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# Optimal design of the structure and settings of nuclear HTR thermodynamic cycles

J. Gosset [a,*], R. Gicquel [a], M. Lecomte [b], D. Queiros-Conde [a]

[a] *Centre Energétique et Procédés, Ecole des Mines de Paris, 60 Boulevard Saint Michel, 75272 Paris cedex 06, France*
[b] *Framatome-ANP, Tour AREVA, 92084 Paris La Défense cedex, France*

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**Abstract**

A thermal integration method has been used by Framatome-ANP since 2001 in order to optimize thermodynamic cycles (cogeneration and combined cycles) coupled to new nuclear high temperature reactors. This method allows the design of complex thermodynamic cycles that comply to a large number of industrial constraints, without any a priori assumption on the structure of the internal heat exchanger network.

This paper briefly recalls the principles of the method and shows how accurate and rigorous exergy analyses can be carried out quite easily in an industrial context. It details on an example how industrial constraints and thermodynamical considerations interact to lead to an optimal cycle structure and settings. The efficiencies obtained are presented and discussed. In particular we discuss what we mean by optimal design. It is shown that this method is well suited to build optimal complex heat exchanger networks. The differences with other methods like the thermoeconomic ones are also briefly discussed.

*Keywords:* Pinch method; Cogeneration; Combined cycles; Nuclear high temperature reactors; Thermal integration; Process integration

## 1. Introduction

Although a large number of thermal science researchers and teachers have now adopted exergy analyses, there is but a few engineers in industry who have done so. The main reason is that there is a lack of appropriate tools to assist them in putting theory into practice.

In this paper we shall present how a tool such as the Thermoptim software (www.thermoptim.com) can be used in an industrial context in order to design high efficiency combined cycle and cogeneration plants coupled to new nuclear High Temperature Reactors (HTR).

A partnership has been set up in 2002 between Framatome-ANP and Armines—Ecole des Mines de Paris, in which the research group built the initial models which were subsequently used and modified by the industrialist in order to fit its requirements.

The paper will show how accurate and rigorous exergy analyses can be carried out quite easily thanks to the thermal integration tools provided by softwares like Thermoptim.

## 2. HTR nuclear reactors and thermodynamic cycles

The Framatome-ANP HTR design [1] will support the expanding worldwide demand for safe, economic and environmentally responsible electricity production. This nuclear heat source product family is an evolution of the Gas Turbine—Modular Helium Reactor (GT-MHR) conceptual design that was developed, with Framatome-ANP participation, for the US/Russian Plutonium Disposition Program. The GT-MHR applies the block-type prismatic core design, in which the coated particle fuel, a common feature of many HTRs, is contained within prismatic graphite blocks that are arranged to form an annular core geometry. The 102 column, 10 block high active core utilizes a once-through low enriched uranium fuel cycle and operates in the epithermal neutron spectrum. The core is sized to produce 600 MW of thermal power, with a core outlet temperature up to 1000 °C for electricity generation. Helium is

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[*] Corresponding author. Tel.: +(33) 1 40 51 91 12; fax: +(33) 1 46 34 24 91.
*E-mail address:* jerome.gosset@ensmp.fr (J. Gosset).

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## Nomenclature

| | | | | | |
|---|---|---|---|---|---|
| $Q$ | heat flow rate | kW | $\dot{m}$ | mass flow rate | $kg\cdot s^{-1}$ |
| $F_S$ | steam flow rate | kW | $C_p^c$ | cold fluid heat capacity | $kJ\cdot kg^{-1}$ |
| $F_G$ | gas flow rate | kW | $C_p^h$ | hot fluid heat capacity | $kJ\cdot kg^{-1}$ |
| $\tau$ | mechanical power | kW | CFDC | Carnot Factor Difference Curve | |
| $T_k$ | source temperature | K | GT-MHR | Gas Turbine—Modular Helium Reactor | |
| $\Delta H$ | enthalpy flow | kW | HEX | Heat EXchangers | |
| $\Delta X_h$ | exergy flow | kW | HRSG | Heat Recovery Steam Generator | |
| $\Delta X_{hi}$ | irreversibility flow | kW | HTR | High Temperature Reactor | |
| $\Delta X_q$ | $= (1 - T_0/T_k)Q$ heat-exergy flow | kW | IHX | Intermediate Heat eXchanger | |

used as the primary heat transport medium. The thermal power produced in the core is transferred to a secondary loop via an intermediate heat exchanger (IHX), where it is used to drive the application of interest.

The IHX comprises multiple modules of a compact heat exchanger design that is optimized for high effectiveness and minimum approach temperatures, while providing high reliability and maintainability. Compact heat exchangers of the types being considered for the IHX are typically designed with an effectiveness ranging from 90% for standard installations to 95% for more aggressive designs. The IHX is sized for an effectiveness of 92% to achieve a 50 °C approach temperature.

On the basis of this HTR design, the thermodynamic problem can be stated as follows: how is it possible to conceive a thermodynamic cycle which would supply the largest power?

Multiple solutions exist, but there are technological constraints at the level of the machines. For example, as shown in Fig. 1, some quite simple gas cycles have very good efficiencies, but the development of economical turbomachines may require 10–20 years, because the working fluid is helium and very few helium compressor or turbines have been built.

Another solution, the one which was selected by Framatome-ANP, is to use an available technology and to adapt it. As most experience gained today at industrial level with compressors and turbines corresponds to air gas turbines, the working fluid selected by Framatome-ANP is an air-like mixture of about 80% nitrogen and 20% helium, coupled to a steam cycle, leading to combined or cogeneration cycles. Although this second solution is theoretically less efficient than the first one, it is practically much better as it allows to design new machines which can be built in a few months instead of years. Furthermore, the costs are largely reduced by the use of conventional air-based gas-turbine technology and a series effect. Therefore, in Framatome-ANP HTR design, the nuclear heat source is coupled via an IHX to a secondary loop combined cycle (Brayton plus Rankine) Power Generation System. The secondary Brayton Cycle employs a working fluid that has nitrogen as its principal constituent. The Rankine bottoming cycle is also based on conventional technology.

