Energétique avancée

Process integration and exergy analysis

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6. Target the Minimum Cost of Energy Requirement

Goals

To be able to compute the integration of the utilities in industrial processes.

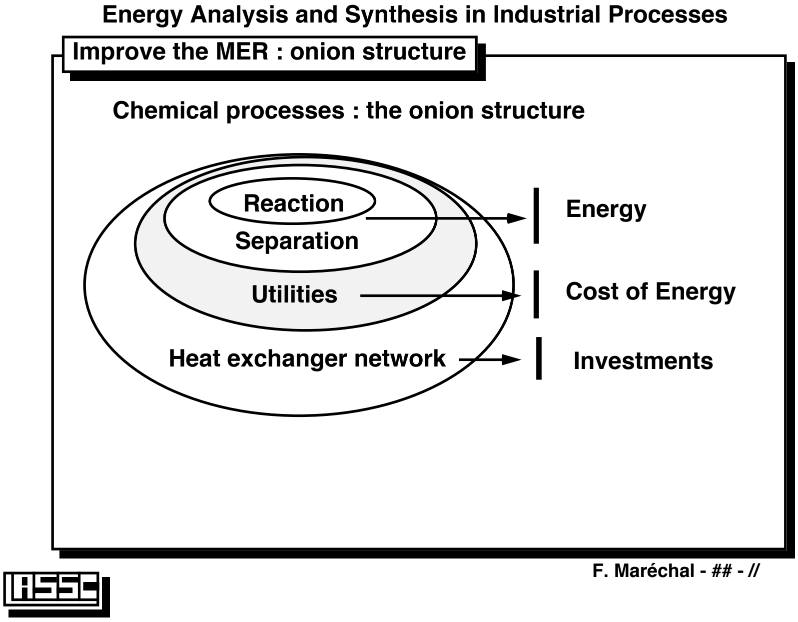
Short summary

The integration of the utilities concern the way the energy ressources (i.e. primary energy and electricity) will be converted into useful energy for the process. This chapter concerns not only convertional energy conversion technologies like combustion and cold water but also combined heat and power, heat pumping and refrigeration systems integration. The methodology presented uses three steps : 1) the analysis of the grand composite curves allows to characterize the utilities to be used, i.e. temperature levels, 2) a MILP (mixed integer Linear programming) formulation is used to optimise the integration and compute the optimal flowrates of the energy conversion technologies , 3) a graphical representation is used to analyse the optimal solutions found and to improve the operating conditions of the energy conversion technologies considered. The apporach implicitely uses the exergy analysis principle.

6. Target the Minimum Cost of Energy Requirement

6.1. Choosing the Utilities

In the onion representation, when the separation system has been determined, the next step is the determination of the utilities that will be used to satisfy the Energy requirements.



Energy Analysis and Synthesis in Industrial Processes

Improve the MER : onion structure

Chemical processes : the onion structure

In the former chapters, the problem table was used to calculate the minimum energy requirements. That is to define the heat to be put in the system by hot utility and the heat to be removed out of the system by cold utility. We only mention that the temperature of the utility streams must be adequate to send Rnk+1 in the process and to remove R1.

The utilities address the problem of determining the cost of energy to satisfy the Minimum Energy Requirements.

The next layer concerning the heat exchangers network will be related to the determination of the investments to achieve the minimum operating cost.

Operating cost introduces the problem of the different types of energy that have to be considered together:

> Energy from combustion (hot utility)
> Mechanical power (combined heat and power)
> Electricity
> Cooling utilities
> Refrigeration

If steam is used as hot utility is as to be produced in a furnace. The pressure at which it will be produced might be different from the one at which it will be used. Expansion through a turbine will produce mechanical power that might be needed by the process. The use of the steam network states the problem of combined heat and power.

For economical analysis, the utility cost is not only linked with the amount of energy but also to its quality.

For example, if condensing steam is used as hot utility, its temperature will be defined by the pressure. The more the pressure is high, the more the utility is expensive. Thus we will try, if possible, to use low pressure steam rater than high pressure steam.

In the following, we will analyse how to determine the amount of low pressure steam to be used as hot utility and the better pressure level to satisfy the energy demand.

6.1.1. Analogy with stream exchange

The pinch point divides the process into two thermodynamically independent sub-systems: the heat sink and the heat source.

Above the pinch point, the heat sink asks for energy. The grand composite curve can be considered as a global process cold stream to be heated up from the pinch point temperature to the maximum temperature of the process.

The choice of the hot utility will be such as the exchange with the global process cold stream will be possible, as illustrated figure 61. To adjust the utility: flow rates, temperatures, pressures and compositions can be tuned to reach the minimum cost.

The same reasoning can take place below the pinch point: the cold utility will be chosen so as to cool down the global process hot stream from the pinch point to the minimum temperature.

Once the temperature is determined, it must be corrected by the chosen DTmin/2 corresponding to the utility stream. When integrating the chosen utilities in the grand composite curve, it will be closed onto the temperature axis.

Be aware that in the graphical representation, the section below the pinch is inversed.

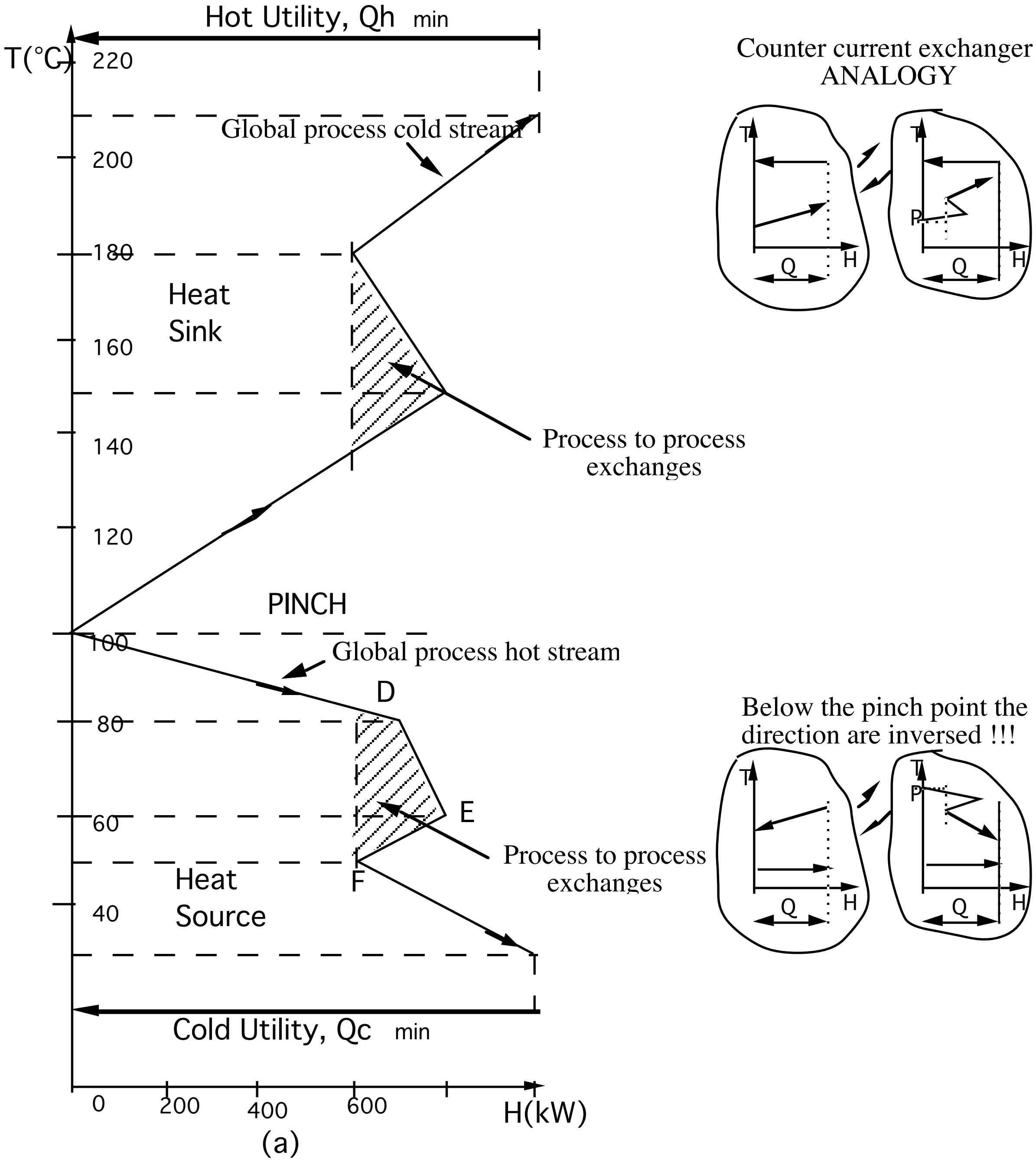


Figure 61. Utility: Analogy with two streams exchange.

Even if below the pinch the process is a heat source, it is possible to identify local heat sink like E-F section. In this section the heat required come from other process streams in the D-E section. The hatch section is called a self sufficient region, because the globally the heat source D-E will heat up the local heat sink E-F. In self sufficient region, only process-process exchanges take place.

6.1.2. Multiple utilities

In the following section, the choice of the hot utility will be described, the same reasoning can be done for the cold stream.

Consider the global process cold stream of figure 62.

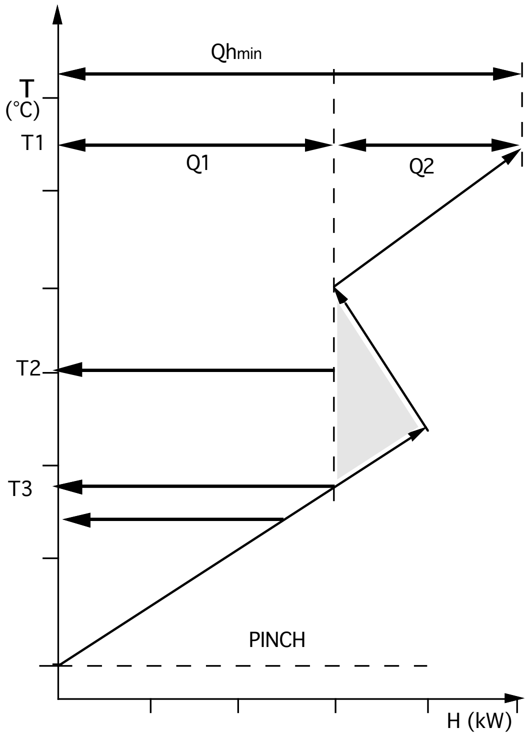


Figure 62. The global process cold stream and the hot utility.

If the hot utility is condensing steam (horizontal line), the total heat load Qhmin must be sent to the process above T1.

When multiple steam pressure are allowed, one can give Q1 at T2 and Q2 (=Qhmin - Q1) at T1 which will feature a smaller operating cost.

According to the figure 62, the load Q2 can be send to the process at any temperature greater than T3. For smaller value of the temperature, Q2 will decrease following the intersection with the global process cold stream.

