

Utilization of THERMOPTIM Optimization Method

Thermoptim optimization method is dedicated to complex systems where a large number of fluids exchange heat, the overall behaviour of the system being governed by non linear 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 which can be optimized 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 non linear functions of temperature and pressure, the steam flow rates may vary depending on the operating conditions, and the heat exchanger 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 their optimization requires to take into account at the same time the steam cycle and the heat exchange with the flue gas.

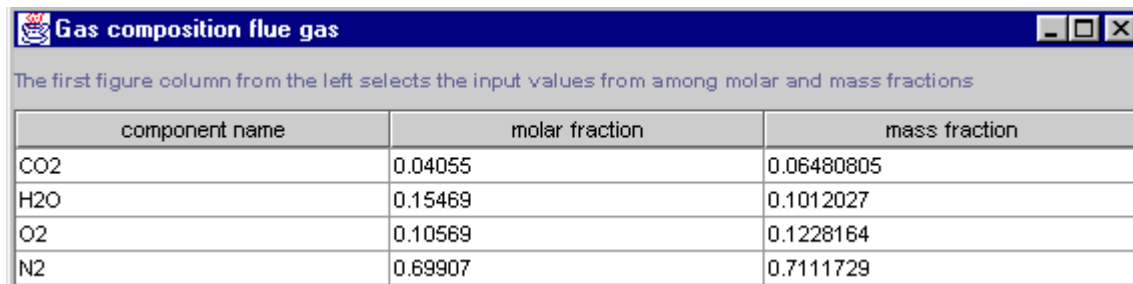
This is why we have chosen to illustrate the application of the optimization method by the design of a dual pressure HRSG.

Definition of the example problem

In this example, we only make use of part of the method, our main goal being to illustrate the use of the different screens which are related to optimization in THERMOPTIM: as the optimization may be made without using the Carnot Factor Difference Curve (CFDC), we restrict ourselves to the use of the temperature composite curves, much easier to understand, which happen to simply be temperature enthalpy diagrams in the case of the single pressure HRSG.

All elements which specifically pertain to optimization can be accessed to from a single frame: the optimization screen. It works in close conjunction with the main project screen, but is separate from it, mainly in order to avoid any confusion and to simplify THERMOPTIM's use for those who do not require the optimization tools.

The problem is the following : exhaust gases are exiting a gas turbine at the temperature of 500 °C (773.15 K), the mass flow rate being 100 kg/s. The gas composition is given below.



The first figure column from the left selects the input values from among molar and mass fractions

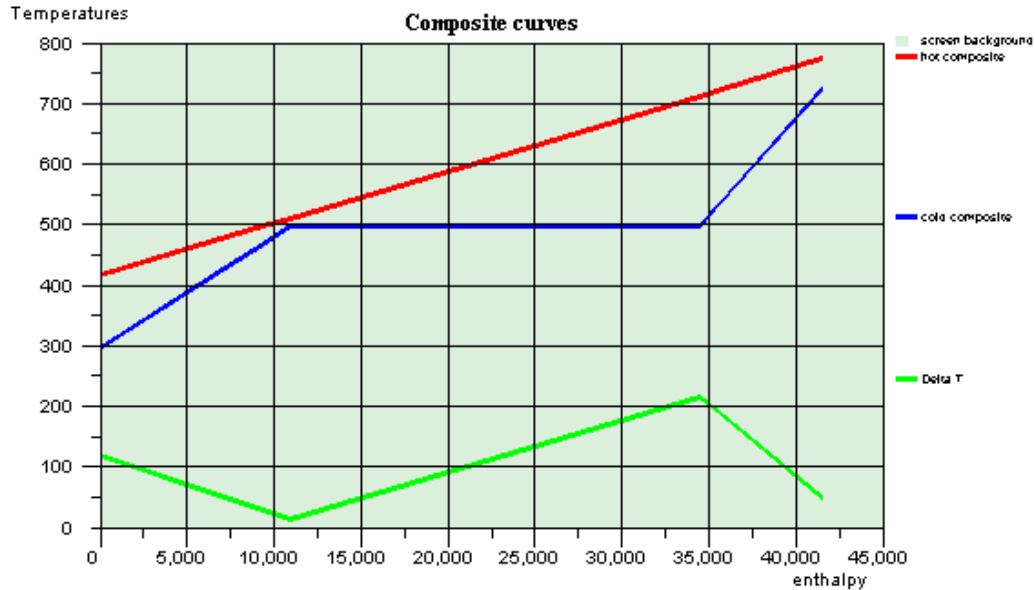
component name	molar fraction	mass fraction
CO2	0.04055	0.06480805
H2O	0.15469	0.1012027
O2	0.10569	0.1228164
N2	0.69907	0.7111729