As a result, the Framatome-ANP HTR nuclear heat source incorporates several important innovative departures from the

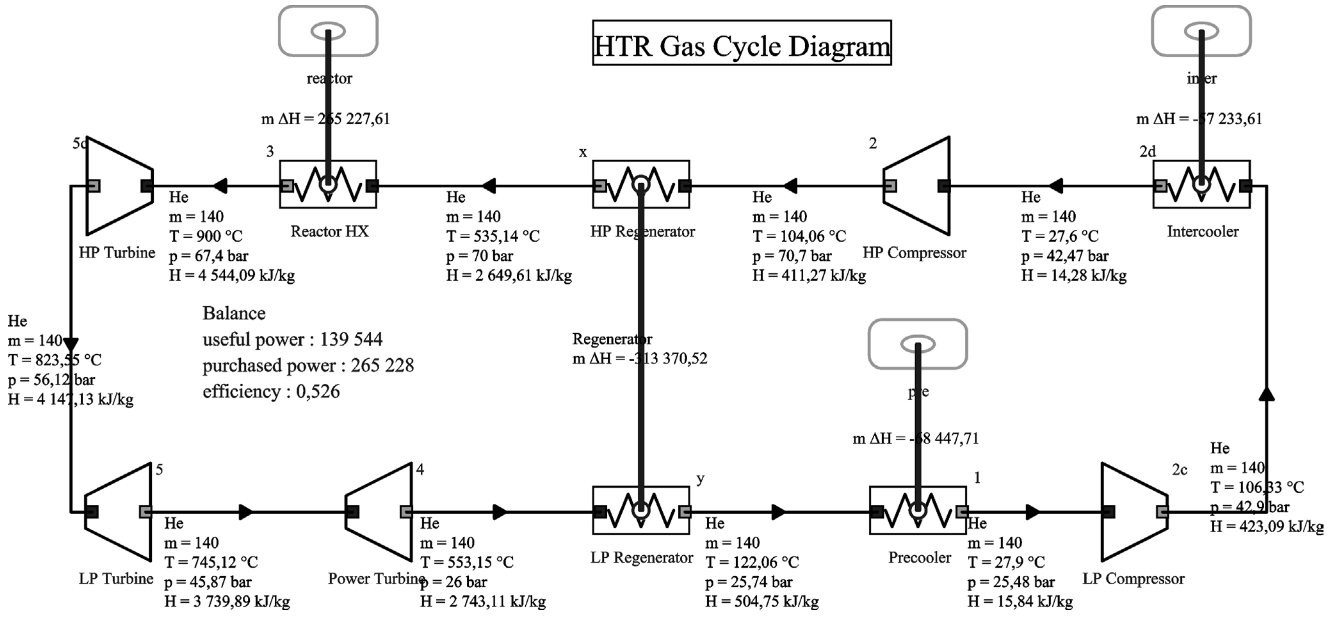


Fig. 1. Example of a HTR gas cycle.

predecessor GT-MHR design. The most significant difference is the use of an indirect combined cycle design for electricity generation, rather than the direct cycle used in the GT-MHR design. The second key difference is the selection of a reduced reactor inlet temperature, relative to that of the GT-MHR.

The indirect cycle offers several advantages. First and foremost, it allows a common heat source to be used for both electricity generation and cogeneration and minimizes the complexity and risk associated with the nuclear part of the cycle.

The second major advantage offered by the indirect cycle design is the freedom to select a secondary coolant other than helium. As has already been said, the Framatome-ANP design for electricity generation uses a mixture of nitrogen and helium with properties similar to air as the secondary heat transport fluid. This mixture allows the use of modified gas-turbine technology, including the same design techniques, materials and testing facilities used for conventional air-breathing gas-turbines.

The third major advantage of the indirect cycle design is to facilitate the use of a Rankine bottoming cycle to improve cycle efficiency. It is relatively straightforward to make the HTR a combined cycle generating plant by adding a steam generator and turbine system to the secondary loop gas-turbine system. This is provided for in conventional natural gas-fired Combined Cycle Gas-Turbines where this technology is well established. This provides the potential to push the plant efficiency above what is normally expected from high temperature gas-cooled reactors and to reduce the cost of the generated electrical power.

The selection of a reduced reactor inlet temperature entails several advantages. The temperatures seen by the reactor vessel are lower. With reduced inlet temperature, the flow rate and circulator power are lower and a reduction in the primary pressure becomes practical as a trade-off. The lower system pressure translates to a reduced vessel wall thickness, which has significant fabrication and cost advantages. In addition, the thermal energy stored in the core is reduced, thus enhancing passive decay heat removal during certain transients.

In conclusion, it appears that the best technological solution to convert the thermal output of the HTR into electric power or heat is to use a combined cycle or cogeneration plant, making use of two sub-systems, a topping $He + N_2$ gas turbine cycle working between about 800 °C and 320 °C and a bottoming water vapor cycle.

However, the thermal integration of such a cycle is quite difficult: it supposes to minimize internal irreversibilities between first the nuclear core thermal fluid and the topping cycle thermodynamic fluid, and second the gas turbine heat rejection and the water vapor cycle. The thermal integration method presented below allows to do that, leading, in combined cycle, to an overall gross efficiency slightly higher than 50%.

As we have mentioned, the heat exchangers (HEX) network design must be made under several industrial constraints. Therefore the thermal integration method employed must be able to take them into account, as they reduce the parameters' space to be explored. We shall show how each constraint is introduced and how it affects the resulting HEX network.

## 3. What do we mean by design optimization

There is currently a large amount of studies dedicated to the optimization of energy cogeneration plants, but to our knowledge very few have been addressing that of cogeneration plants coupled to nuclear reactors.

We do not intend to make a comprehensive review of the optimization methods which are used: most of them start from a given plant structure and try to find an optimal set of parameters whereas the one we have selected makes but a few assumptions on that structure.

Some of the methods, in particular those which are part of what is known as thermoeconomy, try to optimize not only the technical ratings, but also the economic costs [2–5]. In our case, such an attempt is premature: as was already discussed in the previous section, the industrial constraints taken into account have indeed a bearing on numerous parameters, such as the possibility to adapt existing technology. At this stage, although these constraints reflect some cost driven considerations, it would be quite impossible to include them in an economic model.

Besides, more and more, optimization models try to include not only full load by also part load operation in order to take profit of the hourly variation of energy prices in a deregulated market [6]. Here we have also deemed it premature to specify the load curves and economic costs which would have been necessary to implement such optimization methods.

This is why the method that was selected by the industrialist limits itself to the choice, under some given industrial constraints, of the structure and the selection of the best set of parameters from a thermodynamical standpoint. The application of a thermoeconomic method to this structure in order to optimize its costs could be considered as a further step in the design process.