The reasoning here above is not only valid for condensing steam, but also for other utilities such as fumes, outlet gas turbines,...

The figure 63 illustrates the use of multiple hot utilities:

- at high temperature the radiation (RAD)section of a furnace is used
- the fumes (FUMES) are then used in their convective section
- after these high pressure steam (HP) is used
- and finally low pressure steam (LP) satisfies the low temperature requirements.

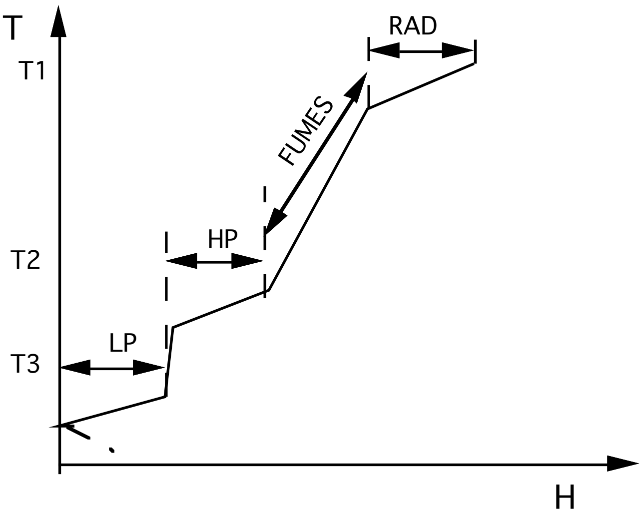


Figure 63. Multiple hot utilities.

Thermodynamically, the energy is better utilized when the utility is close of the global process cold stream. In this case the heat transfer potential is used at the best.

But once more, there is a trade-off between the energy and the capital: the investment increase when the number of utility streams increases even if the operating cost decreases.

The target of the utility selection is to find the utilities that match at best the global process curve and at minimum cost.

Simple heuristic rules can be used to choose the utility to be used by analysing the global process curve:

When the curve features steps: try to match condensing stream.

When the curve is a constant descent: try to use fumes of combustion or exhaust of a gas turbine.

When choosing the utilities, you have to define optimal inlet and outlet temperatures as well as flow rate. In this determination do not forget the technological constraints such as if you need steam you have to produce it. If fumes are chosen, you have to reach given outlet temperature at the exhaust,...

For the cold stream, the same reasoning will be followed.

When multiple utilities are allowed, the selection of the ones to be used becomes rapidly a prohibitively hard problem because of the number of possible choices.

The mathematical method for selecting the optimal utility scheme that minimizes the cost of energy is an extension of the linear programming formulation of the thermal cascade. It allows the calculation of the optimal integration of the utilities.

The engineering work method used to solve the utility optimization is the application of a generic engineering work method. It proceeds in tree main steps that have been named AGE: Analyze - Generate - Evaluate.

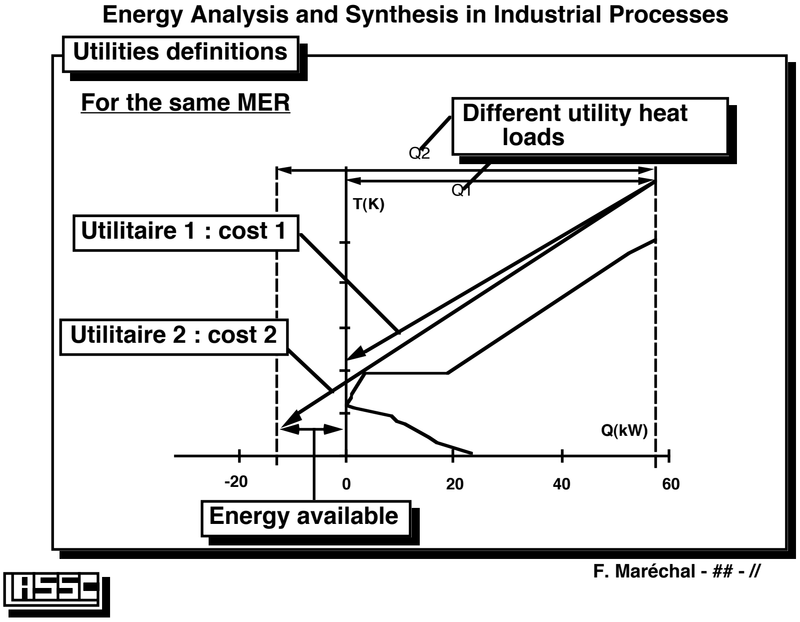
Analyze:	
	determine the value for the intensive variables using the GCC analysis, define a list of possible utilities
Generate:	
	select the appropriate utilities, calculate its optimal integration based on a cost function
Evaluate:	
	verify that the chosen values of the utilities are optimal propose other utilities, restart AGE.

6.1.3. Utility Intensive variables value.

The analysis of the global process stream in the grand composite curve allows to define the characteristics of the potentially good utilities to be used (figure 64). These are the inlet and outlet temperatures, the compositions. To evaluate their optimal flow rate, additional data are required. They are the cost function and the operating range of the flow rate for each utility stream.

Temperatures and composition are referred as intensive variables of the utility characteristic. They can be determined by analysing the grand composite curve and the utility availability on the plant under study. Technological considerations will also be used, and the engineer knowledge is of great help.

Once the intensive variables of the utilities are given, the linear programming formulation can be used to define the optimal set of utility to be used and their optimal integration to the process (i.e. their flow rate).



Energy Analysis and Synthesis in Industrial Processes

Utilities definitions

For the same MER

Different utility heat loads

Utilitaire 1 : cost 1

Utilitaire 2 : cost 2

Energy available

F. Maréchal - ## - //

Figure 64. Characteristics of the utilities on the GCC.

It is important to identify that for the same MER, utility flow rate and the energy produced by the utility might be different.

The only valid criterion is the cost.

It might appear that some of the utilities will produce an excess of energy that will have to be valorized, because it is paid.

6.1.4. Utility flow rate determination.

When utility with unknown flow rates are used, the temperature interval heat balance defined previously is given by:

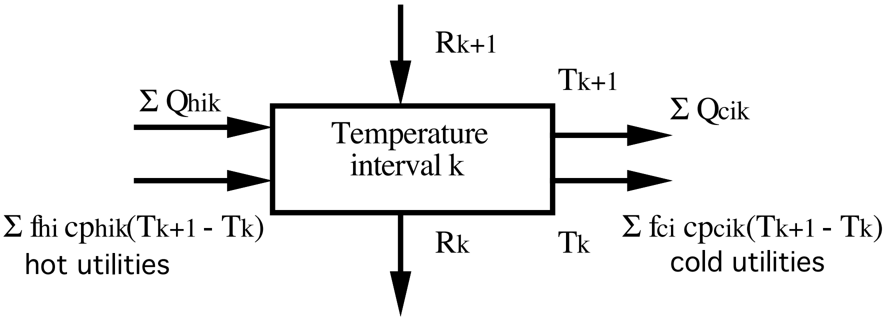


Figure 65. Temperature interval k: heat balance.

Inlets:

- the heat load of all the hot streams in the interval

$$\sum_{i=1}^{nhk} Qhik = \sum_{i=1}^{nhk} fhi\ cphik\ (Tk+1 - Tk) \tag{20}$$

Where
nhk is the number of hot streams in the temperature interval k defined by the temperatures Tk+1 and Tk.
Qhik (kW) is the heat load of the hot stream i in the interval k.
fhi (kmol/s) is the flow rate of the hot stream i. For process streams, fhi is a constant but for hot utility streams, it will be a variable of the system.
cphik (kJ/kmol/°K) is the molar cp of the hot stream i in the interval k.

This value represents the total heat load which can be given to the cold streams in the interval k or in the lower ones.

- Rk+1: the heat cascaded from the upper interval. This is the heat which can not be absorbed by the cold streams in the upper intervals.

Outlets

- the heat load of all the cold streams in the interval

$$\sum_{i=1}^{nck} Qcik = \sum_{i=1}^{nck} fci\ cpcik\ (Tk+1 - Tk) \tag{21}$$

Where
nck is the number of cold streams in the temperature interval k defined by the temperatures Tk+1 and Tk.
Qcik (kW) is the heat load of the cold stream i in the interval k.
fci (kmol/s) is the flow rate of the cold stream i. For process streams, fci is a constant but for cold utility streams, it will be a variable of the system.
cpcik (kJ/kmol/°K) is the molar cp of the cold stream i in the interval k.

This value represents the total heat load which has to be received from the hot streams in the interval k or in the upper ones.

- Rk: the residual heat load which can not be absorbed by the cold streams in the interval k and upper, and which has to be cascaded to the lower ones.

The heat balance of the interval k is given by:

$$Rk+1 + \sum_{i=1}^{nhk} fhi\ cphik\ (Tk+1 - Tk) - \sum_{i=1}^{nck} fcik\ cpcik\ (Tk+1 - Tk) = Rk \tag{22}$$

The linear programming problem became

$$\text{Min } C = \sum_{i=1}^{nu} (ai+bi\ fi) + Cbig\ (Rk+1 + R1) \tag{23}$$

subject to

$$Rk+1 + \sum_{i=1}^{nhk} fhi\ cphik\ (Tk+1 - Tk) - \sum_{i=1}^{nck} fci\ cpcik\ (Tk+1 - Tk) - Rk = 0 \tag{24}$$

☐ k= 1... nI

$Rk \geq 0$ ☐ k=1...nI+1

$fi \geq 0$ ☐ i=1...nu

Where	nu	is the number of utility stream proposed.
	fi	is the flow rate of the utility i.
	Cbig	is an arbitrary big cost which allows Rk+1 or R1 to be different of zero only if the utilities proposed does not have the adequate temperatures conditions. That means no feasible solutions with RnI+1 and R1 = 0 can be found.

The variables are the residues Rk and the utility flow rates fi.

The resolution of such a system has to be done by classic linear programming algorithm.

As only flow rates are adjusted this formulation does not solve the selection problem.

The selection problem is literally defined as follow:

“If a utility stream is used then its flow rate must lies between its bounds and its cost follows the function (a+ b f). But if it is not used, its flow rate must be zero as well as its cost."

In order to represent the selection in the former formulation, let us define the integer variable yi.

If yi = 1 the utility is used
- its flow rate lies between its minimum (fmini) and maximum (fmaxi) bounds
- its cost is given by (ai + bi fi).

If yi = 0 the utility i is not used
- its flow rate and cost must be 0.

The integer variables define new inequality equations:

$$yi\ .\ fmini \leq fi \leq yi\ .\ fmaxi \qquad i=1...nu \tag{25}$$

The cost function of the utility i is:

$$Ci = ai\ yi + bi\ fi$$

When yi = 1 the inequality become $fmini \le fi \le fmaxi$ and the cost is (ai + bi fi), which is the proposition 1.

When yi = 0 the inequality become $0 \le fi \le 0$ thus fi = 0 and the cost = 0, which is the second proposition.

