A Methodology for the Optimal Insertion of Organic Rankine Cycles in Industrial Processes

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Abstract

Integrating energy saving technologies allow the design of more compact industrial processes with improved energy efficiency, better performances and environmental friendliness. The goal of the European project EXSYS II has been to develop a methodology and the related web based tools to quantify the possible application of the energy saving technologies, to determine their proper sizing and their conditions of optimal insertion in existing industrial processes. In the project, one of the goals has been to develop a generic methodology to synthesize and evaluate the integration of organic Rankine cycles (ORC) to valorise low grade waste heat of industrial processes. Starting from the definition of the process requirement, this problem reveals a high number of degrees of freedom and a high level of technological constraints : i.e. identify the fluids, the best operating conditions for available technologies (turbines and heat exchangers).

The methodology proceeds in three major steps. The first aims at identifying the temperature levels to be considered by using a Mixed Integer Linear Programming (MILP) strategy based on the minimisation of the heat exchange exergy losses constrained with the heat cascade feasibility. Knowing the temperature levels, the second step determines a list of possible ORCs characterized for integration (fluid, operating conditions and technologies). The third step consists in selecting, in the resulting list, the best-integrated cycles to be used in the system. This step uses a MILP model that minimises the total cost while satisfying the constraints of the heat cascade and the combined production of mechanical power. This model allows synthesizing integrated solutions where ORCs valorise both process and utility waste heat (e.g. cogeneration) and/or compete with heat pumps. Based on integer cuts technique, a multiple solutions strategy is used to compare competing solutions based on different criteria (Net Present Value, operating cost, CO2, exergy losses).

Introducing the EXSYS II project

If improving energy efficiency of an industrial process system by inserting energy saving technologies reveals itself as an efficient approach, the challenge of European funded project EXSYSII was to develop a methodology that integrates the major difficulties of the optimal technology insertion:

1) the optimal insertion has to be considered in a context of higher process integration at a site scale level considering the possible synergy or mutual exclusion of the different technologies to be inserted and considering the integration in terms of materials, energy and other utilities;
2) the R&D effort made in the development of new intensified energy saving technologies increases the number of technologies available on the market;
3) the size standardisation of the technologies on the market increases the difficulty of selecting the optimal technology and
4) the evolution of the prices on the market may influence the profitability of an ongoing project.

The consortium developed a web-based platform where new emerging technologies are compared with classical solutions in order to quantify their competitive advantage, the corresponding energy savings potential and to characterize the possible synergies between technologies when inserted in a given process.

This computer system (Kalitventzeff and Marechal, 2000) is made of different building blocks built with the contribution of the different project partners. The building blocks are the following:

1. Descriptive report of the technologies and their evolution. The consortium developed the basis for an information web site on the evolution of the intensified energy saving technologies in the industry. The informative reports are organised by technology areas structured using identical templates using the hyperlinks techniques to browse the different aspects related to a given technology.
2. The technology data bases include the structured technical data concerning the technologies available on the market and all the necessary data to allow the selection and the optimal insertion of the technologies integrated in an industrial system.
3. The optimisation tools implement concepts using different objective functions: exergy, energy, operating cost, CO2 emissions, total costs and constraints that aim at representing the integration of the technologies to satisfy the requirement of a process. The optimisation concepts are used by different models to identify, select and optimise the insertion of the technologies in the system. These optimisation tools are used to solve the three major steps of the technology insertion:
    1. Process technology requirement: this tool solves the problem of identifying, for a given process, the types of technologies to be used and their corresponding size. The method combines optimisation models and rules for the different technologies. For example, it gives the heat load to be supplied by a gas turbine.
    2. Technology selection procedures have been developed for each type of technology to select in the technology data bases, the more precise characteristics of the technologies available on the market according to the process technology requirement and the process environment. For example, look on the market the gas turbines that supply approximately the heat load required.
    3. Technology insertion models represent the interactions between the proposed technologies and the industrial process in an optimisation framework that will select the best technologies and compute the optimal sizes to satisfy the process requirements. The parameters of the models are obtained from the values of the databases. For the gas turbine example, this means compute for the select gas turbine model, the degree of the post combustion, the size of the reboiler, the adaptation of the steam production and consumption flowrates, the optimal stack temperature,...
4. Reporting and evaluation tools allow transforming the numerical results of the optimisation into understandable textual reports for evaluating the proposed solutions. This tool also generates the values of different evaluation criteria : energy savings, CO_2 reduction, detailed cost evaluations including investment and operating costs. The use of the web interface allows producing both graphical and textual reports that can be directly printed out.
5. An expert system has been developed to organise the data transfer and the use of the different tools in order to guide the user through the steps of the developed methodology. This system prepares the data for the different steps, executes the requested action, generates and saves the results and proposes the next steps. The communication with the user is made using HTML files with hyperlinks (for the next steps or for the explanations) or forms (when user data are needed). The use of the different tools developed by the consortium is therefore more transparent for the user.

The Organic Rankine Cycles integration in industrial processes

Among the technologies considered in the project, the Organic Rankine Cycles (ORC) have been studied for their ability to transform waste heat into useful and higher value mechanical or electrical energy.

The Rankine cycle is a thermodynamic cycle used to generate electricity in many power stations. It is the practical implementation of the Carnot cycle that produces mechanical power by reversible transformations between one hot and one cold reservoir. In its practical implementation, superheated steam is generated in a boiler as hot heat source and then expanded in a steam turbine. The turbine drives a generator to convert the work into electricity. The remaining steam is then condensed by exchange with the cold heat source and recycled as feedwater to the boiler. A disadvantage of using the water-steam mixture is that superheated steam has to be used, otherwise the moisture content after expansion will be too high and would erode the turbine blades, unless intermediate liquid separators are introduced in multistage turbines.