## 4. Thermal integration method

Most energy conversion technologies can be described by a relatively small number of primitive types which can be calculated independently, except for heat exchangers. This is why a thermal integration method putting a special emphasis on heat exchanger networks is particularly required. The method implemented in Thermoptim is a variant of Linnhoff's pinch method [7] which allows to distinguish between systemic and component irreversibilities. As it is common in heat recovery problems that a single main hot fluid should be exchanging heat with several cold fluids, the method assists the user in the heat exchanger design and fluid matching.

The method has been initially developed in the field of chemical engineering, where it is called process integration, with a view to optimize large heat exchanger networks. Although they obviously must interface with the process simulation tools, such methods are usually separated from them. In the field of energy conversion however, finding an optimum solution often requires to simultaneously modify the system architecture and the component parameters. An integrated environment where the simulation functions and the integration method are deeply interconnected is therefore recommended, especially in an industrial context.

Complex energy systems can bring into play a rather large number of fluids which exchange heat between them, some being heated, the others being cooled. The pairing of these fluids can generally be made in many different manners, and the choice of the best architecture may be far from intuitive. However this choice has a direct incidence on the internal irreversibilities of the system considered and thus on its efficiency: it is by maximizing internal regeneration that one obtains the best performances.

To find an efficient heat exchanger configuration, thermal integration appears today among the most powerful methods, and has in particular the advantage of providing guidance which reinforce the physical direction of the analyst whereas the purely automatic methods do not.

But their principal asset is as follows: it is only after having minimized the exergy destruction of the studied system that one defines the exchanger network architecture. To optimize heat transfer, knowing which fluids are brought into play is sufficient, it is not necessary to make a priori assumptions on how they are paired. This last characteristic is fundamental; it considerably simplifies the thermal integration process, as one will further see.

On the practical level, the implementation of the method can be broken up into two main steps.

The first step consists in describing the system without making a priori assumptions on pairings among the exchangers (one speaks of nonconstrained system), and seeking to maximize the energy recovered (operating capacity, cogenerated power ...) by making sure, thanks to the thermal integration algorithms, that there is no temperature incompatibility. The iterative procedure consists in varying the key parameters of the system (flows, temperatures, pressures) and optimizing their performances, while checking by the pinch method that one does not introduce additional high temperature heat needs and that one minimizes the rejections at low temperature. The distinction between the component irreversibilities (specific of their own operation) and the systemic irreversibilities (related to the architecture of the system) makes it possible to know the available degrees of freedom. It is during this phase that iterations between the people in charge of optimization and those who design the processes take place. One of the interests of the method is that constantly, it is possible to have an idea of the stakes associated with optimization and the limits which one can reach, in particular thanks to the traditional graphic tools of thermal integration [7], as well as the Carnot Factor Difference Curve [8,9], well adapted to this type of problems.

The second step, once the system irreversibilities have been minimized, consists in seeking a compatible configuration of heat exchangers, the thermal integration method guarantees that there is one. This is done by pairing the existing fluid flows judiciously and by dividing (in series or parallel) those which must be. One gradually defines the network, by carrying out the pairing of the fluids starting from the most constrained zones, the pinches. During this step, it may happen that technological or economic constraints require to choose an exchanger network configuration different from that which would make it possible to reach the optimal performances.

The theoretical bases on which it is founded call upon the theory of exergy and irreversibilities. The reader should refer to the papers given in reference [7–12]. We will just recall here the expression of the exergy dissipation flow that is used to draw exergy balances like in Tables 1 and 2:

$$\Delta X_{hi} = \tau - \Delta X_h + \Delta X_q \tag{1}$$

For internal heat exchanges for regeneration, the exergy dissipation flow of two paired HEX is given by:

$$\Delta X_{hi} = \Delta X_h^1 + \Delta X_h^2 \tag{2}$$

This optimization method is dedicated to complex systems with a large number of heat exchanges, the overall behavior of the system being governed by nonlinear functions of the design parameters. Typically, a heat recovery steam generator (HRSG) such as those used to generate steam in combined cycles is a good example of a complex system for which an efficient layout can be systematically designed thanks to this method. In a HRSG, steam is produced at 2 to 4 pressure levels, which can be freely chosen within certain limits. The steam properties are strongly nonlinear functions of temperature and pressure, the steam flow rates may vary depending on the operating conditions, and the heat exchangers matching possibilities are numerous. Furthermore, whereas classical boilers are stack controlled and therefore do not require in depth optimization, combined cycle HRSGs are pinch controlled, so that designing an efficient HEX network requires to take into account at the same time the steam cycle and the heat exchange with the flue gas.

Table 1
Exergy balance of the combined cycle

| Processes | $\Delta H$ | $\Delta X_h$ | $\tau$ | $Q$ | $T_k$ | $\Delta X_q$ | $\Delta X_{hi}$ | % losses |
|---|---|---|---|---|---|---|---|---|
| IHX | 600 005 | 382 677 | | 600 005 | 1123 | 446 070 | 63 394 | 31.0% |
| Gas turbine and compressor | −76 619 | −88 624 | −76 619 | | | | 12 005 | 5.9% |
| HEX Gas-Steam | 523 385 | 262 060 | | 523 385 | | | 95 082 | 46.5% |
| Steam turbine and pump | −228 085 | −247 423 | −228 085 | | | | 19 338 | 9.5% |
| Condenser | −295 306 | −14 637 | | −295 306 | 288 | 0 | 14 637 | 7.2% |
| Total | | | −304 705 | 304 699 | | 446 070 | 204 455 | 100% |
| Mechanical Energy efficiency (%) | | | 50.78 | | | | | |
| Total Energy efficiency (%) | | | 50.78 | | | | | |
| Exergy efficiency (%) | | | 54.17 | | | | | |

Table 2
Exergy balance of the cogeneration and combined cycle

| Processes | $\Delta H$ | $\Delta X_h$ | $\tau$ | $Q$ | $T_k$ | $\Delta X_q$ | $\Delta X_{hi}$ | % losses |
|---|---|---|---|---|---|---|---|---|
| IHX | 600 000 | 382 775 | | 600 000 | 1123 | 446 066 | 63 292 | 48.5 % |
| Gas turbine and compressor | −76 551 | −88 584 | −76 551 | | | | 12 033 | 9.2% |
| HEX Gas-Steam | 523 448 | 262 193 | | 523 448 | | | 31 998 | 24.5% |
| HEX Steam-Cogen | 298 502 | 139 512 | | 298 502 | | | 8442 | 6.5% |
| Steam turbine and pump | −98 027 | −106 340 | −98 027 | | | | 8313 | 6.4% |
| Condenser | −126 920 | −6291 | | −126 920 | 288 | 0 | 6291 | 4.8% |
| Cogeneration pump | 1498 | 1426 | 1498 | | | | 73 | 0.1% |
| Total | | | −173 080 | | | 446 066 | 130 441 | 100% |
| Mechanical Energy efficiency (%) | | | 28.85 | | | | | |
| Total Energy efficiency (%) | | | 78.85 | | | | | |
| Exergy efficiency (%) | | | 70.76 | | | | | |

## 5. Dealing with industrial constraints

As was explained before, the design method adopted by Framatome-ANP is to study new HTR thermodynamic cycles with high efficiency using conventional technology (air and steam turbines). Besides, to control costs, the designed cycles must use standard components (turbines, compressors, pumps) with standard outlet and inlet pressure and temperature levels.