The problem formulation of the thermal cascade is thus given by:

$$\text{Min } C = \sum_{i=1}^{nu} (ai\ yi + bi\ fi) + Cbig\ (Rk+1 + R1) \qquad (26)$$

subject to

$$Rk+1 + \sum_{i=1}^{nhk} fhicphik\ (Tk+1-Tk) - \sum_{i=1}^{nck} fci\ cpcik\ (Tk+1-Tk) - Rk = 0 \qquad (27.1)$$

☐ k= 1... nI

$$Rk \ge 0 \qquad (27.2)$$

☐ k=1...nI+1

$$yi\ .\ fmini \le fi \le yi\ .\ fmaxi \qquad (27.3)$$

☐ i=1...nu

yi ☐☐ ☐ ☐ ☐ ☐

The variables of the problem are Rk, fi, yi.

This problem is a mixed integer linear programming (MILP) problem. A classic method used to solve such a problem is the branch and bound method.

The use of integer variables allows to calculate different situations. It can be applied to select the most appropriate process scheme from alternative configurations.

Examples:

- Choice of the appropriate distillation sequence
- Choice of the appropriate pressure level of a mechanical vapour recompression
- Choice of the appropriate pressure level of a column

We can introduce equations between integer variables to represent affirmations like

Select at least one alternatives of the list

$$\sum_{i=1}^{n} yi \ge 1$$

Select maximum one alternative in the list

$$\sum_{i=1}^{n} yi \leq 1$$

Select one alternative in the list

$$\sum_{i=1}^{n} yi = 1$$

Select maximum m alternatives among the n alternatives (yi) only if yj is selected:

$$m\ yj - \sum_{i=1}^{n} yi \geq 0$$

6.1.5. Representing non linear functions

Non linear function are used to represent the cost of a unit

$$C = a\,(X)\,b \tag{28}$$

with	C	the investment cost
	X	the characteristic size of the unit,
	b	Typically 0.5 to 0.8)
	a	calculated from one reference price

$$a = \frac{C°}{(X°)b} \tag{29}$$

with	X°	the characteristic size of one known unit,
	C°	the cost of the known unit.

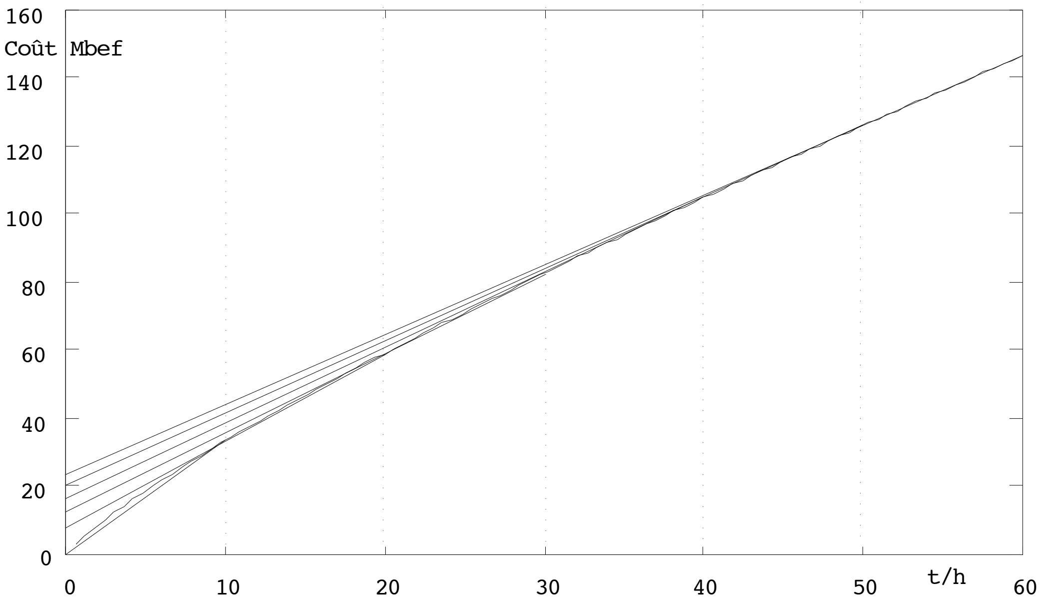


Figure 65.Coût d'investissement d'une chaudière en fonction de sa charge et approximation par segments linéaires.

The non linear function will be represented by a set of linear segments:

$$\begin{array}{lllllll} f(x) & = & c11 + c21\,x & \text{if} & 0 \leq & x & \leq m1 \\ & = & c12 + c22\,x & \text{if} & m1 \leq & x & \leq m2 \\ & = & c13 + c23\,x & \text{if} & m2 \leq & x & \leq m3 \\ & = & c14 + c24\,x & \text{if} & m3 \leq & x & \leq m4 \end{array} \tag{30}$$

Defining the integer variables:

$$\begin{cases} y_i = 1 & \text{if } x \text{ is in the linear segment } i \\ y_i = 0 & \text{if not} \end{cases}$$

The following equations represent the approximation of the non linear function with a list of linear segments:

$$f(x) = \sum_{i=1}^{nz} c1_i\, y_i + c2_i\, x_i \tag{31.1}$$

$$x = {}_{i=1}^{nz}\, x_i \tag{31.2}$$

$$\sum_{i=1}^{nz} y_i \leq 1 \tag{31.3}$$

$$xmin_i\, y_i \leq x_i \leq y_i\, xmax_i \tag{31.4}$$

$$y_i \in \{0,1\} \quad \text{for all } i=1,\dots,nz$$

with

nz	the number of linear segments;
xi	a new variable representing the value of x in the segment i between xmini and xmaxi;
xmini	the lower bound of the segment i: xmini = xmaxi-1 if i >1;
xmaxi	the upper bound of the segment i.

6.1.6. Optimizing the MVR level

Figure 66 gives an example of composite curves where a mechanical vapour recompression might be interesting. Different pressure levels might be proposed for the MVR.

The flow rate going into MVR might be a part of the condenser flow.

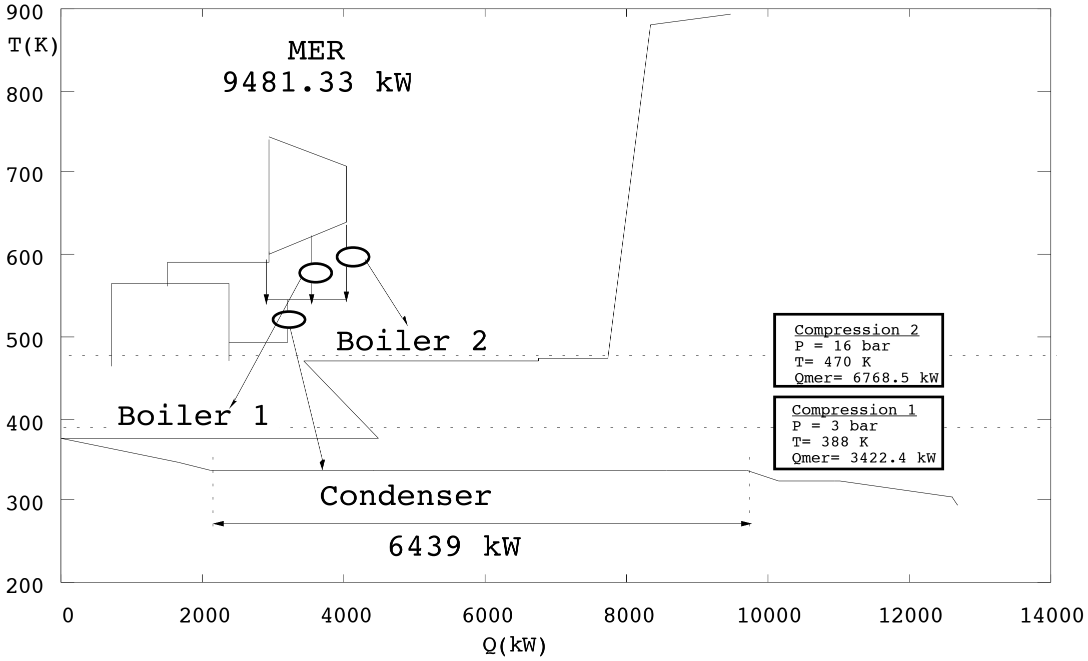


Figure 66.Different pressure levels for the MVR.

Table 1 : recompressed states.

State	Tin (K)	Pin (bar)	Tout (K)	Compression (kW)	Heat (kW)	Process (kW)
P0	342	0,7	341,7	0	7587,9	-
P1	382	3,0	341,7	842,38	8430,3	3422
P2	475	14,8	341,7	2255,25	9731,3	6768
P3	480	16,0	341,7	2308,25	9780,6	7725

The final state is identical for all the stages

The H-T diagrams corresponding to the MVRs are given n figure 67

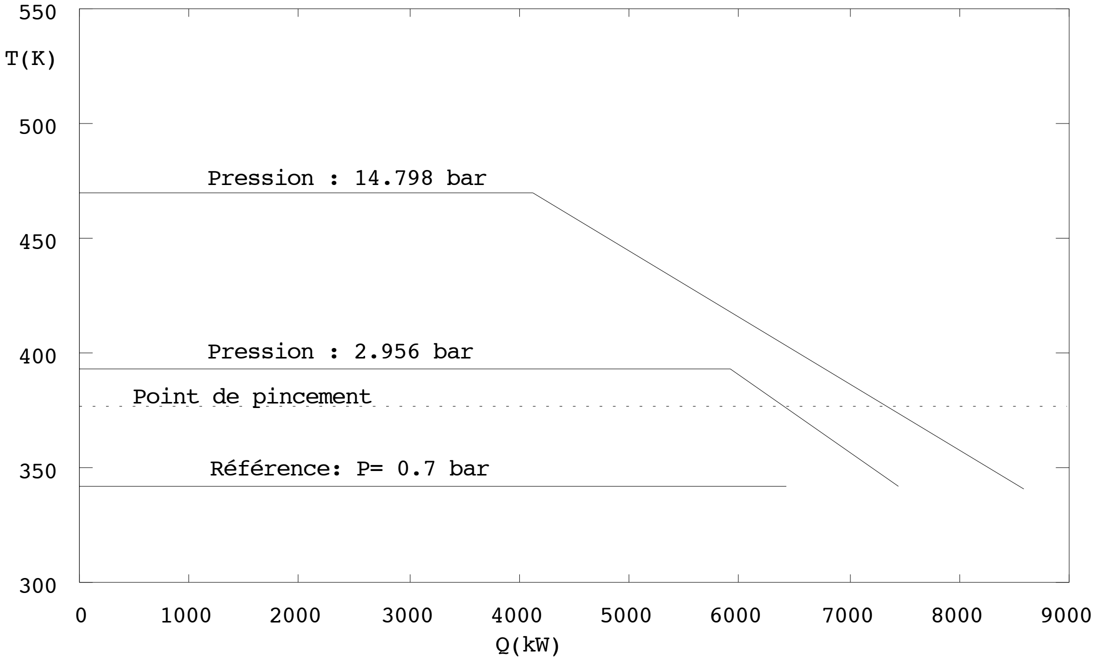


Figure 67. H-T diagrams of the recompressed states

For calculating the optimal flows in the MVRs, we define the following variables:

The reference state will be noted 0.