Organic Rankine cycles use organic fluids instead of water as working fluid. These fluids can be used below a temperature of 400°C. For some organic compounds, superheating is not necessary. This results in higher efficiency of the cycle and a reduced cost. A review of the Organic Rankine Cycles can be found in Favrat (2001). The organic working fluid (confined in a closed and leakage-free circuit) is vaporised using the heat of the hot source in the evaporator. The organic fluid vapour expands in the turbine and is then condensed using cold stream of a process or a utility (air or cooling water). The condensate is pumped back to the evaporator thus closing the thermodynamic cycle. For higher temperature applications, a multistage configuration with heat exchange regenerator between the stages might be used. An alternative solution is to integrate multiple cycles, creating pressures and fluids cascade. Nowadays, the adaptation of largely distributed volumetric machines like scroll compressors to expand the working fluid in the ORC might open new market perspectives for small size ORCs with low cost turbines.

Despite rather high costs, ORCs have several advantages: they easily adapt to different operation load and for hermetic concepts no operator is required. The high molecular mass working fluid allows exploiting efficiently low temperature heat sources to produce electricity in a wide range of power outputs (from few kW to some 2.5 MW electric power per unit) with attractive cycle performances. The turbines have high efficiency (up to 85 %) and feature low mechanical stress due to the low peripheral speed. Lower RPM in the turbine allows the direct drive of advanced electric generator. The absence of moisture in the vapour nozzles leads to practically no erosion of the blades that guarantees long life of the equipment. ORCs have simple start-stop procedures, quiet operation, minimum maintenance requirements, good part-load performances.

The efficiency of the ORC depends mainly on the quality (temperature) and the quantity (heat load) of the heat reservoirs. The maximum efficiency is obtained by the Carnot efficiency :

$$\eta_c = 1 - \frac{T_{Cold}(K)}{T_{Hot}(K)}$$

In practical applications, performances as high as 50% of the theoretical performance might be reached. When the heat source and sink are not at constant temperature but feature a temperature enthalpy diagram, the performances will also be related with the quality of the integration between the source and sink profiles and the hot and cold streams of the ORC.

The best known applications of ORCs are in geothermal energy valorisation. In this case, the source temperature is rather low (150°C or less) and power ranges from 300 kW to 2.5 MW electric. The heat sources are either:

- -hot water from liquid producing geothermal wells
- -hot water obtained as the liquid fraction in steam separators of flash plants
- -low pressure steam, even with a large content of non condensable gases
- -low pressure steam downstream counter-pressure traditional steam turbines

ORCs are also used to valorise renewables and biomass. In this case, the biomass is used in burners or gasifiers and produces heat that is transferred to a heat transfer oil loop that becomes the hot source for the ORC. In this case, typical oil temperature is 250 to 300°C. Compared to steam cycles, the advantages are the following : no skilled operator required, possibly no superheater, high conversion efficiency (typically 20 %). Hot water can be supplied to a district heating loop, using the heat discharged by the ORC condenser. In this kind of applications, the power ranges from 200 kW to 1000 kW electric.

When solar energy or biogas is available, an alternative solution is the combined use of engines and ORC systems using hybrid configurations (Kane, 2000). In such cascaded system, the ORC transforms solar heat into electricity and uses the cooling of the engine as a hot source to produce additional electricity. The use of scroll turbines allows smaller power ranges operation (down to 5kWe).

ORC can efficiently produce electricity from industrial waste heat sources : waste steam, hot water, waste gases, and other process stream cooling. When observing that a lot of industrial systems have a process pinch point near 100°C, the use of ORC cycles should be an appropriate candidate to valorise process energy excess.

Integrating ORCs in industrial processes.

When analysing the energy requirement of a process, engineers have first to identify the possible technologies to be integrated, i.e. "do I need to study the use of a gas turbine, of an ORC, …?". If the answer is yes for an organic Rankine cycle, then its integration requires answering the following questions :

1) what is the fluid to be used ?
2) what are the best operating pressures and temperatures ?
3) what is the ORCs configuration, i.e. how will the ORCs be integrated with the process and how do they integrate together or with other technologies ?
4) what is the efficiency and the related cost of the integrated system in order to compute the profitability of the solution.

To answer these questions, a three steps methodology has been developed. The first step concerns the identification of the most important temperature levels to be considered in the system. Knowing this info it will be possible to confirm whether or not an ORC can be used to produce mechanical power from the available energy of the process. The next step will be the characterisation of the cycles, i.e. the selection of the possible fluids and the calculation of the operating pressures and temperatures to be considered for each of these. Using the results of this step, an ORC system superstructure will be generated and optimised together with the other technologies (heat pumps, cogeneration,…). An optimisation procedure will extract the good configurations out of the superstructure and compute the best integration of the technologies that satisfy the process requirements. By evaluating the solutions, engineers will identify the most promising configurations for which a detailed engineering calculation is needed. This last step, that is not considered in this paper, consists in computing the optimal heat exchangers network and the optimal operating conditions for the selected technologies.

To illustrate the proposed approach, we will use a prototypical example defined by the hot and cold streams given on table 1. The Grand composite curve defining the Minimum energy requirement of this process is given on figure 1 (right).

Table 1: Streams definition for the prototypical example

Type	Tin(°K)	Tout(°K)	Heat load(kW)
Hot	773.00	393.00	100.00
Hot	373.00	373.00	120.00
Cold	523.00	523.00	100.00
Hot	493.00	493.00	100.00

Identifying the most important temperature levels in a process.

The identification of the most important temperature levels in a process is an important step since it will allow characterizing the possible combined heat and power system integration, the possible heat pumps insertion as well as the characteristics for the refrigeration systems. It refers to the fundamentals of the energy integration theory concerning the optimal placement of heat engines (Townsend and Linnhoff, 1983) that has been extended to valorise the exergy of the process by combined heat and power integration (Marechal and Kalitventzeff, 1997). The exergy Grand composite curve uses the Carnot factor as the Y axis to represent the Grand composite curve. In this representation (figure 1, left), the mechanical power production potential available in the process is represented by the area between the composite curve and the coordinates.

