk} = 1$, meaning that the cold ORC stream is saturated and there may be evaporation in stage *k*. When $t_{jk} < t^{\mathrm{evap}}$ ($t_{jk} + \epsilon \le t^{\mathrm{evap}}$), $y_{jk} = 0$, in which case q_{jk}^{Λ} is forced to zero by Eq(6) – no evaporation of the cold ORC stream in stage *k*.

$$\epsilon - \Gamma y_{ik} \le t_{i,k+1} - t^{\mathrm{cond}} \le \Gamma(1 - y_{ik}) \quad \forall i \in \mathbf{I}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{3}$$

$$q_{ik}^{\Lambda} \le Q_i^{\mathrm{U}} y_{ik} \quad \forall i \in \mathbf{I}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{4}$$

$$\epsilon - \Gamma y_{jk} \le t^{\mathrm{evap}} - t_{jk} \le \Gamma\left(1 - y_{jk}\right) \quad \forall j \in \mathbf{J}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{5}$$

$$q_{jk}^{\Lambda} \le Q_j^{\mathrm{U}} y_{jk} \quad \forall j \in \mathbf{J}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{6}$$

To prevent temperature inversion inside the exchanger for streams with phase change and to ensure a correct distribution of latent heat in a stage, the following constraints are needed. Eqs (7) and (8) describe the latent heat balances for hot and cold ORC streams in stage *k*, respectively. Eqs (9) and (10) set upper limits on the latent heat loads, assuming all the process streams are non-isothermal without phase change. Eqs (11) and (12) define the latent heat ratios (r_{ik}^{LH} and r_{jk}^{LH}), which apply to all the branches of the hot and cold ORC streams in stage *k* for isenthalpic mixing. Eqs(13) and (14) set r_{ik}^{LH} and r_{jk}^{LH} to zero if there are no matches between the ORC streams and the process streams in stage *k*.

$$q_{ik}^{\Lambda} = \sum_{j \in \mathbf{J}^{\mathrm{P}}} q_{ijk}^{\mathrm{cond}} \quad \forall i \in \mathbf{I}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{7}$$

$$q_{jk}^{\Lambda} = \sum_{i \in \mathbf{I}^{\mathrm{P}}} q_{ijk}^{\mathrm{evap}} \quad \forall j \in \mathbf{J}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{8}$$

$$q_{ijk}^{\mathrm{cond}} \le \frac{\left(t^{\mathrm{cond}} - \Delta T^{\mathrm{min}}\right) - t_{j,k+1}}{t_{jk} - t_{j,k+1}} q_{ijk} \quad \forall i \in \mathbf{I}^{\mathrm{ORC}}, j \in \mathbf{J}^{\mathrm{P}}, k \in \mathbf{ST} \tag{9}$$

$$q_{ijk}^{\mathrm{evap}} \le \frac{t_{ik} - \left(t^{\mathrm{evap}} + \Delta T^{\mathrm{min}}\right)}{t_{ik} - t_{i,k+1}} q_{ijk} \quad \forall i \in \mathbf{I}^{\mathrm{P}}, j \in \mathbf{J}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{10}$$

$$q_{ijk}^{\mathrm{cond}} = r_{ik}^{\mathrm{LH}} q_{ijk} \quad \forall i \in \mathbf{I}^{\mathrm{ORC}}, j \in \mathbf{J}^{\mathrm{P}}, k \in \mathbf{ST} \tag{11}$$

$$q_{ijk}^{\mathrm{evap}} = r_{jk}^{\mathrm{LH}} q_{ijk} \quad \forall i \in \mathbf{I}^{\mathrm{P}}, j \in \mathbf{J}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{12}$$

$$r_{ik}^{\mathrm{LH}} \le \sum_{j \in \mathbf{J}^{\mathrm{P}}} z_{ijk} \quad \forall i \in \mathbf{I}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{13}$$

$$r_{jk}^{\mathrm{LH}} \le \sum_{i \in \mathbf{I}^{\mathrm{P}}} z_{ijk} \quad \forall j \in \mathbf{J}^{\mathrm{ORC}}, k \in \mathbf{ST} \tag{14}$$

3.3 Objective functions

To assess the benefits from the integration of an ORC with the process, the objective may be to maximise the work production of the ORC within the minimum utility consumption of the process. This can be done in a two-step approach. The objective function in step 1 is to minimise the hot utility consumption (f_{HU}):

$$\min f_{\mathrm{HU}} = \sum_{j \in \mathbf{J}^{\mathrm{P}}} q_j^{\mathrm{hu}} \tag{15}$$