We introduce the following integer variables

$y0i$ =1 if the reference situation is used
$y1i$ =1 if the state P1 is used
$y2i$ =1 if the state P2 is used

Cost is given by:

$C0i$ = 0 cost in the reference situation
$C1i$ = cost of MVR at P1
$C2i$ = cost of MVR at P2

The choice of the optimal pressure level is given by:

$$\sum_{m=0}^{2} ypm = 1 \qquad (32)$$

If only part of the flow might be recompressed, we will use the following definition:

$$f_{min\,pm}\, y_{pm} \leq f_{pm} \leq f_{max\,pm}\, y_{pm} \qquad \text{for all } m=0,...,np$$

with
fpm the fraction of the flow rate that is compressed in the state m;
fminpm the minimum value accepted for fpm;
fmaxpm the maximum value accepted for fpm;
np the number of compressed states.

The next constraint imposes that the sum of the fractions will equal 1:

$$\sum_{m=0}^{np} f_{pm} = 1$$

The cost function is related to the fraction of each compression state:

$$\sum_{m=1}^{np} (C1_{pm}\, y_{pm} + C2_{pm}\, f_{pm}) \qquad (33)$$

With
C1pm the fixed cost of the MVR at pm;
C2pm the proportional cost of MVR at pm.

The proportional and fixed cost might include the investment required.

Table 2 gives the solutions obtained for three pressure levels. The solutions have been calculated for different values of electricity cost. We can observe that according to the economical context, the solutions proposed will be different.

Table 2

Electricity cost	5	10	100
P0 (%)	-	43,94	1
P1 (%)	10,82	56,06	-
P2 (%)	78,86	-	-
P3 (%)	10,32	-	-
Hot utility (kW)	2287,2	6058,9	9481,3
Cold utility (kW)	8231,6	10464	13438
Electricity (kW)	2129,8	477,0	0

When considering simultaneously the integration of a rankine cycle (see later), the results will be different (table 3). The reason is that combined production mechanical power and hot utility is performed.

Table 3

Electricity cost	5	10	100
P0 (%)	-	43,94	63,92
P1 (%)	10,10	56,06	36,08
P2 (%)	78,83	-	-
P3 (%)	11,07	-	-
Hot utility(kW)	2287,2	6314,4	7606,3
Cold utility (kW)	8210,5	10464	11524
Rankine mec (kW)	31,4	258,00	330,66
Electricity (kW)	2111,4	237,5	0

6.1.7. Evaluate the integration of a utility

The thermal cascade of optimal multiple utilities will features multiple pinch points in addition of the process pinch point. They are called "utility pinch points". The reason of utility pinch point is that the cheaper utility are used at maximum. That is defined either by the maximum bounds of the flow rate or by one of the constraints Rk ≥ 0 that becomes active defining a pinch point. This is the case in figure 62 when Q1 is given by the hot utility at T3 or T2.

The multiple pinch points is not a problem because the utility flow rate can be manipulated. Decreasing the flow rate of a cheap utility will be compensated by the increase of another utility more expensive.

As we will see further, the utility integration combines heat and mechanical power. For example, condensing steam comes from a steam network system with steam engines and heat exchangers, gas turbines produces heat and mechanical power together. On the other hand, refrigeration cycles used as cold utilities will require mechanical power to drive their compressors.

The work method proposed to select the utility assumes that the quality f the utility is well chosen. It is useful to verify that the characteristics of the selected utility are optimal and lead to an optimal integration.

The integrated composite curve of the utilities allows to visualize the integration of the utility and to identify the utility pinch points.

The characteristics of these curves are:

> The utility curve is drawn with respect to the MER of the process
> The process pinch point is taken as reference
> Energy penalty can be read in the negative enthalpy

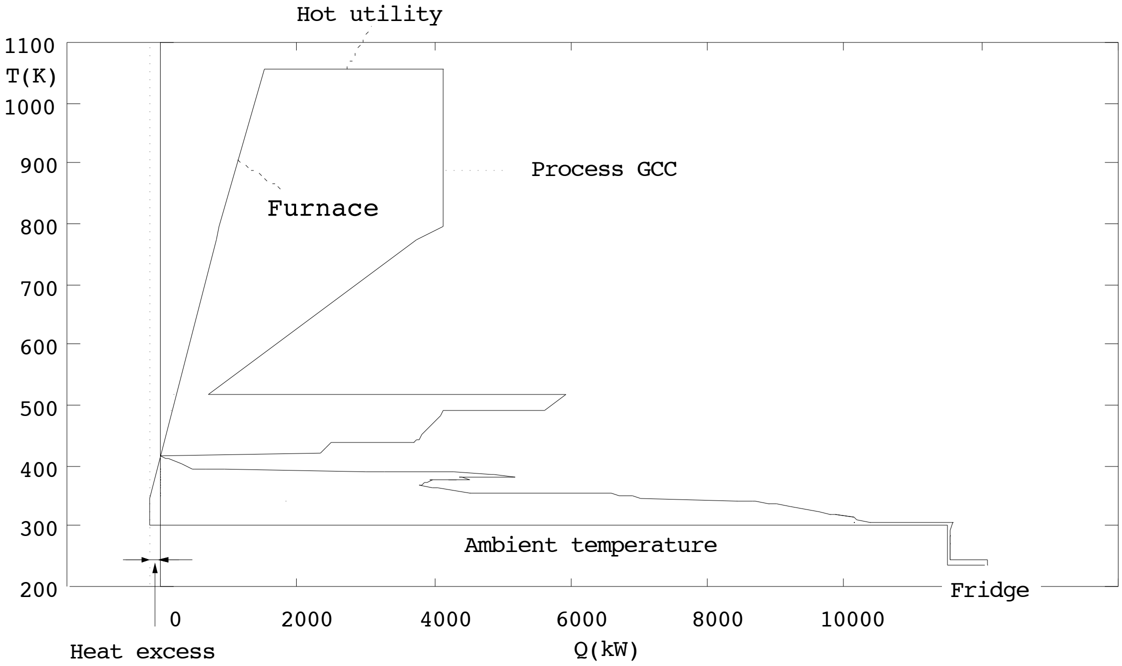


Figure 68. Example of integration of hot utility by combustion

The curve on figure 68 allows to visualize the excess of heat available in the fumes below the pinch point. The excess of heat is read in the negative enthalpy.

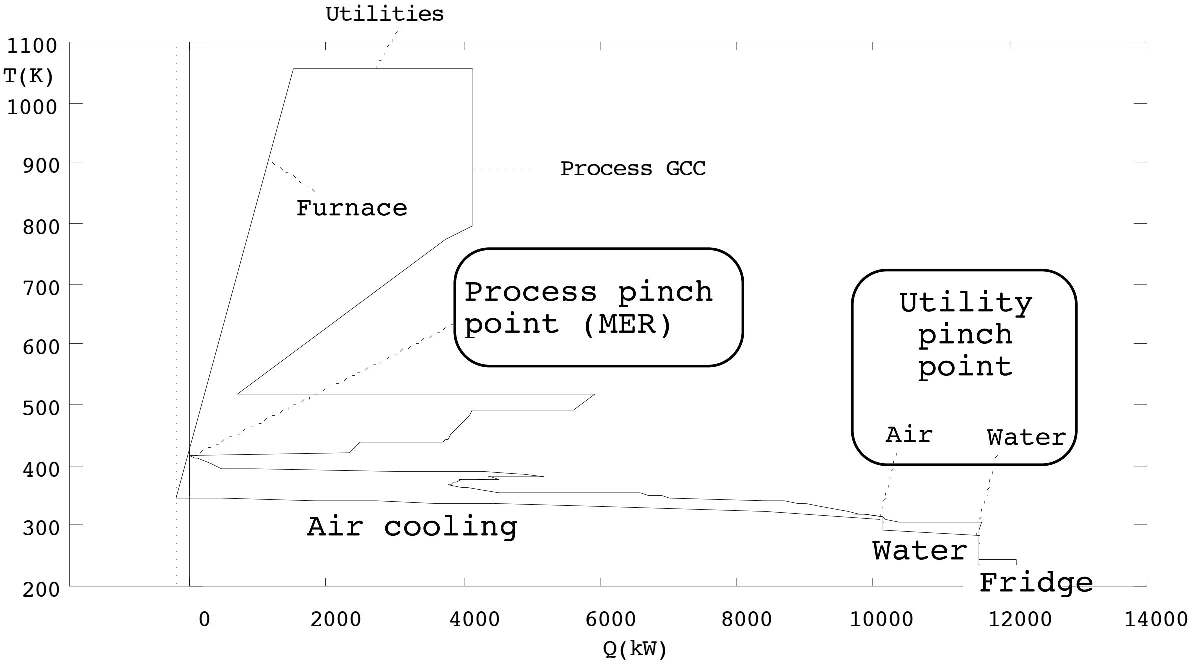


Figure 69. Example of integration of hot and cold utilities.

6.2. Heat and Power Integration

As shown here above, heat and mechanical power are closely integrated and have to be studied together. In this chapter we will study the heat pump, a mechanical power consumer and the Rankine cycle, a mechanical power producer.

Both are cycles which will take the heat to process streams to send back the transformed heat to process streams after mechanical power transformation. In the contrary of the mechanical vapour recompression, the process streams will not be modified and an intermediate stream will transfer the energy and undergo the modifications. The compression (expansion) ratio will thus be greater (smaller) since the intermediate stream will require two times the DTmin/2.

Let us analyse the heat pumps and its most important application the refrigeration cycle.

6.2.1. Refrigeration cycles

Refrigeration cycles are used as cooling utility below the ambient temperature.

A typical refrigeration cycle is given figure 70.

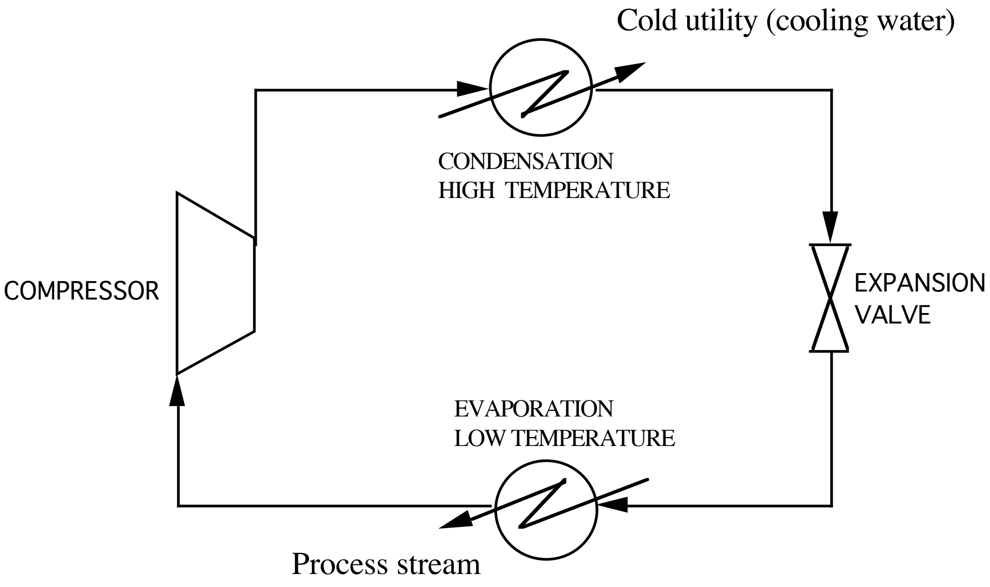


Figure 70. Simple single stage refrigeration cycle.