These are far reaching choices as they set or restrain a lot of parameters, and limit the set of possible layouts for the system. Among the set parameters are:

- the gas composition, with a nitrogen content close to air,
- the steam cycle (Rankine), a classical cycle is chosen,
- the isentropic efficiencies of turbines, compressors and pumps, as conventional technology is used,
- the main temperatures and pressures defining the gas and steam cycles (turbines inlet and outlet, IHX inlet and outlet), because standard components are to be used or because it is desired not to modify the inlet and outlet temperatures of the nuclear reactor. Some of these parameters can vary slightly as far as they remain in the tuning range of the conventional components.

Furthermore, as different thermodynamic cycles are considered, gas cycle, combined cycle, combined and cogeneration cycle, it is an industrial requirement that they be compatible in order to reduce development costs and not to have to define a complete line of products with different levels of complexity, efficiency, and outputs (electricity, steam). This implies that the design of the combined cycle does not modify the IHX parameters, and that the design of the cogeneration and combined cycle does not modify the coupling between the gas and steam power cycle. Therefore the coupling of the cogeneration line is to be made with the steam cycle only and the branchings must be made between existing components (turbines, HEX, pumps). This reduces to a few the possible temperatures at which steam can be taken from the power cycle to produce cogeneration steam, the flow rates taken can however be chosen at will.

In designing the combined cycle, the problem is to find an efficient way to couple the gas and power steam cycles to realize the general layout sketched on Fig. 2 with the best possible efficiency. As we chose to use standard components and Rankine Cycle, we started the thermal integration process with the situation depicted on Fig. 3. The upper cycle is the gas cycle, the lower one being the power steam cycle. The two cycles are completely defined in terms of temperature and pressure levels, the problem is to divide the “GT ex” process in order to optimize heat transfer between the two cycles.

The first step of the procedure consists in balancing the enthalpy exchanges within the system. Once the gas flow rate $F_G$ has been set so that the power transferred in the IHX is equal to the nuclear one, for example 600 MWth, we then need to find by iterative tests the maximal steam flow rate $F_S$ that can be heated with the heat available from the gas flow rate after expansion. This will ensure that no other heat source is needed to power the steam cycle, but in general some low temperature gas heat will not be used and would have to be disposed of. This disposal clearly has a negative impact on efficiency as energy is going directly from the hot source to the cold sink and can be seen on Fig. 4 where the horizontal segment on the lower left represents the fictitious heat need added by Thermoptim to balance the heat availability.

It is the existence of the pinch point (see Fig. 4) that sets the upper limit on $F_S$. It is necessary to shift up slightly the hot composite curve in order to be able to enlarge the temperature difference at the pinch point and give a margin that will be used to raise $F_S$ up to the point where all the available enthalpy is transferred from the gas to the steam. Several parameters can be varied to this aim, and one has to take into account industrial constraints to make a choice. For example, we did not choose to raise the compressor inlet temperature because this is strongly limited by the maximum IHX inlet temperature requirement. Instead we chose to raise the low gas pressure. This may be acceptable within certain limits if this does not induce a modification of the gas turbine and compressor. By raising this pressure, the heating of the gas during compression will be less important and higher compressor inlet temperature are compatible with the maximum compressor inlet temperature requirement. Note that an adjustment of $F_G$ may be needed to maintain constant power in the IHX if its inlet temperature is modified. As less work is extracted from the gas during expansion, the gas is hotter at the outlet of the turbine also, therefore this low gas pressure modification shifts the whole hot compos-

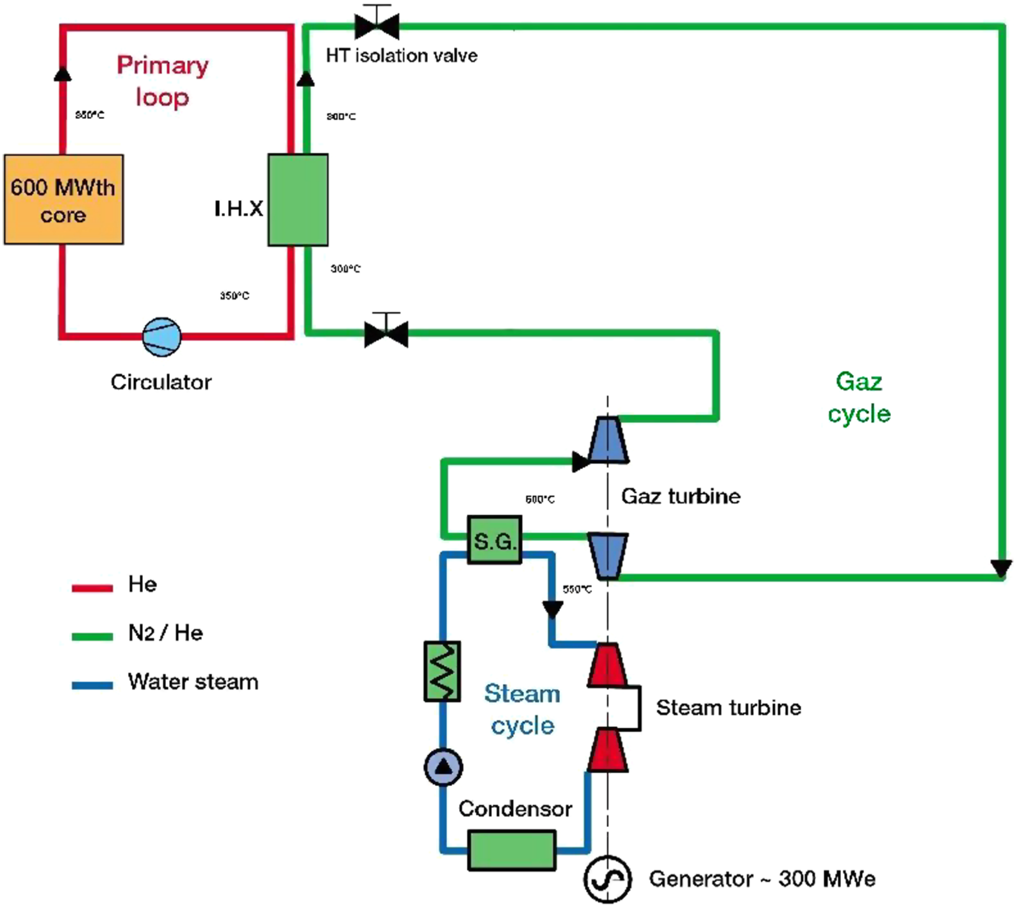
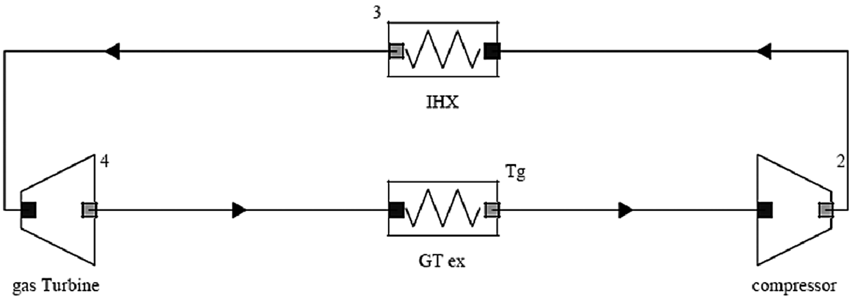