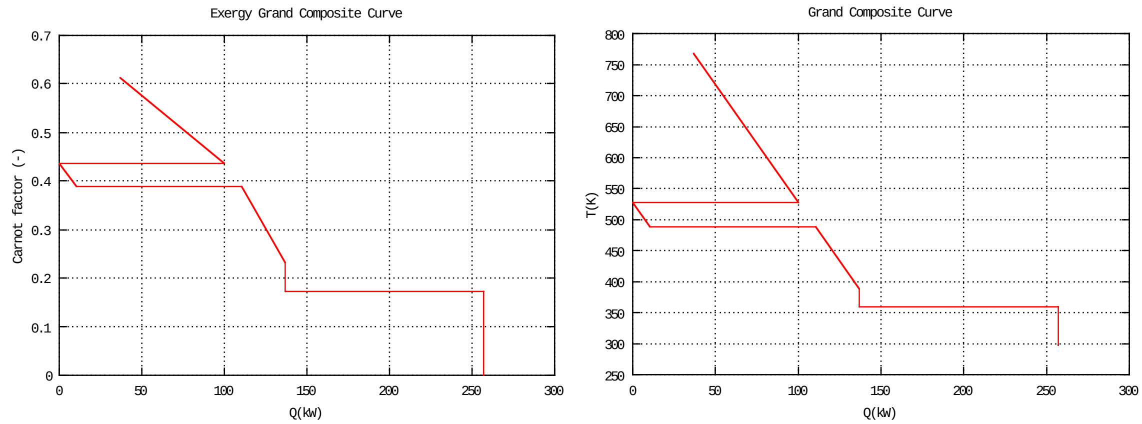

Figure 1 : the exergy composite curve and Grand composite of a process.

The model developed to identify the possible temperature level is based on the minimum heat transfer exergy losses model (P1) that allows the selection and the calculation of the optimal flowrates in a utility system that will satisfy the energy requirements of a process. In this formulation, the list of constraints represents the heat cascade and the mechanical power balance. The decision variables are the flowrate of the proposed utilities. The integer variables allow choosing the best among the proposed utilities. The constraints and variables formulation originaly presented in Marechal and Kalitventzeff (1991) is very flexible and allows the calculation of complex utility systems like steam network (Marechal and Kalitventzeff, 1999), cogeneration and combustion systems (Marechal and Kalitventzeff, 1998) and more complex systems (Marechal and Kalitventzeff, 2000). The novelty is here to replace the cost function typically used as the objective function by the exergy losses associated with the use of the utilities. The definition of the exergy being unique, this definition will not depend on the market conditions and by introducing the heat cascade model, we ensure that the computed process configurations will be feasible with a limited cost (inclusion of the DTmin principle of the pinch technology).

$$\underset{R_k, y_w, f_w}{\text{Minimise}} \sum_{w=1}^{n_w} f_w \left\{ \Delta Ex_w + \sum_{k=1}^{n_k} \Delta ex_{kw} \right\} + EL_i - EL_o \qquad (P1)$$

Subject to :

heat balance of the temperature interval k

$$\sum_{w=1}^{n_w} f_w q_{wk} + \sum_{i=1}^{n} Q_{ik} + R_{k+1} - R_k = 0 \qquad \forall k = 1,\dots,n_k$$

$$\text{Electricity production : } \sum_{w=1}^{n_w} f_w * w_w + \eta_i * EL_i - \frac{EL_o}{\eta_o} = 0$$

$$\textit{Electricity consumption}: \sum_{w=1}^{n_w} f_w * w_w + \eta_i * EL_i \geq 0$$

$$f\min_w y_w \leq f_w \leq f\max_w y_w \qquad \forall w = 1,\dots,n_w$$

$$y_w \varepsilon \{0,1\} \qquad \forall w = 1,\dots,n_w$$

$$R_k \geq 0 \qquad \forall k = 1,\dots,n_k + 1$$

$$R_1 = 0, R_{n_k+1} = 0$$

with
- n the number of process streams for which the flowrate is considered as constant
- R_k the energy that has to be cascaded from the temperature interval k to the lower temperature intervals
- Q_{ik} the heat load of the process stream i in the temperature interval k
  $Q_{ik} \geq 0$ for hot streams, $Q_{ik} < 0$ for cold streams
- n_W the number of utility streams
- ΔEx_W the cumulated exergy losses to produce the effects linked with the utility w.

w_w the mechanical power produced by the utility w. If $w_w < 0$, it corresponds to a consumption that will be considered as an exergy loss.

f_w the multiplication factor of the reference flowrate of the utility w in the optimal situation.

$fmin_w$, $fmax_w$ respectively the minimum and maximum value of the multiplication factor f_w of utility w

y_w the integer variable associated to the use of the utility stream w

n_k the number of temperature intervals

q_{wk} the heat load of the utility w in the temperature interval k for a given reference flowrate. $q_{wk} \geq 0$ for a hot stream

Δex_{wk} the exergy supplied by the utility w when it exchanges heat in the temperature interval k for a given reference flowrate. Given a ambient temperature T_0, Δe_{wk} is computed by :

$$\Delta ex_{wk} = q_{wk}(1 - \frac{T_0}{T_{lmwk}}) \qquad where \quad T_{lmwk} = \frac{T_{k+1} - T_k}{\ln(\frac{T_{k+1} + DT\min/2_w}{T_k + DT\min/2_w})}$$

$DT\min/2_w$ the contribution to the DTmin of the utility w, $DT\min/2_w > 0$ for the hot stream and <0 for the cold streams

EL_i the electricity imported. In the electricity production and consumption balance, we assume an efficiency of η_I for the conversion of electricity into mechanical power

EL_o the electricity exported from the system. In the electricity production balance, we assume an efficiency of η_o for the conversion of mechanical power into electricity.

The cumulated exergy losses of the utility w (ΔEx_W) is the sum of the exergy losses related to the production of the heat transfer and mechanical power effects of utility w. It includes the exergy inputs of the fuels used, the exergy losses related to the mechanical power transformation, the mixing and chemical reactions as well as the output streams and their possible processing: e.g. stack emissions. The exergy losses in the heat cascade are considered in a balance where hot streams supply exergy (computed by Δe_{wk}) and cold streams consume exergy. By difference between hot and cold streams in the heat cascade, we compute the exergy losses in the ideal heat exchanger network that satisfies the energy requirement of the process with a minimum temperature difference in counter-current heat exchangers defined by their respective DTmin/2 contributions.