A mixture, called refrigerant, circulates in a cycle where it is successively compressed, condensed, expanded and evaporated. The objective of the refrigeration cycle is to pump the energy of a hot process stream with low temperature by evaporation. The compression changes the temperature level of the fluid phase change so as the refrigerant gives the pumped heat load to a cooling utility at higher temperature while condensing. After adiabatic expansion in the valve the mixture reenter the evaporator.

This is a simplified scheme, the real refrigeration cycles feature temperatures regulations at the compressors inlet and usually multi stages compressors, but this will not change the philosophy of the refrigeration cycles integration.

The composites curve of the refrigeration cycle described here above are given in figure 71. For the energy integration, the refrigeration cycle introduces two streams: the hot stream (F1) at high temperature which condenses and the cold stream (F2) at low temperature which evaporates. The two other streams are the process stream to cool down (P) and the cold utility (U). The cold utility can be either cooling facilities above the ambient temperature or another refrigeration cycle if the temperature is not high enough. In this case the refrigeration cycles will be interconnected.

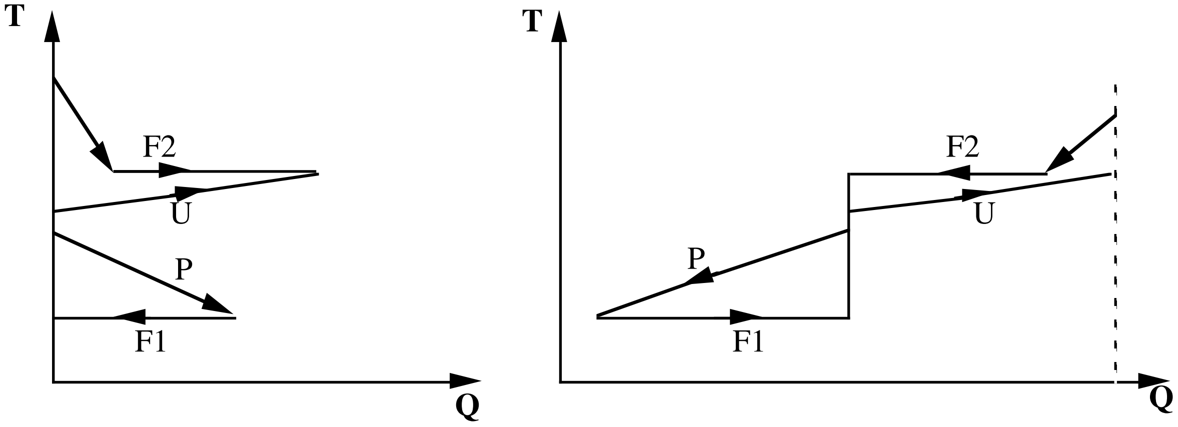


Figure 71. Composite curve of a refrigeration cycle.

The optimal integration of a refrigeration cycle (or a heat pump) follows the same rules than the mechanical vapour recompression: the heat has to be pumped from below to above the pinch point as shown figure 72.

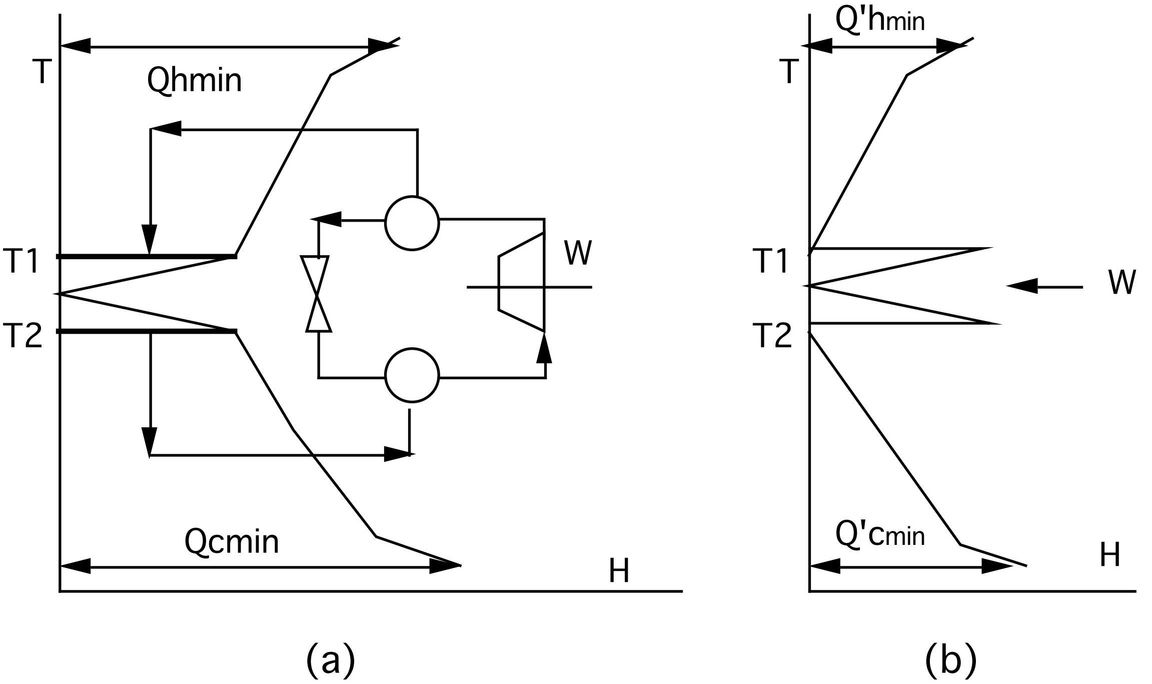


Figure 72. Optimal integration of refrigeration cycles and heat pumps.

Refrigeration cycles can not always be optimally integrated because their aim is to cool down streams which can not be cooled with another utility. This is usually the case: the refrigeration cycle leads to cold utility energy penalty of W, the mechanical power required for the compression in the cycle (see figure 57 case (b)).

Indeed, the ambient cooling utility will produce a utility pinch point and the refrigeration cycle will respect the former rule.

As the others utilities, the refrigeration cycle requires the definition of intensive and extensive variables.

6.2.1.1. The intensive variables.

The composition of the mixture is very important in the refrigeration cycle determination. The choice of the component(s) is based on the temperature required for the process stream to cool down. The key temperature will be the minimum temperature of the stream to be cooled down - DTmin/2. The component or the mixture composition will be taken such as the dew point at atmospheric pressure will be smaller than the key temperature. The sub-atmospheric refrigeration cycles are not usually used because of technological difficulties (leaking,...).

The upper pressure will be chosen so as to discharge the heat above the pinch point or above the temperature of the chosen cold utility. The cold utility can evidently be the cold part of another refrigeration cycle. On the high pressure side, the key temperature is the boiling point of the refrigerant.

Tables of chemical engineering handbook and the use of thermodynamic calculation program are of great help in choosing the intensive variables of the refrigeration cycle.

The intensive variables of the refrigeration cycle will be chosen by analysing the composite curves.

The cold side of the refrigeration cycle is a cold utility which has to exchange with the global hot process stream. Multiple levels can be used to decrease the energy cost (mechanical power) of the refrigeration. The reasoning is the same as for the multi level condensing steam.

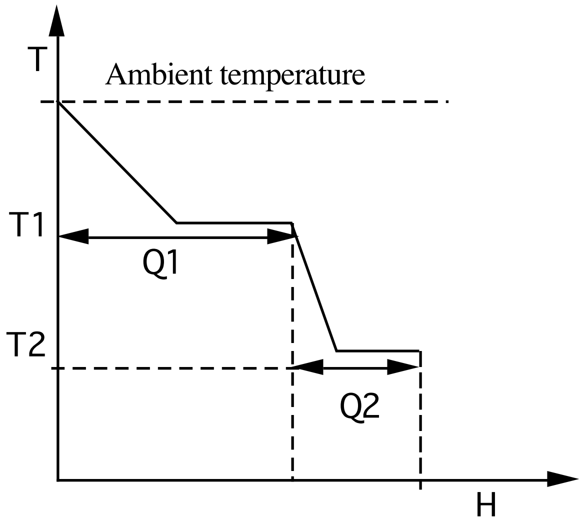
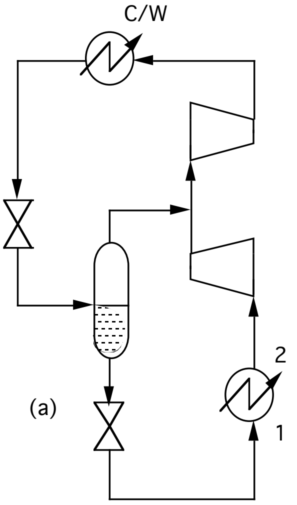


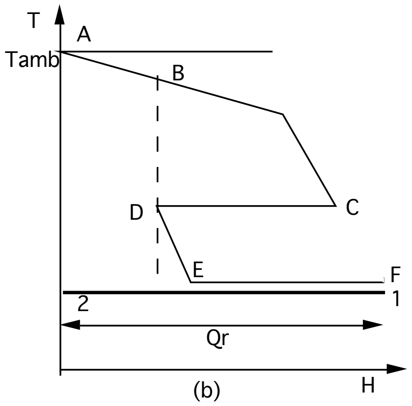
Figure 73. Multiple refrigeration levels.

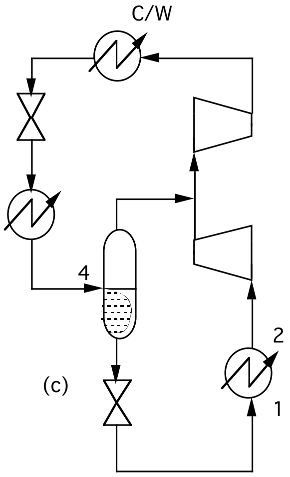
The figure 73 gives an example of multiple levels for refrigeration cycles. Q1 can be removed at T1 or lower temperature but Q2 must be removed at T2. The heuristic will be:

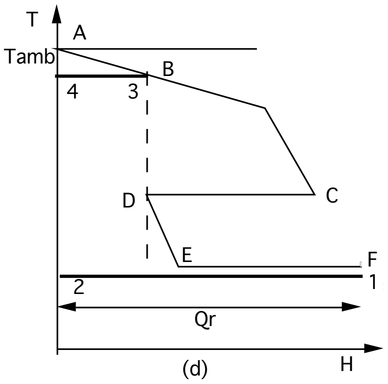
"Try to fit the global hot process composite curve and the cold utility as close as possible".