Fig. 2. Layout of the cycle.



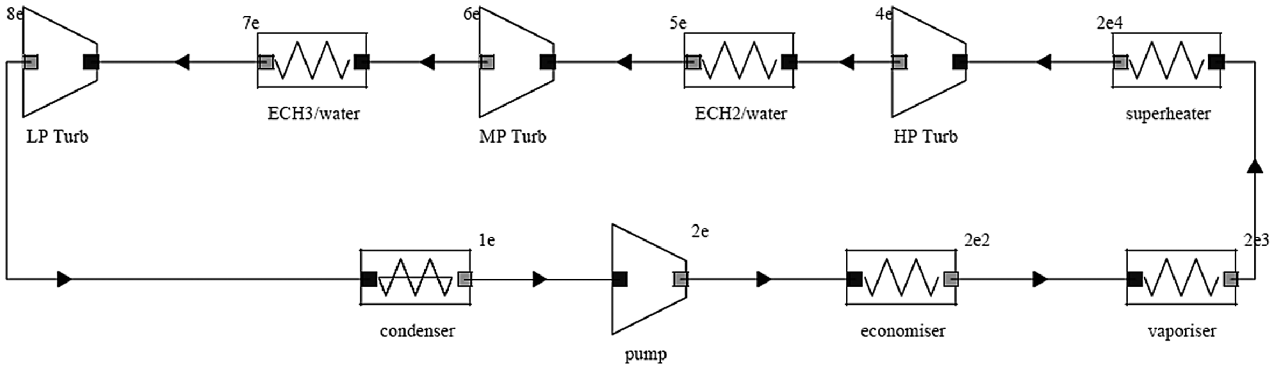


Fig. 3. Start of the optimization process.

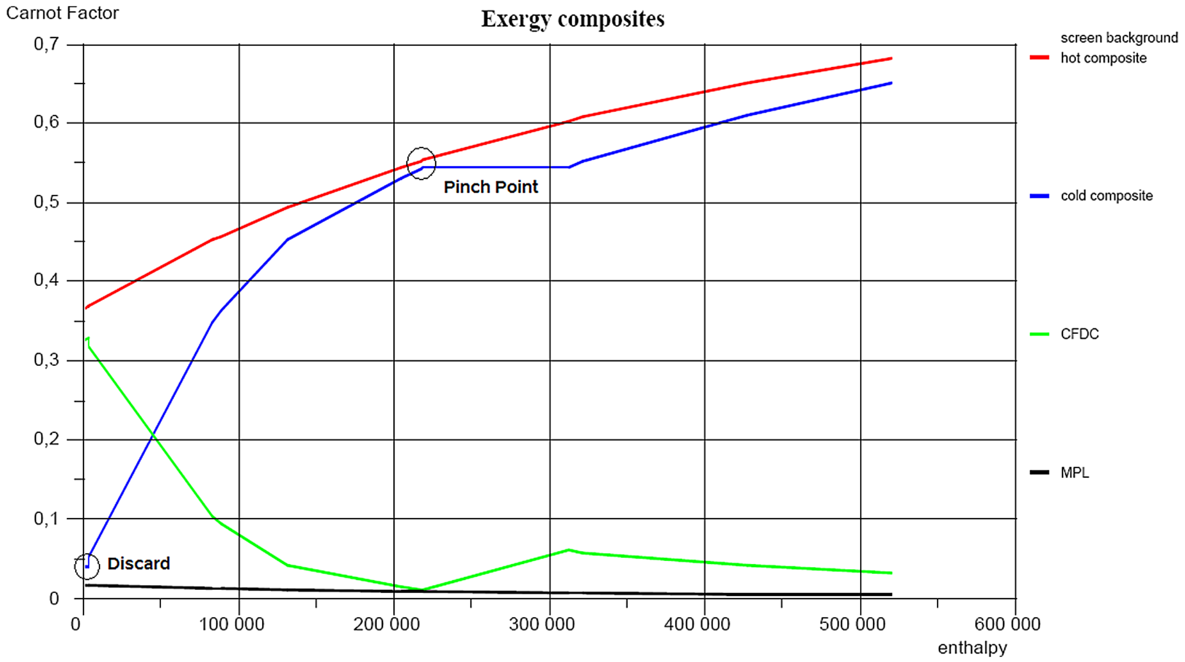


Fig. 4. Composite curves with enthalpy needs satisfied but with a wasteful discard.