Next, the minimum hot utility consumption (f_{HU}^*) is added as a constraint, and the objective function in step 2 is to maximise the net power production (f_{P}):

$$\max f_{\mathrm{P}} = w_{\mathrm{turb}} - w_{\mathrm{pump}} \tag{16}$$

$$\sum_{j \in \mathbf{J}^{\mathrm{P}}} q_j^{\mathrm{hu}} \le f_{\mathrm{HU}}^* \tag{17}$$

Alternatively, to optimise the energy efficiency in a simultaneous manner, the objective may be to minimise the overall energy cost (f_{EC}), which is defined as the difference between the utility cost and the revenue from work production, as given in Eq (18).

$$\min f_{\mathrm{EC}} = \sum_{i \in \mathbf{I}} C^{\mathrm{cu}} q_i^{\mathrm{cu}} + \sum_{j \in \mathbf{J}^{\mathrm{P}}} C^{\mathrm{hu}} q_j^{\mathrm{hu}} + C^{\mathrm{e}}\left(w_{\mathrm{turb}} - w_{\mathrm{pump}}\right) H \tag{18}$$

The overall ORC-HEN model is an MINLP. In the next section, an illustrative example is solved to demonstrate the proposed approach. The MINLP model is implemented in GAMS and solved utilising BARON.

4. Illustrative example

Taken from Desai and Bandyopadhyay (2009), this example involves a process of two hot streams and two cold streams. Table 1 shows the process stream data. A basic ORC using n-pentane as the working fluid is to be integrated with the process. The condensation temperature for the ORC is fixed at 40 °C, whilst the evaporation temperature can vary between 67 and 117 °C, based on observation of the process Grand Composite Curve.

Isentropic efficiencies of the turbine and the pump are assumed to be 80 and 65%, respectively. The minimum temperature difference for condensation, evaporation and process-process heat exchange is set to 10 °C. Two scenarios are considered. Scenario 1 maximises the net power output of the ORC with the minimum hot utility consumption, whilst scenario 2 minimises the overall energy cost.

Table 1: Process data for the example

Stream	Supply temperature (°C)	Target temperature (°C)	Heat capacity flowrate (kW/°C)
H1	187	77	300
H2	127	27	500
C1	147	217	600
C2	47	117	200