Ones seeks to design a heat recovery steam generator (HRSG) capable of producing as much useful energy as possible in 0.85 isentropic efficiency turbine(s), the condensation pressure being set to 0.03 bar (24,1 °C). Single and dual pressure HRSGs are to be investigated. The maximum cycle temperature is 50 K below that of the flue gas, and the maximum cycle pressure is set to 100 bar. Pump isentropic efficiencies are equal to 0.95, and the low pressure superheating temperature is set to 548.15 K (275 °C). In this study, the cycle will be a simple reheat Rankine cycle, but the method can be used with much more complex ones. The minimum flue gas stack temperature is set to 76.85 °C (350 K).

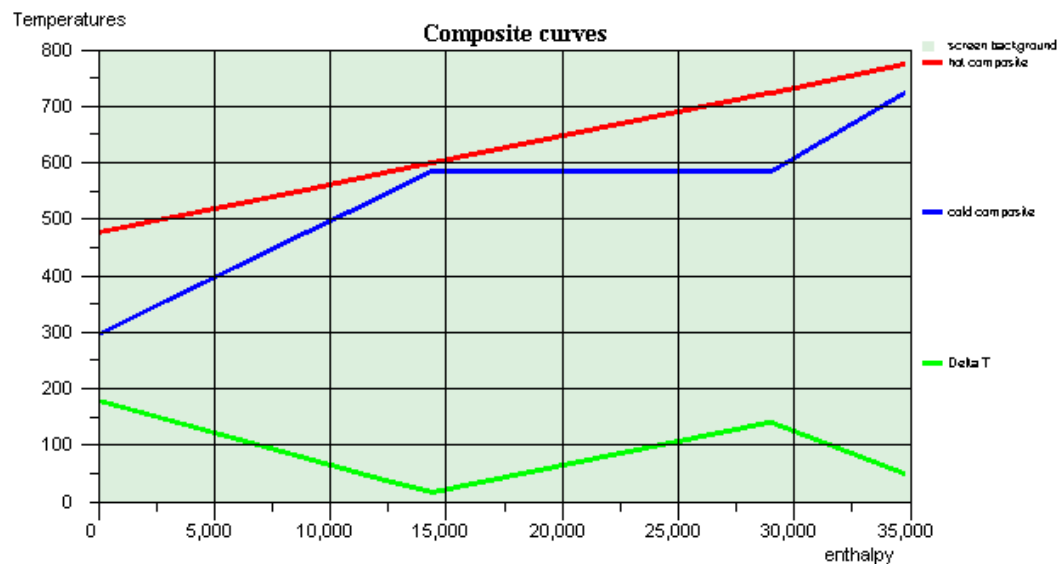
Single pressure HRSG

We shall start by defining a single pressure HRSG. This requires 2 points and an exchange process for the flue gases, and at least 6 points and 5 processes for the steam cycle (pump compression, economizer, evaporator, superheater and turbine). As we want to make the pressure vary, we declare pressure settings for the HP pressure at least.

Then, the problem is the following: when the pressure increases, the cycle efficiency gets higher, but on the other hand, as is shown on the charts below, the total amount of recoverable energy may decrease due to the existence of a minimum pinch value between the flue gas and the evaporator.