This generic formulation has been adapted to compute the most important temperature levels in the system: first, the overall temperature range is discretized with a fixed precision using the values defined by the inlet and outlet states of the streams considered in the problem. For each temperature in the list, we introduce a utility stream with a constant temperature and an unknown flowrate. Computing the heat load of these utility streams (q_k), we obtain a curve that will match the grand composite curve of the process. If now we consider 1) that the heat used must be significant with respect to the heat requirement (10%), 2) that the number of such utilities (levels) are limited, we obtain a new problem (P2):

$$\underset{R_k, y_k, q_k}{\text{Minimise}} \sum_{k=1}^{n_k} q_k \left\{1 - \frac{T_0}{T_k}\right\} \qquad (P2)$$

Subject to :

heat balance of the temperature interval k

$$q_k + \sum_{i=1}^{n} Q_{ik} + R_{k+1} - R_k = 0 \qquad \forall k = 1,\ldots,n_k$$

$$q\min_k y_k \leq q_k \leq q\max_k y_k \qquad \forall k = 1,\ldots,n_k$$

$$\sum_{k=k_p}^{n_k} y_k \leq N\max_3, \sum_{k=k_a}^{k_p} y_k \leq N\max_2, \sum_{k=1}^{k_a} y_k \leq N\max_1$$

$$y_k \varepsilon \{0,1\} \qquad \forall k = 1,\ldots,n_k$$

$$R_k \geq 0 \qquad \forall k = 1,\ldots,n_k + 1$$

$$R_1 = 0, R_{n_k+1} = 0$$

with
- q_k the heat requirement at the temperature level k;
- k_p the interval corresponding to the pinch point temperature;
- k_a the interval corresponding to the ambiant temperature
- $N\max_1$ is the maximum number of temperature levels to be considered below the ambient temperature;
- $N\max_2$ between the ambient temperature and the pinch temperature;
- $N\max_3$ above the pinch point;
- y_k the integer variable associated to the use of the heat requirement k;
- $q\min_k$ the minimum heat load accepted for a hot utility at temperature k;
- $q\max_k$ the maximum heat load of accepted for a hot utility at temperature k.

The result is a list of heat consumption (above the pinch point) and heat production (below the pinch point) that will be used to define the energy saving technology candidate that will apply for heat pump levels identification, refrigeration system synthesis. In order to exploit the exergy potential of the self-sufficient zones in the Grand composite curve, we will care for negative or limited heat load for the utility by defining $q\min_k$=-$q\max_k$ for the temperatures in self sufficient zones. The list of the most important temperature levels of the process obtained by solving (P2) will help in the definition of the most appropriate pressure levels to be considered in the steam network and in the organic Rankine cycles and to identify opportunities for heat pumping.

If this approach appears to be interesting to automate the analysis of the Grand composite curve and compute the optimal insertion of the energy conversion technologies, some difficulties have to be reported. The efficiency of the optimisation software used to solve the MILP problem is strongly depending on the appropriate definition of the minimum and maximum bounds ($q\min_k$ and $q\max_k$). In our implementation, that is designed to be as generic as possible, we have used the analysis of the process Grand composite curve combined with some heuristic rules to estimate the value of the bounds. The precision of the results is defined by the degree of discretisation of the temperature range. A higher precision requires a higher number of integer variables and leads as well to lower differences between the different optimal integer sets. In this case, the efficiency of the branch and bound algorithm is penalized because the algorithm has to distinguish between the exergy losses at similar temperatures. In practice, the precision does not have to be very high because it relies also on the DTmin assumption made to compute the heat cascade constraints. One has to remind that the goal of this procedure to solve the first targeting step in the design procedure. To overcome this difficulty, we developed a discretization procedure that corrects the temperature levels to better match the Grand composite curve.

1.1.1.1. The ORC selection procedure

For the ORC selection, we will use the list of heat production (heat available for evaporation) and heat consumption (available for condensation). Two temperature ranges will be analysed : 1) above the pinch point and below 300°C (we considered that above 300°C steam will be preferred to organic fluids) and below the pinch point to the ambient temperature. In this range, we first apply a modified problem of exergy losses minimisation in order to identify the optimal preheating heat load to be considered between the temperature levels. To do this, we systematically add streams to be heated from one selected temperature level T_i up to the next T_{i+1}. Solving the modified problem (P2) by minimising the energy losses allows obtaining the curves like the one shown on figure 2. As a result of this procedure, we define a list of ORC requirement profiles defined by one vaporisation and one condensation level and a maximum preheating heat load between these temperatures. When one vaporisation temperature is considered between the vaporisation and the condensation temperature, the intermediate temperatures are considered as additional condensation levels to allow the generation of interconnected cycles.