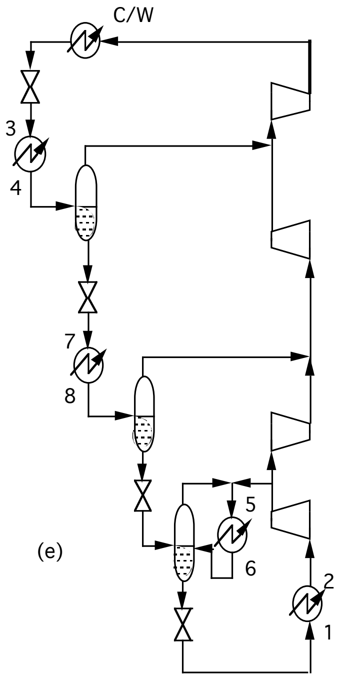
The multi levels refrigeration cycles are of different types. One way is to couple single stage refrigeration cycles (figure 70) with different pressures levels and/or refrigerant. Another way is to design multi stages cycles. Example of multi stages refrigeration cycles are described figure 74. In this case, simulation tools will be of great help in determining the intensive variables.


C/W
2
1
(a)


T
A
Tamb
B
C
D
E
F
2
1
Qr
(b)
H


C/W
4
2
1
(c)


T
A
Tamb
B
4
3
C
D
E
F
2
1
Qr
(d)
H


C/W
3
4
7
8
5
6
2
1
(e)

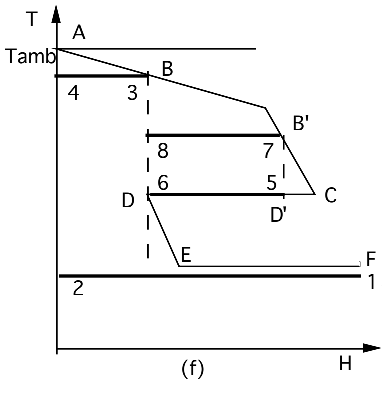

T
A
Tamb
B
4
3
B'
8
7
6
5
D
C
D'
E
F
2
1
(f)
H

Figure 74. Examples of multi stages refrigeration cycles.

6.2.1.2. The extensive variables.

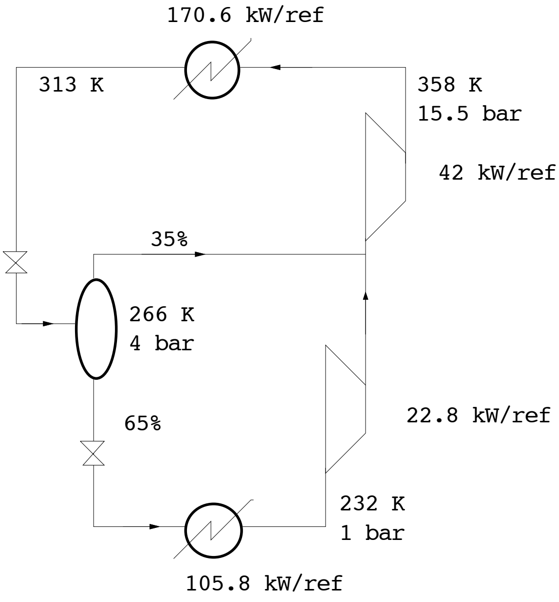
A lot of valid refrigeration cycles can be found to perform the cooling requirements. To select among these the one(s) to be used and calculate their optimal integration, the cycles flow rates will be added in the MILP formulation (22). Their cost will be defined by the formula:

$$C = a_i y_i + b_i f_i \quad (34)$$

Where
ai is the fixed cost related to the investment.
yi is the integer variable associated to the cycle
yi = 1 if the cycle is used
yi = 0 if not
bi is the operating cost related mainly to the compression work.
fi is the flow rate cycling in the refrigeration cycle.

To obtain the optimal configuration, multiple calculations will be performed to tune the refrigerants proposed. The composite curves including the cycles integration will be analysed and new cycles conditions will be proposed to better fit hot and cold composite curves.

The following data refer to a typical refrigeration cycle given for a given reference flow rate.



The thermal effects used for calculating the integration are given on the following table.

	Tin (K)	Tout (K)	P (bar)	DTmin/2	Q (kW/unité)
Evaporation	232,0	232,0	1	2	105,08
Desuperheating	358,7	313,3	15,5	2	27,01
Condensation	313,3	313,3	15,5	2	143,65

The composite curves resulting of the refrigeration cycles integration will feature multiple pinch points corresponding to the maximum use of the selected cheaper cycles. They can usually be removed by increasing the flow rate of a more expensive cycle.

A typical grand composite curve obtained after refrigeration cycle integration is given figure 75. Only the lower part of the curve is given.

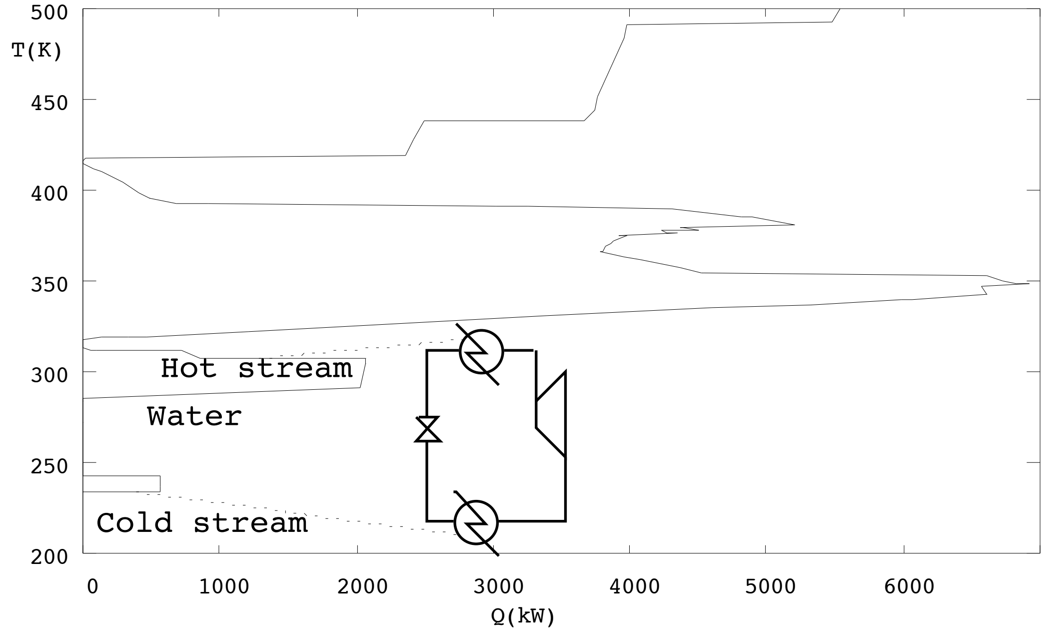


Figure 75. Composite curves after refrigeration cycles integration.

6.2.1.3. Integrated composite curves

The integrated composite curve allows to visualize the impact of the integration of the refrigeration cycle.

We can visualize the energy supplement to be evacuated for the process by the cold utilities. Two cold utilities are used: the cheaper: air cooling is used to desuperheat the refrigerant at the outlet of the compressor and water is used afterwards to condense the refrigerant at high pressure.

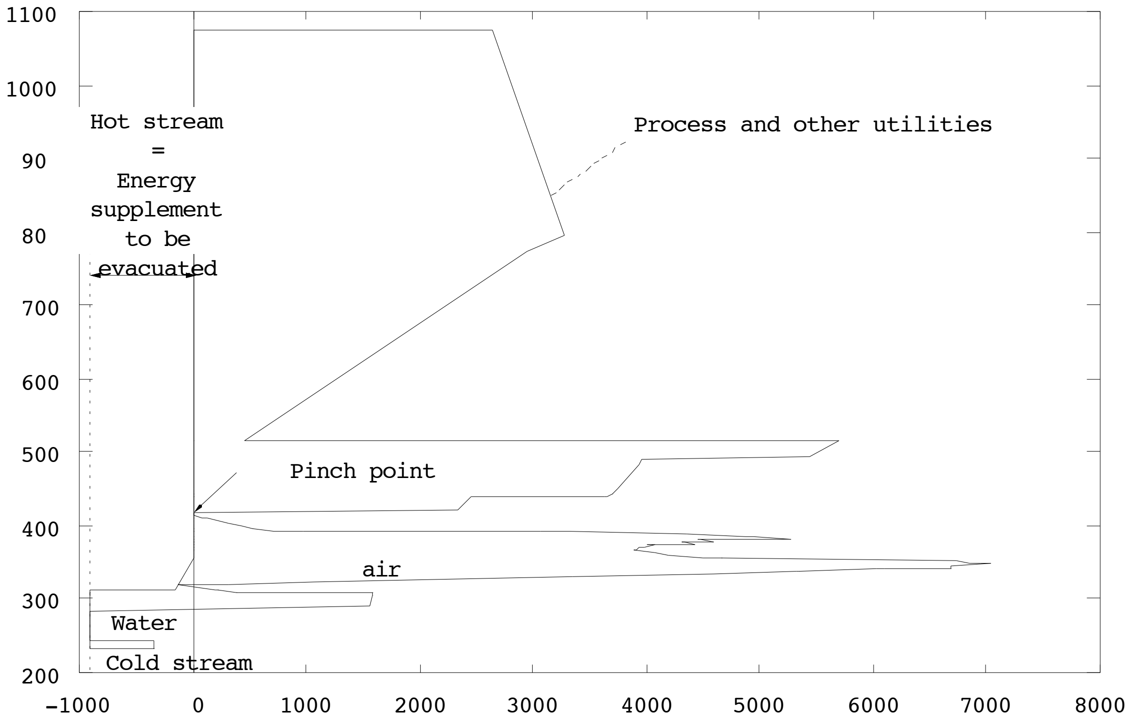


Figure 76.Integrated composite curves of a refrigeration cycle.

Expanding the lower part of the curve (figure 76) allows to visualize the mechanical power consumed by the cycle (balance between hot and cold streams heat loads in the refrigeration cycle).