Optimum cycle enthalpy diagram (25 bar)



Non-optimum cycle (100 bar)

The problem is somewhat difficult, as there is not always an optimum: when the temperatures of the gases exiting the gas turbine increase, the higher the pressure, the better the efficiency. It is therefore necessary to try several pressures and to make the steam flow rate vary in order to find the best solution.

The criterion is the pinch method minimum target: for a given cycle pressure value, one seeks the maximum flow rate which does not require an additional heat input.

In practice, the procedure is the following:

- set the flue gas stack temperature to 350 K
- set up a simple steam cycle project with a pressure setting for the cycle pressure
- select all exchange fluids (the gas turbine flue gas, the economizer, the evaporator and the superheater) as pinch fluids with the appropriate minimum pinches (16 K for gases, 8 K for liquids, 6 K for the evaporator)
- select the autoflow checkbox
- make vary the pump flow rate ; as the other cycle processes are located downstream from it, their flow rates will be automatically updated

When the cycle is described and the different settings made, notify the cycle pressure and try a pump flow rate by calculating the pump process. A certain number of types are invalidated. Press the recalculate button several times until there are no more invalidated types.

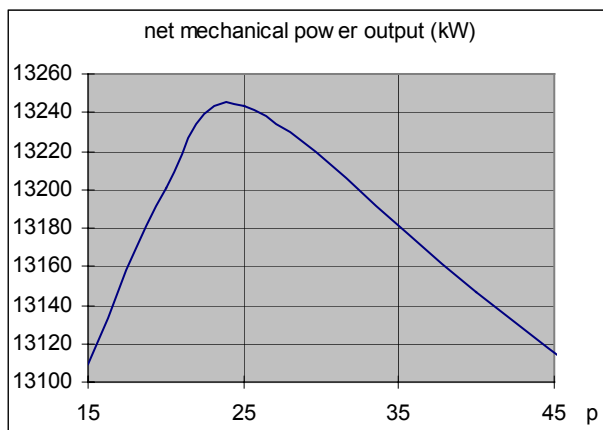
Go to the Optimization frame by pressing Control M or selecting the appropriate menu item.

In the optimization frame, select the menu item "Update and minimize target" or press Control U. If the flow rate is lower than the maximum limit, the tables are updated and no message appears. If the flow rate is too large there is a need for a heat input and a message informs you. In the first case, you may increase the flow rate. In the second case you must decrease it.

You can have a graphical display of the exergy composite curves by selecting the menu item "Plot the Carnot Factor curves" of the "Charts" menu. This will give you a hint on how far you are from the flow rate limit.

Go back then to the pump screen, modify the flow rate value, calculate the process, and iterate until you find the maximum flow rate corresponding to the selected pressure.

In this case, trying several pressures shows that there is an optimum pressure value of 25 bar:



At the optimum, the useful power generated is equal to 13,243 kW, with a 32% steam cycle efficiency, while there is a need for extracting 7,343 kW of heat, which means that all the available enthalpy is not recovered. The steam flow rate is equal to 12.78 kg/s.

The temperature enthalpy diagram shows the existence of a pinch point around 500 K. It is impossible to extract all the flue gas heat with a single pressure steam cycle because the problem is pinch-controlled.