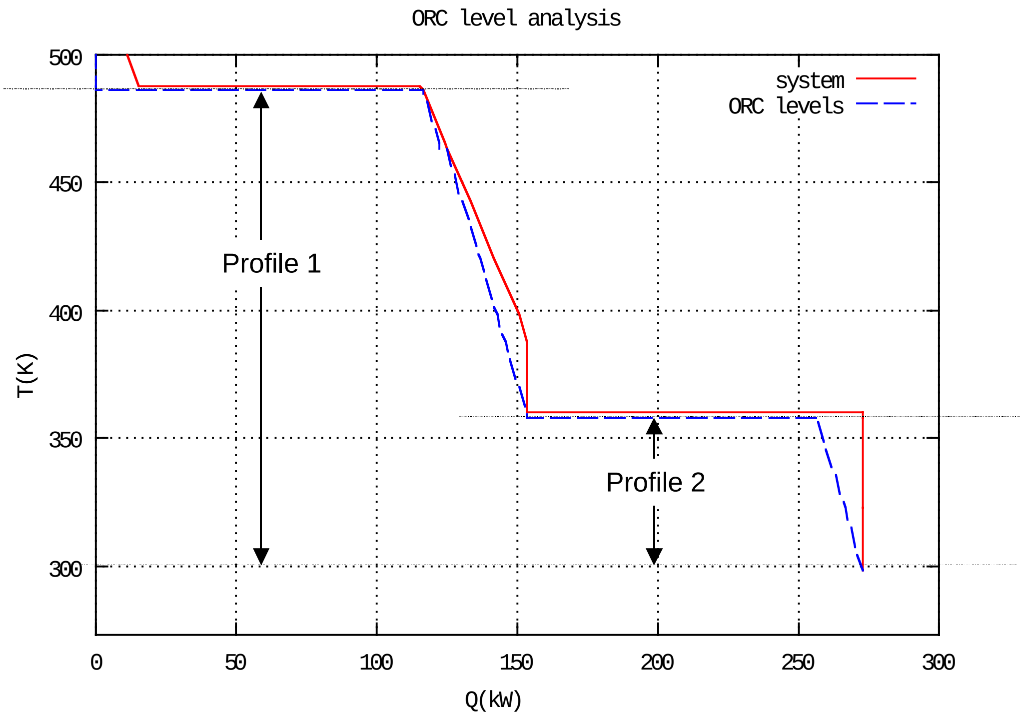

Figure 2 : results of the ORC profiles calculation

For each of these profiles, the algorithm shown on figure 3 will identify the best fluids to be used and determine for each of them the operating conditions, i.e. the condenser and evaporator temperatures and pressure conditions, the opportunity for superheating, the expected flow-rate and efficiency of the cycle.

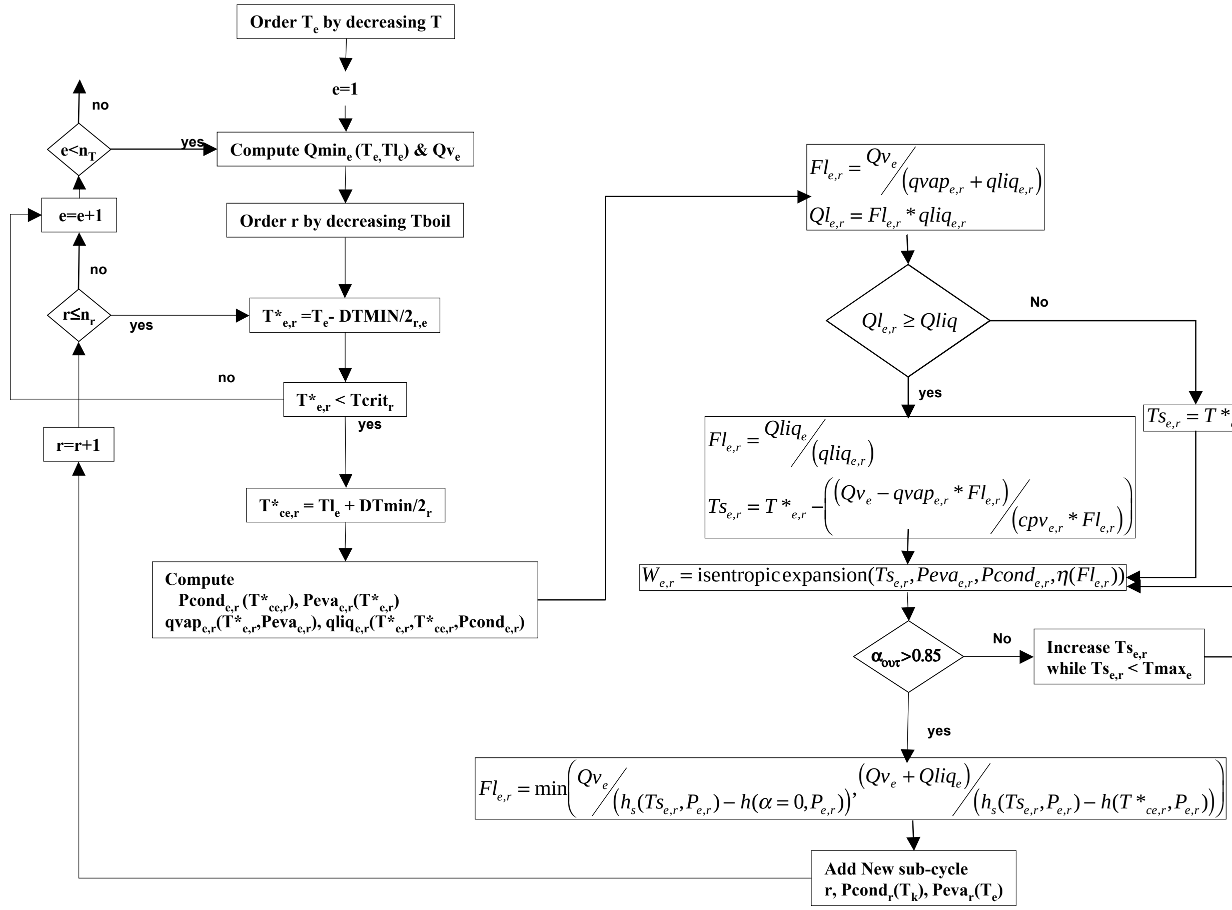

Figure 3 : the ORC selection algorithm

Comments on the algorithm

- The exergy losses minimisation method defines the vaporisation (*Te*) and condensation temperatures (*Tc*), the minimum liquid preheating heat load ($Q\min_l$) and the corresponding vaporisation heat load at *Te*.
- The fluids are chosen among the fluids described in a fluid data base. A pre-screening procedure included heuristic rules is first applied to constitute an initial list of fluids that will be processed by the algorithm This allows to apply rules like “use fluids that are already in the use in the process”.
- Critical temperature $Tcrit_r$ is used to reject the fluid, when the fluid is above the critical temperature it is not possible to compute the evaporation pressure. We look at the next key temperature, if this is lower then critical temperature, the pressure is computed by considering a temperature of $Tcrit_r - 2$. The fluids list is ordered according to decreasing boiling point, this allows to reject all the fluids that follow the first rejected.
- The flowrate is computed from the vaporisation heat load and the preheating heat load by identifying the intersection between the profile and the vaporisation composite in the cycle. By this way, we compute T_p the activated pinch temperature of the cycle. In the integrated conditions, we have *Qp* the heat available in the process above T_p. The flowrate in the cycle is therefore computed by :

$$Fl_{e,r} = \frac{Qp}{cp_{liq,r}(T_e - T_p) + qvap_r(T_e) + cp_{vap,r}(T_{s,r} - T_e)} \tag{1}$$

- The isentropic efficiency is computed using the correlations obtained from the technology data bases based on the volumic flowrate computed at the inlet of the turbine.