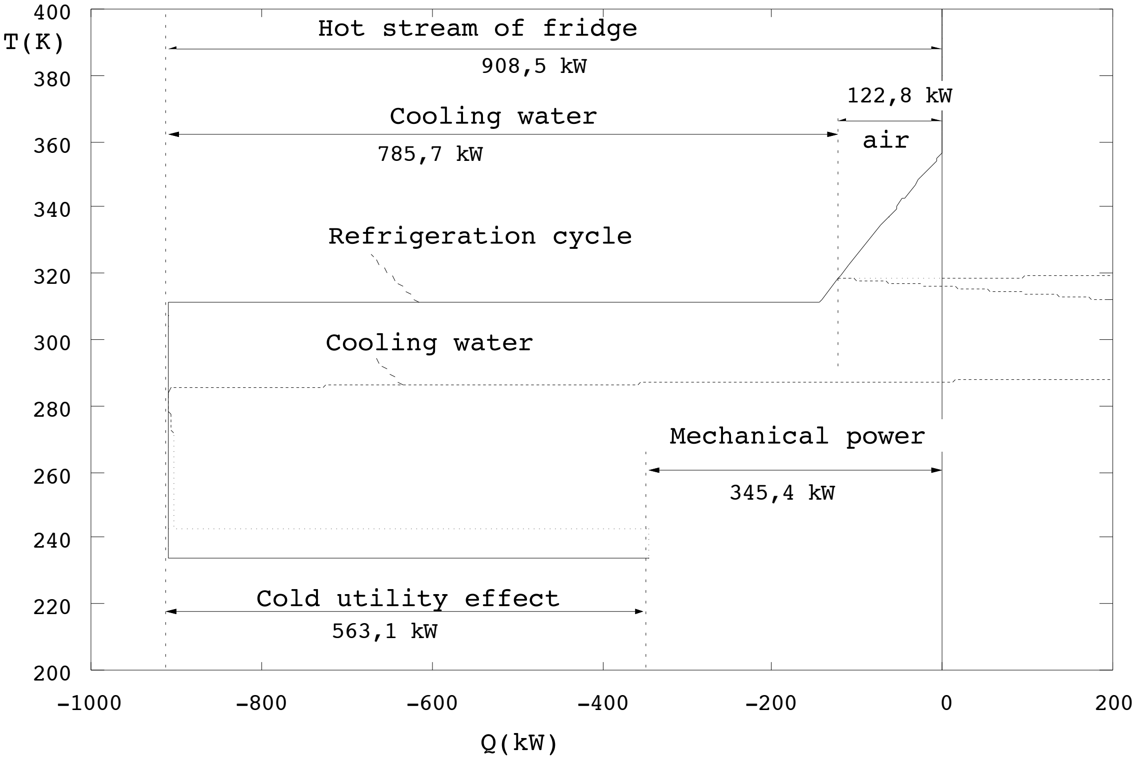


Figure 76'.Integrated composite curves of a refrigeration cycle.

6.2.2. Rankine cycles.

The energy integration involves both mechanical and thermal power. They are strongly linked together as explained in the former sections. If mechanical power demands are often necessary for optimal integration, the production of mechanical power can also be integrated. In the utility choice section, we have seen that the exhaust gases of a gas turbine can be used as hot utility in the thermal cascade.

Another way of producing mechanical power is the Rankine cycle. In this section, the single stage Rankine cycle will be described. In real process, the utility systems used for mechanical power production are more complex but the principle applied will be the same.

The single stage Rankine cycle of figure 77 proceeds usually with water. The circulating water is heated up in a heater, passed through a steam engine to produce the mechanical power according a given isentropic efficiency. The outlet of the steam engine is condensed and the liquid is pumped to the heater.

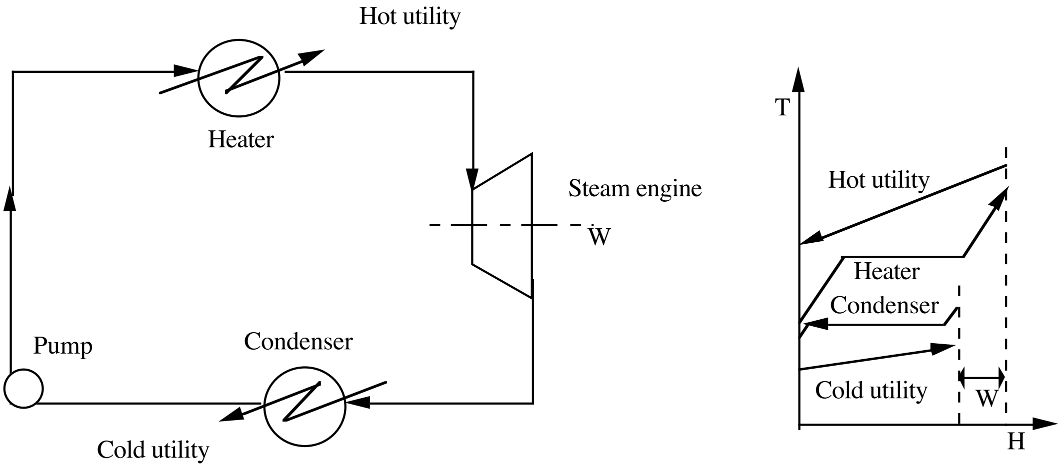
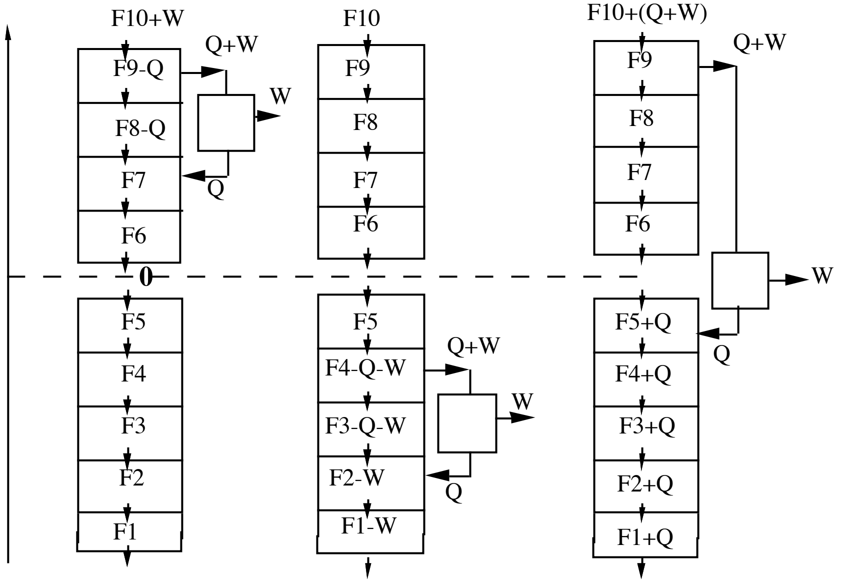


Figure 77. Single stage Rankine cycle.

The composite curves of the Rankine cycle show both hot and cold requirements. The efficiency is approximately 1/3 of the thermal power transformed in mechanical power, the remaining heat being transferred through the condensation to the cold utility.

6.2.2.1. Integration of a Rankine cycle

When integrating the Rankine cycle in the process, it is possible to obtain better mechanical power to thermal power ratio. The steam evaporation and superheating is a cold stream and the condensation is a hot stream. When integrating a Rankine cycle, the pinch point localization is once more very important. Let us examine the thermal cascade of figure 78.



(a) (b) (c)

Figure 78. Thermal cascade and mechanical power production.

In the case a, the heater and condenser are both above the pinch point. The condensation hot stream is used as hot utility in the heat sink. The hot utility requirement is increased of W, the mechanical power produced. The efficiency of the mechanical-thermal ratio is 1. In the second case, the heater and condenser are both below the pinch point. The heater takes the heat in the higher temperature the heat source, and the heat is send back to the utility after mechanical power production. In this case, only the cold utility requirements are changed. They decrease of the energy taken out of the system in mechanical power form (W). The energy efficiency ratio is infinite. When in case c, the heater is above the pinch point and the cooler below, the hot and cold utility requirements are both increased. In this case, the non integrated scheme features the same energy efficiency.

The conclusion is that mechanical power integration is effective when it takes place all above the pinch or all below the pinch point.
Above the pinch point, the energy penalty will be an increase of W for the hot utility.
Below the pinch point no energy penalty is found: a part of energy of the heat source is transformed into mechanical power.

As for the refrigeration cycle, the definition of the Rankine cycle includes intensive and extensive variables. The intensive variables are the pressure levels, the undercooling and superheating temperatures. As the only extensive variable is the total flow of circulating water, all the intensive variables can be calculated by simulation for any fixed flow rate.

The grand composite curve shape is of great help for fixing the intensive variables values. In figure 78, the value Fk are the cascaded heat loads before the mechanical power integration, the feasibility condition is that the new residues cascaded have to be greater than zero. To satisfy this condition, the composite must feature self sufficient zones. The Rankine cycle will pump the heat in the upper part of this zone, transform part of the heat in mechanical power and restitute in heat to the lower part of the self sufficient zone. This is illustrated figure 79. Do not forget to take DTmin/2 value into account during the calculations.

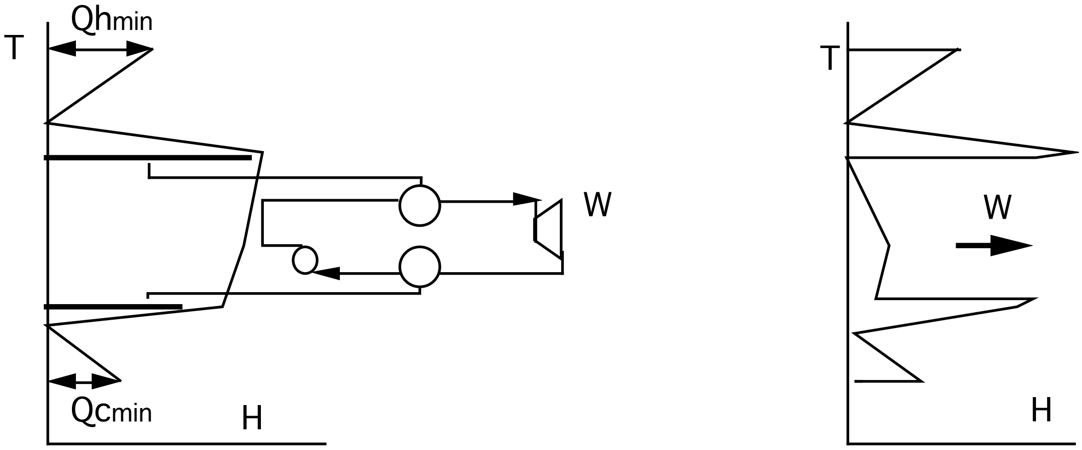


Figure 79. Self sufficient zones and mechanical power production.

Once potentially good cycles are defined, their hot and cold streams are added in the heat integration data set. The selection and the optimal integration of the chosen cycles is done by the MILP formulation of the thermal cascade (26) where the circulating water flow will be added in the variable set. The cost function will feature negative value since mechanical power is produced. Note that if the Rankine cycle is used above the maximum value for optimal integration, the extra mechanical power is produced with the same efficiency than if it is not integrated.