Dual pressure HRSG

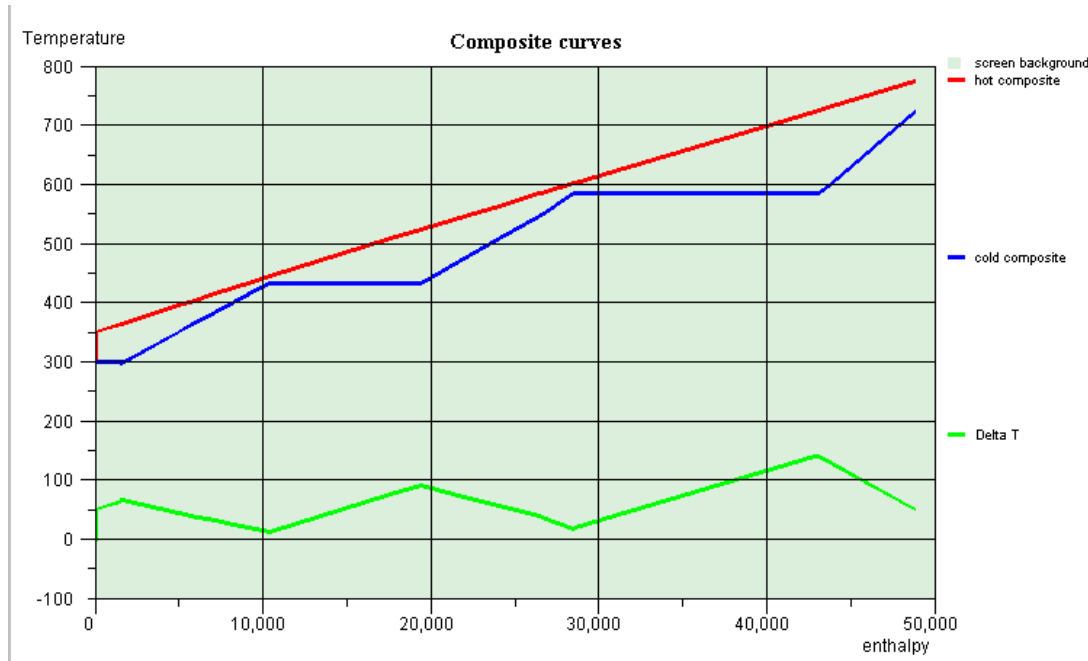
In order to improve the heat recovery efficiency, we introduce a second cycle at lower pressure, by adding new points and processes. Now it is worthwhile to set the HP pressure at its maximum value, 100 bar and to set the HP flow rate so that the HP pinch gets its minimum value (11.1 kg/s). We then have to make the LP pressure and flow rate vary in order to maximize the recovered enthalpy.

The procedure is the same as that used before. After a few trials, it appears that a pressure of 2.62 bar and a flow rate of 4.82 kg/s allow one to cool the exhaust gases down to the minimum limit set: 350 K.

The net power output is 15,552 kW, which corresponds to a 17.4% increase as compared to the single pressure HRSG, the steam cycle efficiency being a little lower than the previous one (31.8%).

Now we have maximized the enthalpy recovered, but not the exergy. If we slightly increase the LP pressure and calculate the maximum LP flow rate setting the LP pinch at its lowest value, we increase the power output while some enthalpy remains available at low temperature. Varying the pressure between 2.62 bar and 8 bar shows that there is an optimum at a 4 bar pressure and a 4,305 kg/s flow rate. The net power output is 15,427 kW and the available enthalpy is 1,330 kW.

The composite curves are given below:



Two pinch points can be seen, one just below 580 K (310 °C) and the second one around 420 K (148 °C).

The charts shown above can be printed. When you print one, ThermoOptim gives you the opportunity to add a comment which appears in the headband above the curves.

Fluid matching in heat exchangers

As the maximum number of constraints for fluid matching in heat exchangers is located around pinches, one must analyze the intervals at their level, knowing that the thermal capacity flow rates of the fluids matched in each exchanger must comply with the following inequations (in absolute values):

- just above the pinch : $m C_{ph} < m C_{pc}$
- just below the pinch : $m C_{ph} > m C_{pc}$

The upper pinch (interval 4), is created by the appearance of the HP evaporator. At that level the existing fluids are the following:

- just above, the constraints are met if the HP evaporator is matched with the flue gas (the constraint writes $115.43 < 146,485$), the superheater being moved upstream (for the latter, the constraint writes $0 < 41.18$)

process name	mCp
GT exhaust	-115.43509393831...
EVHP vap	146485.5
SHHP1 vap	41.18514778566047

- just below, the constraint is also verified ($115,435 > 50.22$)

process name	mCp
GT exhaust	-115.43509393831...
ECOHP vap	50.2206905289782...

However a third fluid appears in the following interval: the LP superheater. We shall see later that, even if the pinch constraint is verified below the HP evaporator, it will be necessary to parallelize the LP superheater and the HP economizer.