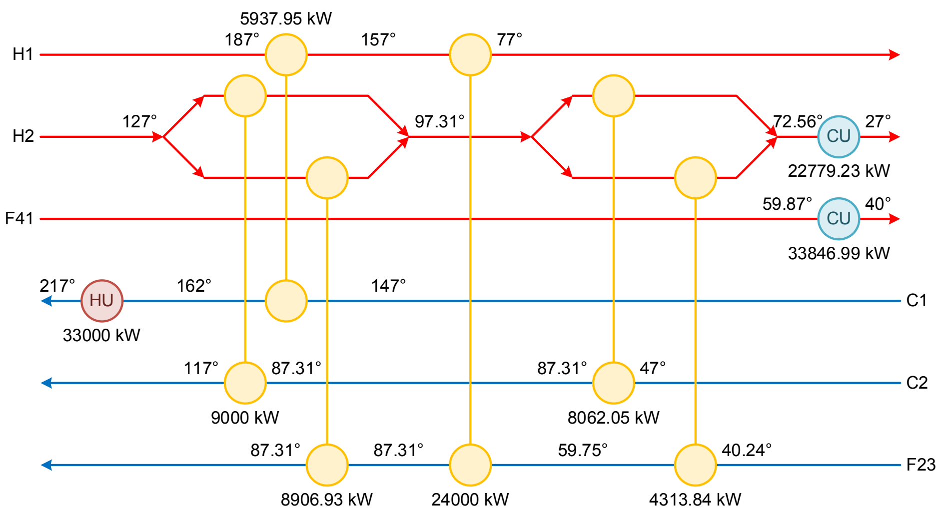


Figure 3: Optimal HEN for scenario 1

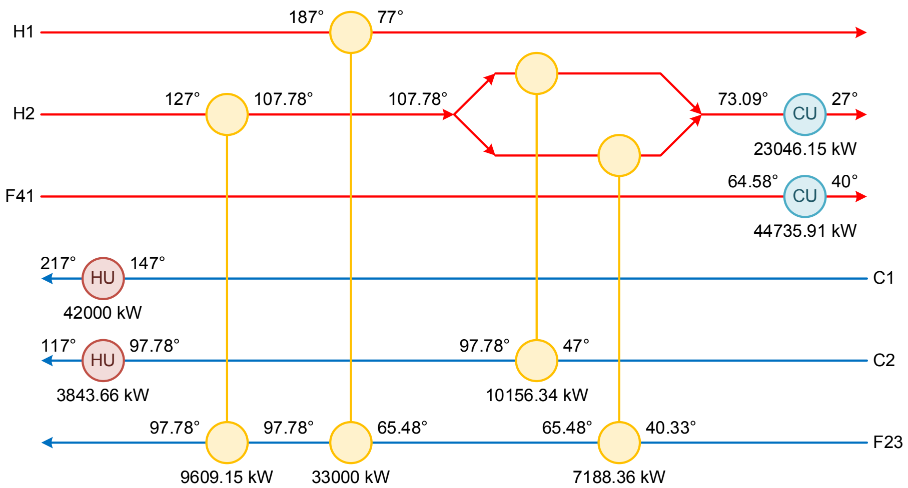


Figure 4: Optimal HEN for scenario 2

4.1 Scenario 1: Maximum net power output

First, the minimum hot and cold utility requirements of the process are determined to be 33,000 and 60,000 kW, respectively. The ORC-HEN model is then solved with the hot utility consumption limited to 33,000 kW, and the maximum net power output is found to be 3,297.58 kW. The optimal evaporation temperature and flowrate of the working fluid (n-pentane) are determined to be 87.31 °C and 86.53 kg/s, respectively. Compared to the results of Desai and Bandyopadhyay (2009) – 86.07 kg/s of n-pentane evaporated at 87.5 °C to produce 3,292 kW of work, the optimum can be more accurately located and a better solution is found using the proposed model. Figure 3 shows the optimal HEN configuration. Apart from work production, the ORC integration also results in a reduction in cold utility consumption from 60,000 to 56,626.22 kW.

4.2 Scenario 2: Minimum overall energy cost

In this scenario, the ORC-HEN model is solved with economic parameters taken from Dong et al. (2020): C^{CU} = \$20/kW/y; C^{HU} = \$100/kW/y; C^{e} = \$0.14/kW/h; H = 7,000 h/y. The minimum overall energy cost is found to be \$941,822/y. The optimal evaporation temperature and flowrate of n-pentane are determined to be 97.78 °C and 111.88 kg/s, respectively. Compared to the results for scenario 1, this solution is to produce more power (5,100.19 kW) at increased hot (45,843.66 kW) and cold utility requirements (67,782.06 kW). Figure 4 shows the optimal HEN configuration.

5. Conclusions

A simultaneous approach for the optimisation of ORC-integrated HENs has been presented in this paper. The superstructure-based mathematical model allows the ORC operating conditions and the HEN to be optimised simultaneously. A literature example was solved to illustrate the proposed approach. Comparing the results for both scenarios shows that the overall energy cost is minimised by increasing ORC power production (+54.7 %), despite increased hot (+38.9 %) and cold utility requirements (+19.7 %). Future work will consider the trade-off between energy and capital cost through the minimisation of total annualised cost. Pareto analysis may also be performed to explore the trade-off between the overall energy cost and the number of heat exchangers.

Nomenclature

h_* – enthalpy at state point $* \in \{1,2,3,4\}$, kJ/kg
m – flowrate of the working fluid, kg/s
Q_i^{U} – upper limit on the heat load of stream *i*, kW
q_{ijk} – heat load of match (*i*,*j*,*k*), kW
q_{ijk}^{cond} – condensation heat load of match (*i*,*j*,*k*), kW
q_{ijk}^{evap} – evaporation heat load of match (*i*,*j*,*k*), kW
q_{ik}^{Λ} – latent heat load of stream *i* in stage *k*, kW
Q_j^{U} – upper limit on the heat load of stream *j*, kW
q_{jk}^{Λ} – latent heat load of stream *j* in stage *k*, kW
t_* – temperature at state point $* \in \{2,4\}$, °C
t_{ik} – temperature of stream *i* at location *k*, °C
t_{jk} – temperature of stream *j* at location *k*, °C
z_{ijk} – 1 or 0, whether or not there is match (*i*,*j*,*k*), -
ϵ – arbitrary small value, °C
Γ – arbitrary large value, °C

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