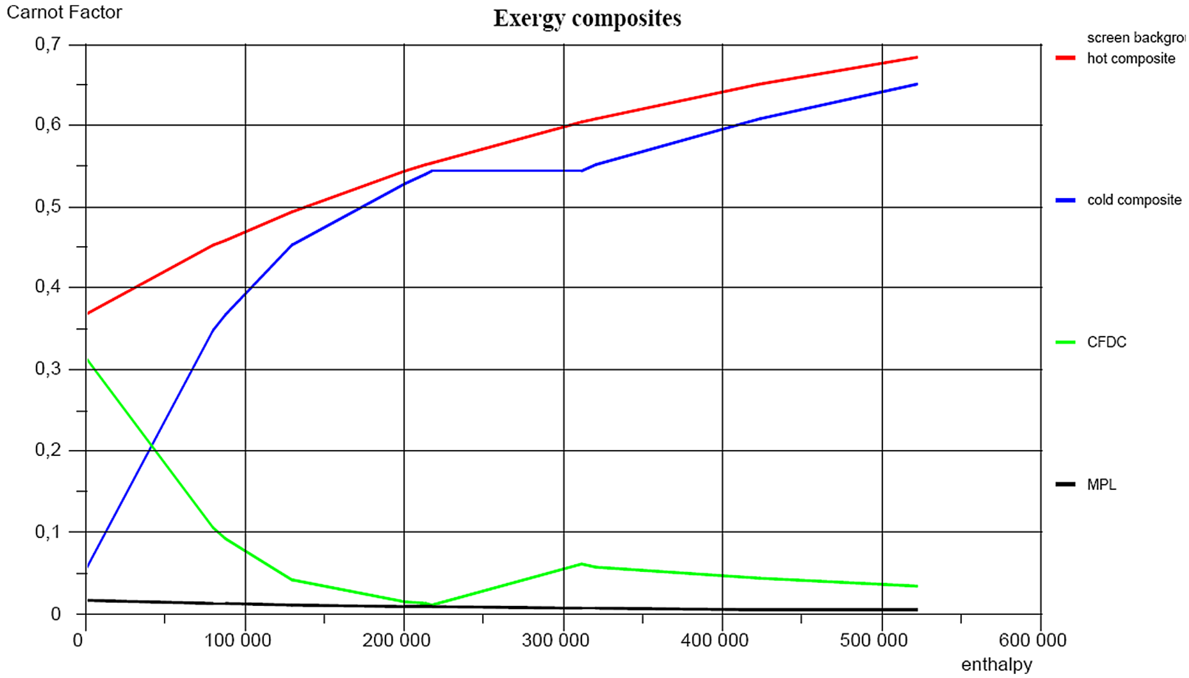


Fig. 5. Composite curves with satisfied needs and no discard.

ite curve upwards and allows for a raise of $F_S$. Fig. 5 gives an example of a completely balanced cycle.

Once the enthalpy balance has be obtained, the requirement for the highest possible efficiency has been addressed as the pinch is minimized and no enthalpy is wasted.

The design of the HEX network is done by studying first the pinch point zone [6, vol. 2, Chapter 12]. The pinch point is characterized by the following conditions [6]:

$$\sum \dot{m} C_p^h \geqslant \sum \dot{m} C_p^c \quad \text{in the exothermic zone}$$
$$\sum \dot{m} C_p^h \leqslant \sum \dot{m} C_p^c \quad \text{in the endothermic zone}$$

so heat must be brought in the endothermic zone, and brought out only in the exothermic one. This rule will be violated if one process (or more) crosses the pinch. It happens that in our combined cycle some heat is taken from the endothermic zone, so we had to split the processes concerned in two, as indicated on Fig. 6, to prevent heat transfers through the pinch point. This

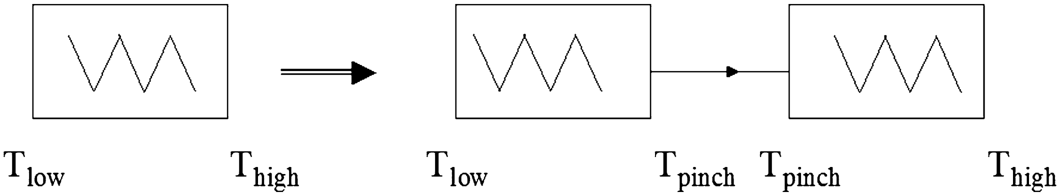


Fig. 6. Process splitting.

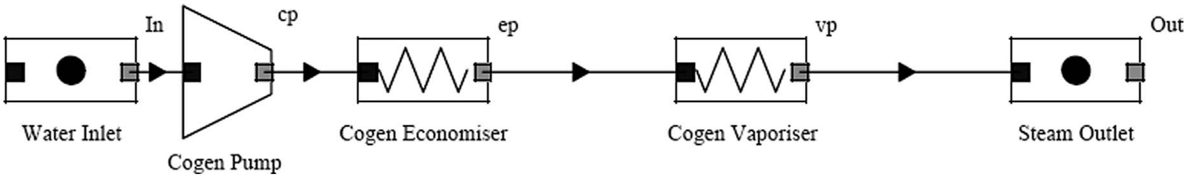


Fig. 7. Cogeneration part of the system.

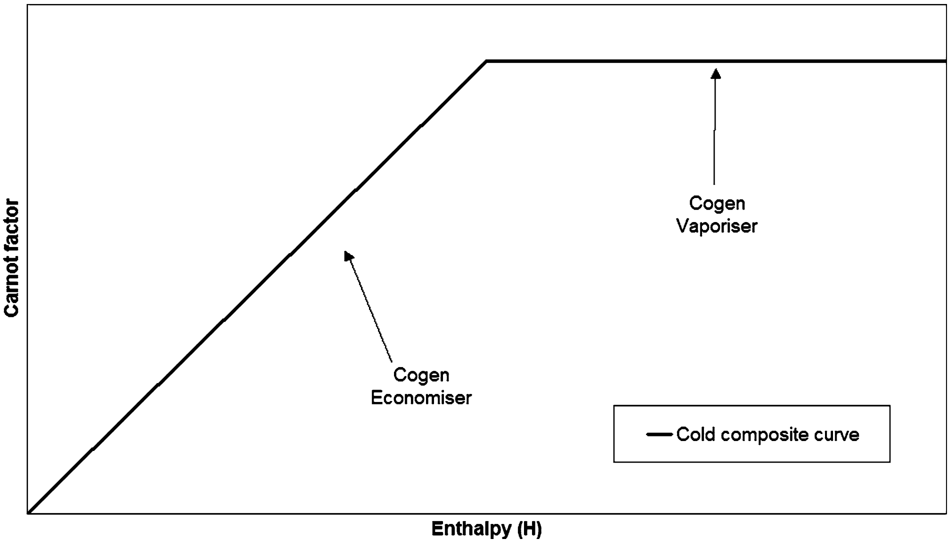


Fig. 8. Cold composite curve for cogeneration.

splitting allows to realize in practice the thermal integration obtained and shown on Fig. 5.