Obviously the flue gas has to be divided in two parts, one above and one below the pinch. This will also be true for the lower pinch (interval 6), which is created by the appearance of the LP evaporator.

- above the pinch the following fluids exist:

process name	mCp
GT exhaust	-115.43509393831...
ECOHP vap	50.2206905289782...
EVLP vap	104997.299999999...
SHLP vap	9.953799724569357

As previously, the constraints can be met by matching the evaporator with the flue gas at that level ($115.435 < 104,997$) and moving the other exchangers upstream ($0 < 50.22$, and $0 < 9.95$).

- below the pinch, the situation is as follows:

process name	mCp
GT exhaust	-115.43509393831...
ECOHP vap	50.2206905289782...
ECOLP	20.2697511424947...

The LP evaporator and superheater have disappeared, replaced by the LP economizer. Here the thermal capacity flow rate constraints can only be met if the flue gas vein is split into two parts, as there is only one hot fluid and the constraints are that each cold fluid capacity flow rate must be lower than that of a hot fluid: the HP and LP economizers have to be parallelized.

Furthermore, the HP economizer crosses the pinch zone and must therefore be cut into two parts, which we will name ECOHP vap 1 and ECOHP vap 2.

You can see that this information has been directly obtained by analyzing the fluid distribution at pinch level. Knowing that, it becomes possible to start matching the fluids in heat exchangers. Using the heat exchanger blocks enables to do that progressively, without having to decide on the detailed placement of the heat exchangers in a first step.

As we have seen that the need for parallelization occurs only below the lower pinch point, and that other heat exchangers can be put in series, we will divide the HRSG in two main blocks. To do that, begin by creating two intermediate points, one inside the HP economizer and one inside the flue gas vein, and separate these two units into two parts. For the time being it is not necessary to know the exact temperature values of these points.

Go to the optimization screen and double-click in the headband of the heat exchanger blocks zone located at the upper right of the screen. The following screen appears:

It is similar to a node, the controls being of course different. Name it (for instance "block 1") and select the main vein by double clicking in the corresponding field. Choose "GT exhaust" from among the list of exchange processes proposed. Its inlet and outlet temperatures are displayed. Select then the different elements which have to be matched with the main vein, either by double-clicking in the headband of the table, or by clicking on the button named "add an element". Start by the HP superheater, and add all the steam cycle elements which are located above the lower pinch point. Set then the checkboxes located in the upper left part of the screen: "series", "upper constraint" as the upper temperature of the main vein is set (here the inlet one), and "active" to indicate that the block is selected. You obtain the following result:

process na...	n°	T inlet	T outlet	T main outlet	m main
SHHP1 vap	1	584.11	723.15		
EVHP vap	2	584.11	584.11		
ECOHP2 v...	3	401.5	584.11		
SHLP vap	4	401.23	548.15		
EVLP vap	5	401.23	401.23		

Now that the different fluids are selected, you can adjust the block enthalpy balance by clicking on the button named "adjust main process". Thermoptim calculates the total enthalpy corresponding to the different elements which have been selected and sets that of the main vein to that value. If the "upper constraint" is selected, the minimum temperature of the vein is modified (the outlet one for a hot fluid, and the inlet one for a cold one).

If the "lower constraint" is selected, this is done conversely. In this case, when you adjust the block, a problem arises concerning the LP superheater, whose temperature is too high for it to be put downstream from the second HP evaporator.

It is thus necessary to further divide the main vein in order to build a new parallelized block at that level. Finally, you end up with four blocks, two of which are parallelized:

- block 1 corresponds to the HP superheater and evaporator, which can be put either in series or in parallel. The outlet temperature of the main vein is set to 601.8 K. You can check the consistency of the series matching by clicking on the button named "test the block", so that the intermediate temperatures of the main vein be displayed in the table:

process na...	n°	T inlet	T outlet	T main outlet	m main
SHHP1 vap	1	584.11	723.15	725.69293...	100.0
EVHP vap	2	584.11	584.11	601.78225...	100.0

- in block 2 the HP economizer and LP superheater are parallelized:

process na...	n°	T inlet	T outlet	T main outlet	m main
ECOHP2 v...	3	401.5	584.11	506.07616...	86.864699...
SHLP vap	4	401.23	548.15	506.07616...	13.135300...