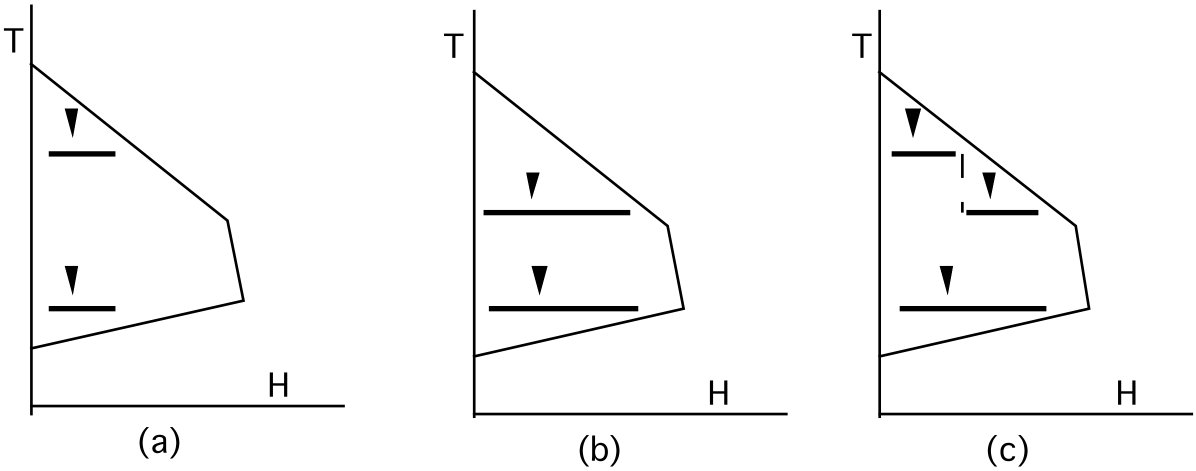


Figure 80. Different pressure levels.

As for refrigeration cycles, multiple pressure levels can be used to better match the composite curves and increase the mechanical power production by increasing the expansion ratio. The figure 80 shows three different options. In case a, the expansion ratio is high but the amount of energy used is small and so is the circulating flow rate. In the case b, the flow rate is high but the expansion ratio is small. The third case shows a two stages evaporation which uses better the energy potential for mechanical power production.

The rules for identifying the opportunity for mechanical power integration and selecting the pressure levels are thus:

- 1 Identify self sufficient zones with sufficient temperature difference and if possible with upper and lower stages.

- 2 Integrate the Rankine cycle above or below the pinch point not across. If possible integrate it below the pinch point.

- 3 Choose the pressure levels so as to match the as well as possible the composite curve.
Above the pinch point the condenser will be hot utility for the process.
Below the pinch point the heater will be the cold utility for the process.
To calculate the temperature, do not forget the DTmin/2 contribution.

The choice of the optimal pressure levels is made by inscribing rectangles between the GCC and the temperature axis (figure 81).

Maximizing the height of the rectangle correspond to maximize the expansion ration.

Maximizing the width of the rectangle correspond to maximize the flow rate in the rankine cycle.

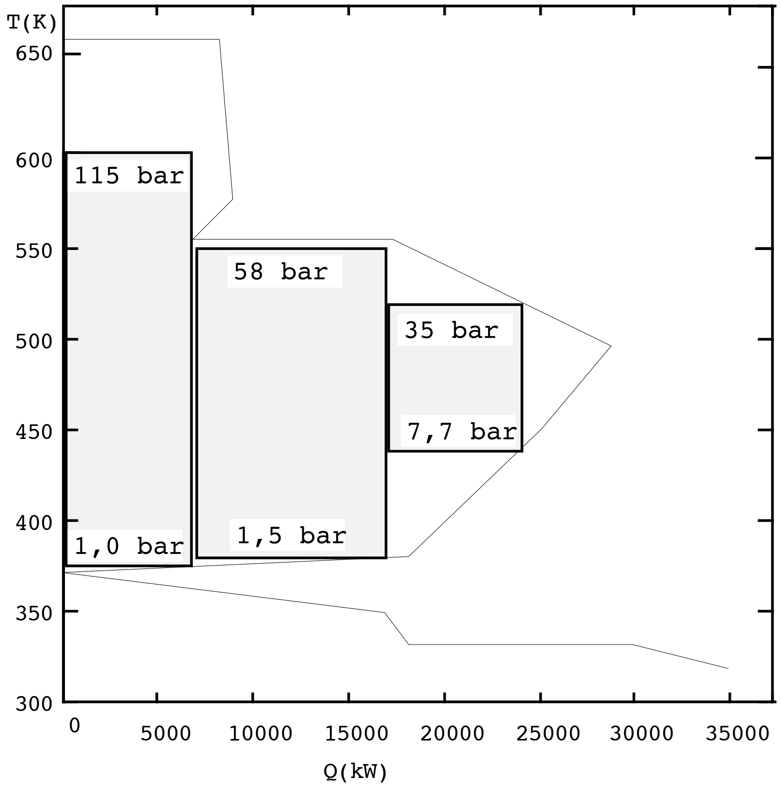


Figure 81. Choice of the optimal pressure levels.

It is important to note that this approach is used to maximize the combined heat and power production. It has to be applied only if the mechanical power produced can be exported or used in the process under study.

6.2.2.2. Integrated composite curves of a Rankine cycle

The grand composite curve resulting from the integration of the different utilities (figure 82), including the Rankine cycles presents a lot a utility pinch points and it is very difficult to confirm the integration of the utilities.

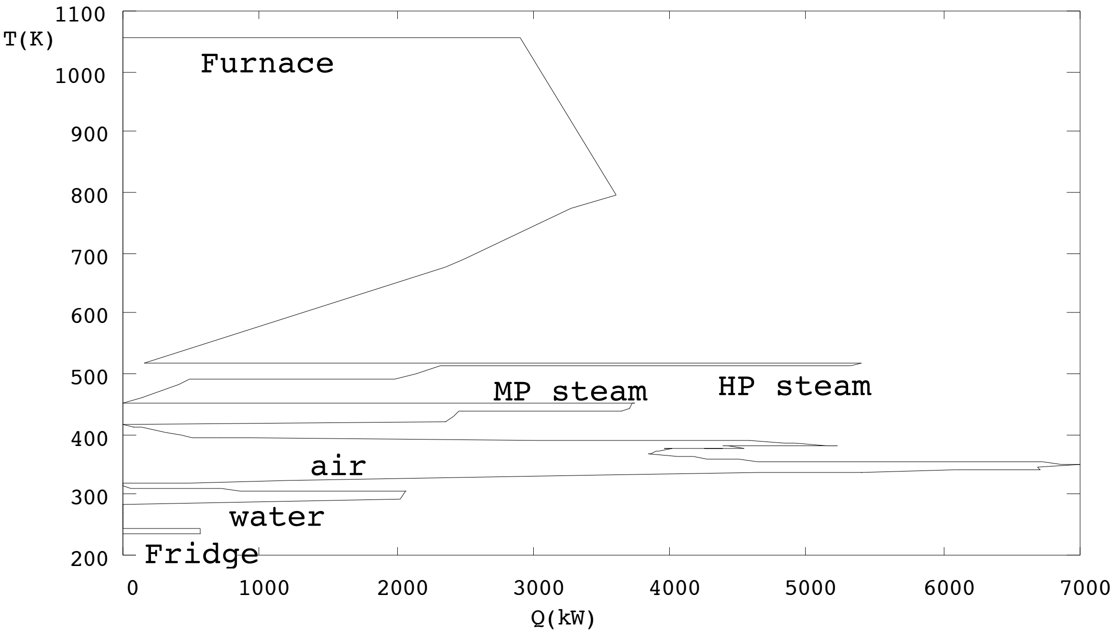


Figure 82.GCC of the integrated process and utilities

The integrated composite curves of the rankine cycle (figure 83) allow to read the mechanical power produced and the excess of hot utility required to produce the heat. Equality between the two entities allows to confirm the good integration of the Rankine cycle.

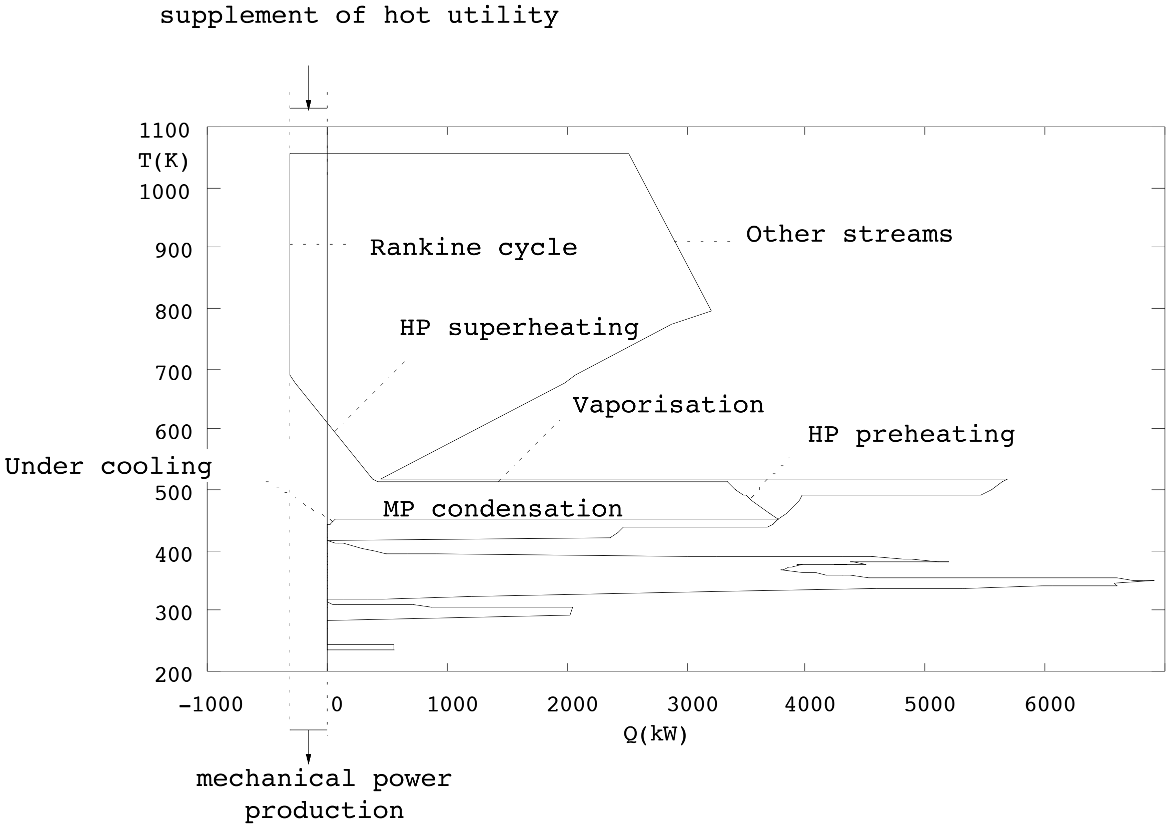


Figure 83.Integrated composite curves of a Rankine cycle