- The mechanical power of the integrated cycle is obtained by computing the expansion with the given isentropic efficiency and the flowrate that comes from the optimal integration:

$$W_r = Fl_{e,r} * \eta is_r * \frac{\gamma_r}{1-\gamma_r} R * Ts_r * \left[\left(\frac{Pv_r}{Pc_j} \right)^{\eta is_r \frac{\gamma_r}{1-\gamma_r}} - 1 \right] \quad (2)$$

This value is used to generate a limited list of proposed cycles by eliminating the one that have lower efficiencies.

- The superheating temperature is computed in such a way that the vapour state at the outlet of the turbine is higher than 85%. The superheating temperature should be lower than the maximum temperature. When the vapour fraction is greater than 85% then superheating is used only if the mechanical power of the integrated cycle is increasing. This is true if $\frac{\partial W_{e,r}}{\partial T_{s,r}} \geq 0$. Using equations (1) and (2) we can demonstrate that superheating will be energetically valuable if :

$$cp_{vap,r} T_e \geq cp_{liq,r}(T_e - T_p) + qvap_r(T_e) \quad (3)$$

In this formula the temperatures are expressed in K.

- The nominal sizes of the equipments in the cycle are computed from the value of the cycle flowrate. For this reason the flowrate is always computed in such a way that the cycle integrates with the Grand composite curve, ignoring the cycles that have already been selected.

The list of candidate organic Rankine cycles obtained by applying this procedure are characterized by the fluid, the operating temperatures and pressures and a reference flowrate. A more rigorous simulation model is then applied to compute the thermodynamic characteristics of the fluids and to estimate more rigorously the sizing and costing parameters.

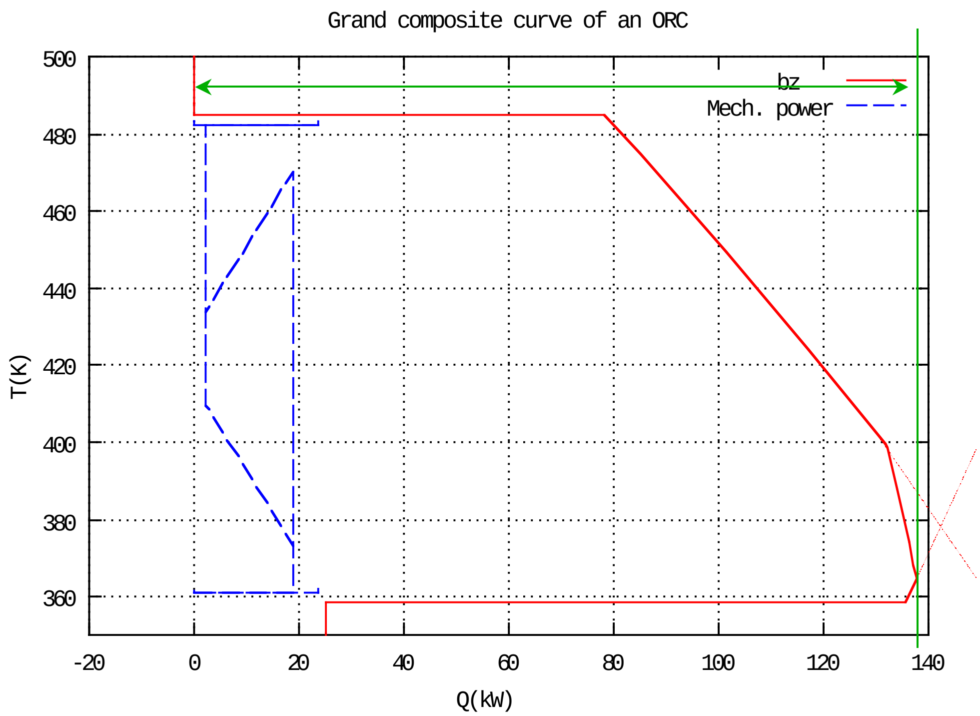

Figure 4 : composite curves of an integrated ORC

Figure 4 gives the integrated composite curve computed for one cycle. The values used to compute this curve have been computed by simulation with the following characteristics: the hot stream representation includes desuperheating and condensation. The condensation temperature is computed from the cycle temperature that is corrected by the DTmin/2 contribution of the fluid that is obtained by:

$$\frac{DT\min/2_i}{DT\min/2_r} = \sqrt{\frac{u_r}{u_i}} \qquad (4)$$

where $DT\min/2_i$ is the DTmin/2 contribution used for the fluid i;

$DT\min/2_r$ is the DTmin/2 contribution used for a reference fluid;

u_r reference heat transfer film coefficient;

u_i the computed heat transfer film coefficient computed for the operating temperature and pressure of the condenser.

This allows representing the heat transfer differences between the fluids used. The pressure of the condenser is computed by imposing the saturated liquid state at the outlet of the condenser. The saturated liquid and saturated vapour temperatures are added to the list of the key temperatures used in the heat cascade calculation. The inlet state of the hot stream is obtained by computing the expansion assuming a constant isentropic efficiency whose value has been obtained from a correlation that depends on the reference flowrate computed in the previous step. The cold stream includes, preheating, vaporisation and superheating (when needed). We use the a similar approach to compute the vaporising pressure giving an estimation of the DTmin/2 contribution of the fluid used in the cycle. The superheating temperature is a result of the previous step. The inlet temperature is computed assuming a fixed isentropic efficiency for a pump. As for the condenser, the saturated liquid and vapour temperatures are automatically added to the temperatures considered in the heat cascade calculation.