The calculation is made here with the assumption that the main vein flow rate is divided proportionally to the enthalpy variation in each element, and the corresponding flow rate of the main vein is displayed in the table: here 86.86 kg/s of flue gas will be matched with the HP economizer, and 13.14 kg/s with the LP economizer.

- block 3 includes only the LP evaporator:

process na...	n°	T inlet	T outlet	T main outlet	m main
EVLP vap	1	401.23	401.23	413.55555...	100.0

- and finally the LP and HP economizers are parallelized in block 4

block main process

parallel series active

upper constraint lower constraint compatible

T inlet T outlet

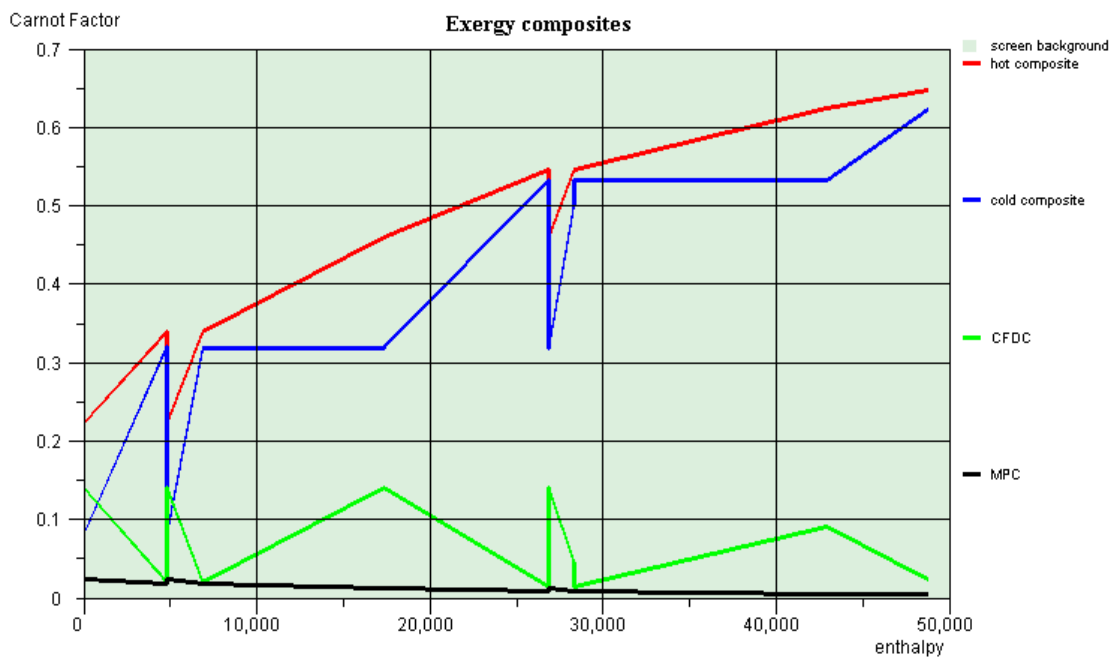
process name	n°	T inlet	T outlet	T main outlet	m main
ECOHP1 vap	1	297.57	401.5	351.18517876	69.78577...
ECOLP	2	297.3	401.23	351.18517876	30.21422...

element order

Once this matching is done, the main structure of the heat exchanger network is determined. It becomes possible to go into more details using the button named "divide main process" which builds up the various heat exchangers which appear in the block, either in series or in parallel, depending on the case.

It is also possible to come back to the systemic optimization phase after having set some of the heat exchangers. In our rather simple case this is however not particularly interesting.

For instance, you can plot the composite curves of the heat exchangers or of a mixture of set heat exchangers and pinch method composite curves by selecting the menu item "Plot the mixed HX-TI curves". The result you obtain is the following:



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