Let us now turn to the design of the combined and cogeneration cycle. As we mentioned earlier, we want to integrate the cogeneration line in the Combined cycle HEX network we just obtained, in order to satisfy some of the industrials constraints described above.

Let us first notice, as can be seen on Fig. 5, that huge system irreversibilities remain in the exothermic zone, for the combined cycle. To improve this situation, there is only one way: creating new low temperature needs. This can be done by adding a second steam cycle to the system, a low pressure one. This would certainly make the heat exchanger network more complex, but might be interesting in some cases. Another way of increasing the low temperature enthalpy needs can be to produce water steam in a cogeneration process. So the industrial objective of designing an HTR with an optional cogeneration line join up with improving efficiency.

Note that we can define for the combined and cogeneration cycle three kind of composite curves: global, cycle and cogeneration. The first ones are the composite curves of the whole system, taking into account all the fluids that are heating or cooling in the system (except the IHX and the condenser for which the enthalpy is to be taken from or given to an external body). The second ones are the composite curves obtained when the enthalpy needs and availabilities considered are only those involved in the processes located on the water and gas power cycle. The last kind of composite curves are those of the processes involved in the cogeneration only: those shown on Fig. 5, and those to be added on the vapor cycle where water will be cooled.

In our case, the cogeneration part of the system can be simulated as is presented on Fig. 7. A water pump compresses the water to the pressure corresponding to the desired saturation temperature. Then two HEX heat and vaporize the water flow. The water vapor production rate is given, therefore the additional enthalpy needs are entirely defined, that means the cogeneration cold composite curve too. Its shape is sketched on Fig. 8.

Recall that these needs are to be satisfied by taking the enthalpy on the power steam cycle, by withdrawing some steam or some water at certain points between components and putting it

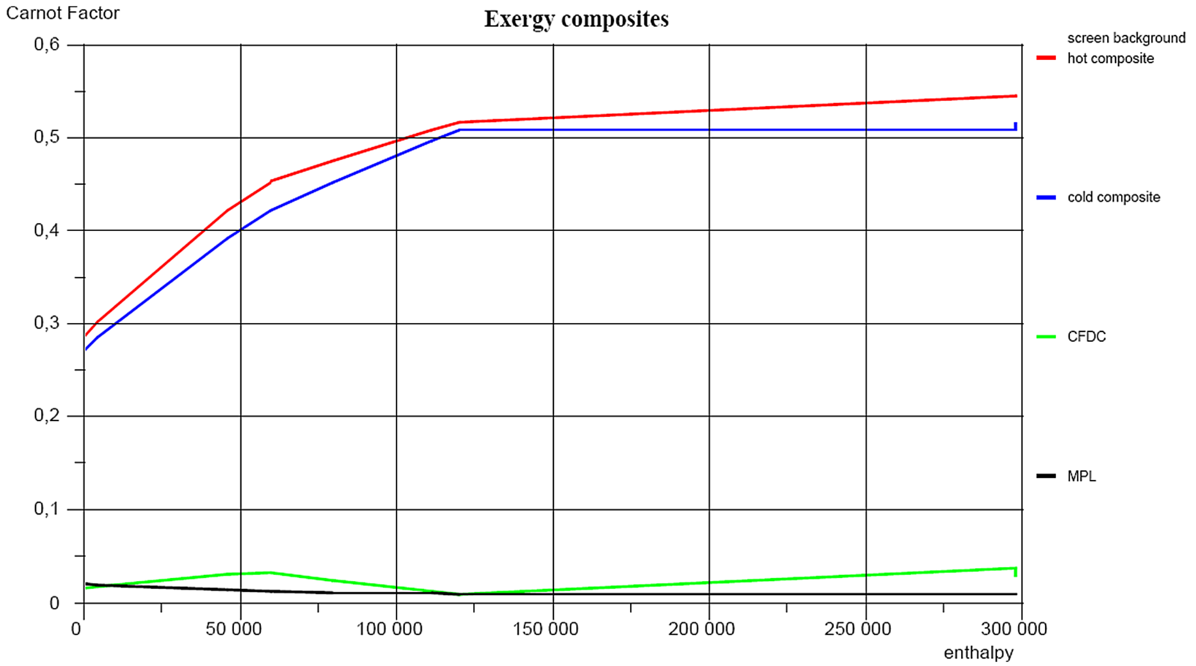


Fig. 9. Cogeneration composite curves.

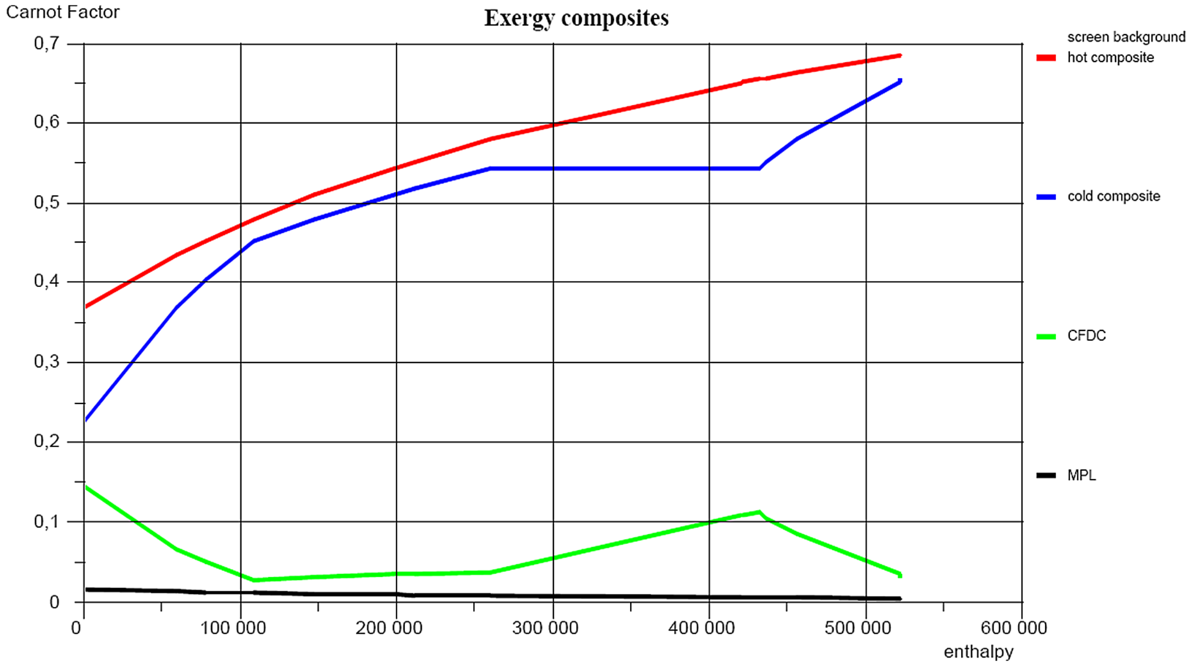


Fig. 10. Cycle composite curves.

back at others. This is the industrial constraint, which does leave free the choice of the flow rates withdrawn and the exact locations. In other words, this time the cogeneration hot composite curve is not predetermined but can be built to a large extent at will. Note that this is quite different from the combined cycle design where the two composite curves were predetermined and could only be slightly adjusted to match as well as possible.