The cost of a cycle is estimated using the exponent correlations given by Turton et al. (1998). The difficulty is here to estimate the boiler and condenser costs before knowing the heat exchanger network structure. Therefore, we assumed that condensers and boilers of the ORCs system will operate near the DTmin conditions, the size of the heat exchangers will therefore be proportional to the heat load of the exchange Q : $A = \frac{Q}{U\,DT\min}$. The heat transfer coefficient U is computed using correlations depending on the refrigerant and the temperature and assuming a film coefficient for the opposite stream: DTmin = $DT\min/2_i + DT\min/2_{ref}$.

As shown on figure 4, the use of hot and cold streams to represent the integration of the cycle allows to represent the integration of the cycle with himself: the heat of desuperheating at the outlet of the turbine is used to preheat the high pressure liquid of the cycle. In terms of integration, this leads to a reduction of the heat requirement of the cycle for a given mechanical power production and therefore to a maximisation of the cycle production. In the example, this corresponds to an increase of 9% of the mechanical throughput.

1.1.1.2. The insertion procedure

Starting with the data of the simulation model computed for each proposed cycle, the goal of the insertion procedure is to extract from the list of the proposed Rankine cycles, the one(s) that should be used in the optimal configuration. The superstructure model (P3) allows computing the integration of the ORCs in the process as well as their interactions with the other technologies proposed to satisfy the global energy requirement of the process.

$$\underset{R_k, y_w, f_w}{\text{Minimise}} \sum_{w=1}^{n_w} \left(y_w Co1_w + f_w Co2_w\right) + Cel * EL_i - Cel_o * EL_o \qquad (P3)$$

$$+\frac{1}{\tau} * \left[\sum_{w=1}^{n_w} \left(y_w C1_w + f_w C2_w\right) + \sum_{r=1}^{nr} \left\{ \begin{array}{l} \left(yr_r * C1w_r + W_r * C2w_r\right) + \left(yr_r * C1c_r + Qc_r * C2c_r\right) \\ + \left(yr_r * C1b_r + Qb_r * C2b_r\right) + \left(yr_r * C1p_r + Wp_r * C2p_r\right) \end{array} \right\} \right]$$

subject to :

heat balance of the temperature interval k

$$\sum_{w=1}^{n_w} f_w q_{wk} + \sum_{r=1}^{nr} \left(qc_{k,r} - qb_{k,r}\right) * f_r + \sum_{i=1}^{n} Q_{ik} + R_{k+1} - R_k = 0 \qquad \forall k = 1,\ldots,n_k$$

$$Qc_r - \sum_{k=1}^{n_k} \left(qc_{k,r}\right) * f_r = 0 \qquad \forall r = 1,\ldots,n_r$$

$$Qb_r - \sum_{k=1}^{n_k} \left(qb_{k,r}\right) * f_r = 0 \qquad \forall r = 1,\ldots,n_r$$

$$W_r - \left\{ \eta is_r * \frac{\gamma_r}{1-\gamma_r} R * Ts_r * \left[\left(\frac{Pv_r}{Pc_j} \right)^{\eta is_r \frac{\gamma_r}{1-\gamma_r}} - 1 \right] \right\} * f_r = 0 \qquad \forall r = 1,\ldots,nr$$

$$Wp_r - \frac{v_r * (P_v - P_c)}{\eta p_r} * f_r = 0 \qquad \forall r = 1,\ldots,nr$$

$$f_r^{\min} yr_r \leq f_r \leq f_r^{\max} yr_r \qquad \forall r = 1,\ldots,nr$$

$$\text{Electricity production : } \sum_{w=1}^{n_w} f_w * w_w + \sum_{r=1}^{nr} \left(W_r - Wp_r\right) + \eta_i * EL_i - \frac{EL_o}{\eta_o} = 0$$

$$\textit{Electricity consumption} : \sum_{w=1}^{n_w} f_w * w_w + \sum_{r=1}^{nr} \left(W_r - Wp_r\right) + \eta_i * EL_i \geq 0$$

$$f \min_w y_w \leq f_w \leq f \max_w y_w, y_w \varepsilon \{0,1\} \qquad \forall w = 1,\ldots,n_w$$

$$R_k \geq 0 \quad \forall k = 1,\ldots,n_k + 1 \qquad R_1 = 0, R_{n_k+1} = 0$$

with
- f_r the flowrate in the elementary ORC cycle r.
- yr_r the integer variable associated to the use of the cycle r.
- nr the number of ORC proposed in the superstructure : i.e. for all the selected fluids and for the identified temperatures.
- Qb_r the heat load of the boiler in the cycle r;
- Qc_r the heat load of the condenser in the cycle r;
- w_r the mechanical power produced by turbine of cycle r computed by a polytropic expansion with constant efficiency ηis_r.
- wp_r the mechanical power consumed by the pump in the cycle r assuming a constant efficiency.
- Ts_r is the real superheating temperature at the inlet of the turbine of cycle r.
- $C1_w$, $C2_w$ are respectively the fixed cost and proportional cost related to the investment of the energy transformer w.
- $Co1_w$, $Co2_w$ are respectively the fixed cost and proportional cost defining the operating cost of the energy transformer w (including fuel cost).
- $C1w_r$, $C2w_r$ are respectively the fixed cost and proportional cost related to the investment of the turbine in cycle r.
- $C1b_r$, $C2b_r$ are respectively the fixed cost and proportional cost related to the investment of the boiler in cycle r.
- $C1c_r$, $C2c_r$ are respectively the fixed cost and proportional cost related to the investment of the condenser in cycle r.
- $C1p_r$, $C2p_r$ are respectively the fixed cost and proportional cost related to the investment of the pump in the cycle r.
- τ is the actualisation ratio.

In the objective function, the non linear cost estimation of the condensers, boilers, turbines and pumps have been linearised. The linearisation includes two terms, one that is proportional to the flowrate and one that is related to the integer variable yr_r representing the decision of using or not the ORC r in the integrated optimal system. In order to obtain coherent values for the identification, we linearise the cost by using the minimum and maximum bounds considered for the cycle flowrate f^{max}_r and f^{min}_r. This mechanism is shown for the turbine cost estimation on figure 5.

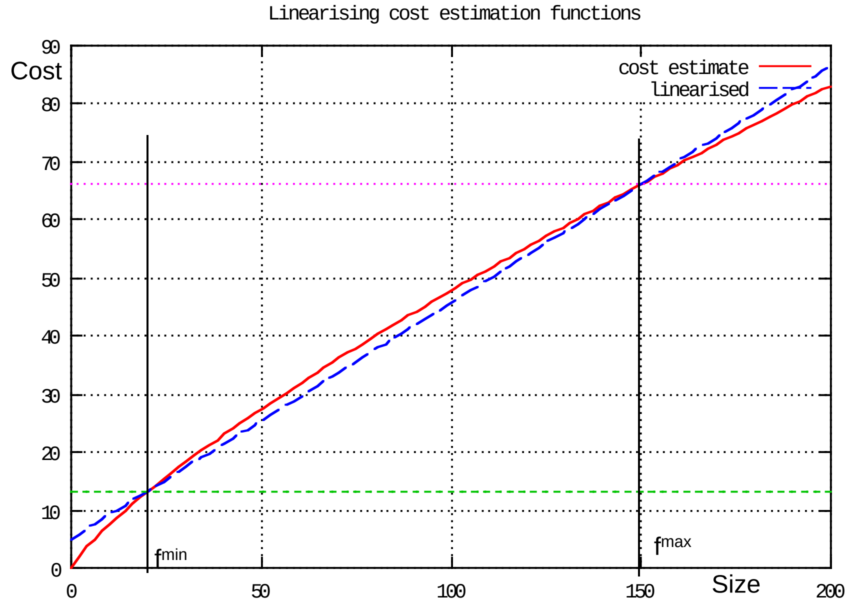

Figure 5 : Linearisation of the cost between minimum and maximum bounds

The use of the MILP (Mixed Interger Linear Programming) optimisation tool will allow to represent the selection of the best ORCs systems and compute the interrelationship (competition or synergies) with the other technologies. This is particularly useful to model in the superstructure the possible competition between ORCs and heat pumps or the synergies by valorising low grade energy from cogeneration engines or gas turbines. The interest of such global model is the possibility of using integer cuts to generate multiple solutions and so allow comparison and sensitivity analysis. (Marechal and Kalitventzeff, 1997b).

Table 2 : description of one of the solutions proposed for the example

Minimum Energy Requirement : pinch located at 523 °K	
	Hot utility = 36.8 kW Cold utility = 256.8 kW
Utility system	
Fuel :	41.76 kW
Cooling water :	213.13 kW
Organic Rankine cycle system	

	Fluid	Heat(kW)	Wmec(kW)
ORC1	C6H6	157.6	21.6
ORC2	R134a	237.0	22.4
Total			44.0 (17%)

Graphical representation of the integrated ORC system using the integrated composite curves (Marechal and Kalitventzeff, 1996) allows the analysis and a better understanding of the optimisation results. The integrated composite curve of the selected ORC system for the example is given on figure 6. The results are displayed on table 2. The computed fuel efficiency is 88%. This is explained by the fact that the pinch point is high (255°C). Two organic Rankine cycles have been integrated. The first operates between the first and the second temperature levels identified for the process. It exchanges heat (157.6 kW) with the process at high temperature. The second cycle operates between the second temperature level and the cooling water level. It receives heat from the first ORC (136 kW) and from the process (101 kW). The overall efficiency computed for this system is of 17 % assuming an isentropic efficiency for the turbines of 75 %.

The integrated composite curves of the ORC system given on figure 6 shows the results of the insertion procedure.

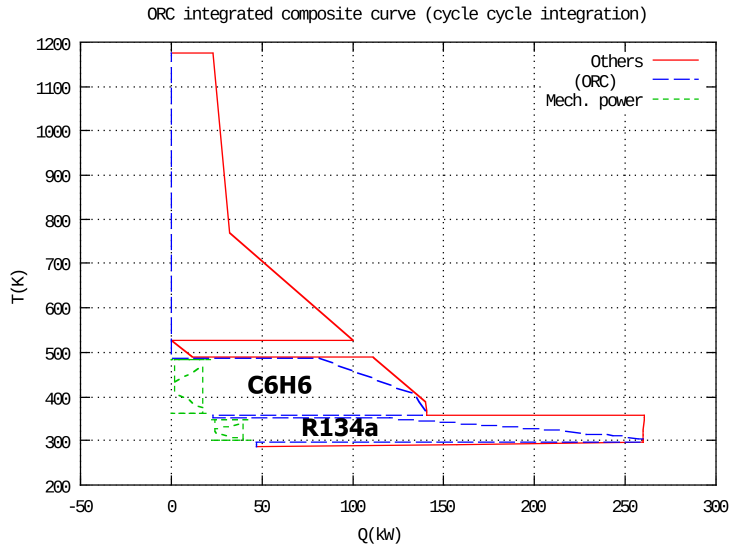

Figure 6 : Integrated composite curves of the Organic Rankine cycles system.

Conclusions

A method for targeting the optimal integration of organic Rankine cycles has been developed. This method based on the analysis of the shape of the Grand composite curve combines the use of minimum exergy losses concept, heuristic rules and cost optimisation technique. Starting from a list of available fluids to be considered, it allows selecting the best fluids, determining the best operating conditions to be considered in an integrated solution where ORCs will compete or collaborate with other technologies to synthesize integrated solutions. The results allow characterising the type of technologies to be considered in the integrated system and to define the complete list of streams to be considered to design the integrated heat exchanger network. Used in the early design steps of integrated system, the method allows to quickly generate optimal solutions that will be further analysed (detailed engineering) and optimised (thermo-economic and/or environomic optimisation). When superstructure optimisation strategies are used (e.g. Kane, 2000), this preliminary method will allow eliminating sub-optimal solutions defining the major characteristics of the most promising configurations.

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