The points where water is withdrawn from the power steam cycle are chosen so that the cogeneration hot composite curve parallels the cold one as much as can be. This defines the new components in the HEX network. The flow rates control the slopes of the cooling processes, so they are set by minimizing the surfaces between the cogeneration composite curves. Fig. 9 shows the hot cogeneration composite curves that could be built in our case compared to the cold one.

The main flow rate on the steam power cycle has to be reduced to balance the enthalpy flows in the whole system. As a result, we obtain a layout for the combined and cogeneration cycle, which has high efficiency. The composite curves of the combined cycle can then be sketched, see Fig. 10. The global composite curves (for the whole system) are shown on Fig. 11.

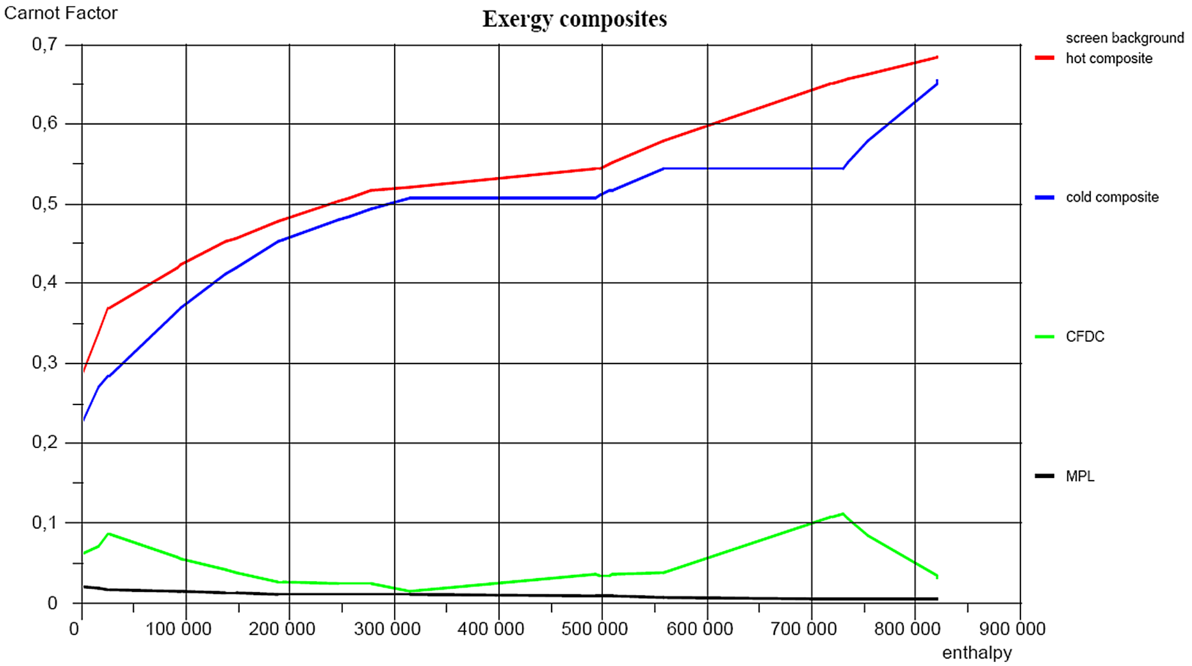


Fig. 11. Global composite curves.

The high level of efficiencies of these two layouts is reflected in the Exergy balances of the systems given in Tables 1 and 2, the environment temperature $T_0$ being set to 15 °C.

The overall irreversibilities for the combined and cogeneration cycles are the following: about 48% for the IHX, 24% for the heat exchanger network between the gas and steam cycles, 7% for the heat exchanger network between the steam cycle and the cogeneration line, 17% for the turbomachines, and 5% for the condenser. Those numbers confirm that irreversibilities associated to the heat transfer between the gas and steam cycles have been reduced in the second case. On the whole there are reduced, so the irreversibilities in the IHX grow relatively to the others.

Throughout this thermal integration procedure, the analysis of the composite curves and their respective positions has been the visual guide that oriented the design steps: it indicated which composite curve characteristics was to be improved. This is a valuable tool for discussing the possible degrees of freedom and the industrial constraints that might be reconsidered.

## 6. Conclusion

The thermal integration method used with the help of Thermoptim is a powerful tool to guide the designer through complex optimization processes. The graphical and intuitive help it gives is appreciable.

This method helps identifying the reasons why efficiency losses are made in the system, and leave it to the designer to choose the improving solutions. Then coupled to the Framatome-ANP approach that reduces the number of potential solutions to be explored it is a very efficient combination that enables high performance and readily constructible solutions to be systematically designed. It has been shown that this method is well suited to go back and forth between the industrial constraints and the thermodynamic optimization algorithms.

It must be noted that the solution obtained can be qualified as optimal, in the sense that as the physical sense of the designer was guided by the method, there are but a few chances that exists a far better solution with the given set of industrial constraints. It is also interesting to note that this optimal solution is built during the process. The approach is very different from others like the thermoeconomic one where one or several layouts are given and an optimization algorithm is applied to find the set of parameters that maximize a given criterion, say kWh cost. The use of the thermal integration or pinch method is somehow a preliminary step to the use of the thermoeconomic one: it is intended to design potentially interesting structures and settings for complex thermodynamic cycles, before cost studies may be undertaken with the thermoeconomic approach [13].

This article gives an example of the industrial application of the pinch method with the help of the Thermoptim software that takes care of all the computation burden. Without a software tool to carry out the exergy optimization procedure, this would be a very cumbersome task, and would deviate the focus of the designer from the solutions to improve the system. It is therefore important for such elaborated and powerful thermodynamical methods to be useful in the industry that be developed user-friendly operational software tools, gathering the scientific knowledge and making it easily applicable.

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