Guidance page for practical work: optimization of combined cycles by the pinch method

1) Objectives of the practical work

The objective of the practical work is to study the implementation of the pinch method for the optimization of combined cycle power plants and show how they can be realistically modeled with Thermoptim. To do this work, it is necessary to have access to the Professional or Industrial version of Thermoptim.

Its value is to guide you step by step in this process a bit difficult. It has two parts: the first (section 3) is a reminder of the pinch method and the second (section 4) is the practical implementation of this method.

2) References

LINNHOFF B. - Introduction to Pinch Technology. *Document web:* www.linnhoffmarch.com, copyright 1998 Linnhoff March

GICQUEL R. - Méthode d'optimisation systémique basée sur l'intégration thermique par extension de la méthode du pincement : application à la cogénération avec production de vapeur. *Revue Générale de Thermique,* tome 34, n° 406, octobre 1995.

GICQUEL R. – Energy systems: a New Approach to Engineering Thermodynamics, *CRC Press*, Boca Raton 2011.

3) Optimization by the pinch method

3.1 Basic principles

Heat integration is a rigorous and structured method for efficient use of available energy in a plant and thus energy consumption reduction.

It allows one to design an optimal network of exchangers in leading the designer to identify how to properly match the fluids in the system.

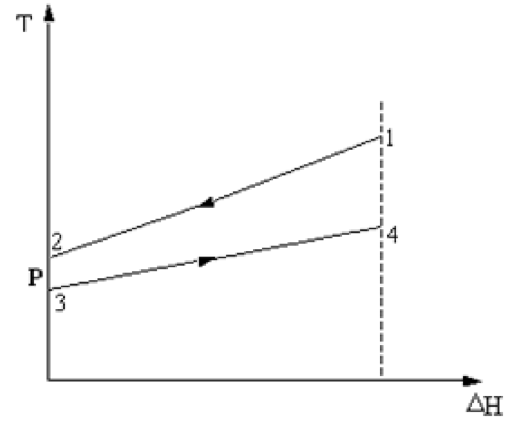


Figure 3.1

For a simple counter-flow heat exchanger in which flow two fluids exchanging heat, as work exchanged is zero, the enthalpy exchanged is equal to the amount of heat transferred and is given by relation:

$$Q = \Delta H = (\dot{m}c_p)_h(T_1 - T_2) = (\dot{m}c_p)_c(T_4 - T_3) \qquad (3\text{-}1)$$

The enthalpy-temperature diagram of the heat exchanger is shown in Figure 3.1.

In this figure, the minimum difference in temperature between the hot fluid and cold fluid is called pinch (**P**). According to the second law of thermodynamics, the exchange is only possible if the pinch is greater than zero. If it were zero, the heat exchanger should have an infinite surface.

The value of the pinch is chosen depending on the problem considered, i.e. the designer chooses its value:
- either it is set by considerations external to the optimization
- or it is chosen by experience, common values being 16 K pinch for gases, 8 K for liquids and 6 K for vaporization or condensation. However, these values may be changed as desired, for example in case a high performance heat exchangers made of special material is used.
- or is a parameter to vary in a systematic study to find the technical and economic optimum.

The sizing of the heat exchanger depends on the value chosen for the pinch. If it is too small, the surface of the heat exchanger increases and consequently the investment cost as well. If it is too large, there will be plenty of irreversibility, loss of performance eventually surpassing the investment savings.

In the case of a complex system where several exchanges between hot fluids and several cold fluids are performed, heat integration can determine the minimum amount of energy supplied by utilities but also find an appropriate exchanger network.

The fundamental principle of the approach is to meet the needs of each device by an appropriate source (from another part of the system or an external source).

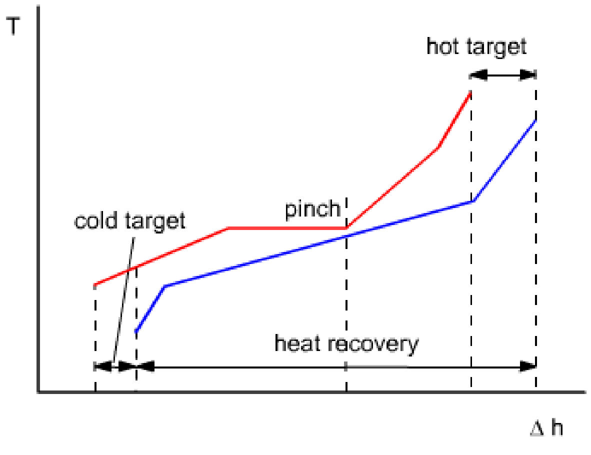


Figure 3.2

3.2 Composite curves

To obtain the required minimum energy, we use a tool called "composite curves." It is to draw in an enthalpy-temperature diagram the profile of energy availabilities (hot composite curve) and the profile of energy requirements (cold composite curve) based on temperature.

The construction of these curves is simple. They are built by combining, by level of temperature, enthalpy available in the hot fluid (respectively cold). We will detail the construction method a little later.

In an enthalpy-temperature diagram, we put the hot composite curve at the origin of the abscissa. It remains to calibrate the cold composite curve by translation along the horizontal axis so as to respect the value chosen for the pinch. That is to say that the minimum distance between the two curves at the nearest point on the axis of ordinates corresponds to the value of pinch used (Figure 3.2). The heat recovery area represents the area where heat is exchanged between hot fluids and cold fluids.

We would like to point out that the bounds of the composite curves are generally shifted, because these curves are placed according to the pinch. Qh is in fact a need for heating and Qc the complementary cooling need.

At this stage of optimization, the system is a priori unbalanced: there is both a need for energy at high temperature and a rejection at low temperatures.

Point position (P), where the temperature difference is minimal between the two curves indicates the location of the system where heat exchange is the most constrained. This separates the problem into two distinct areas: the exothermic area below the pinch and the endothermic area above the pinch.

In the exothermic area hot fluids contain more energy than cold fluids need. The hot fluids are cooled more slowly than cold fluids warm, and at this stage of the method there is usually a heat surplus Qc to be evacuated by an external cooling fluid, this zone behaving as a source heat.

In the endothermic when the available energy in the hot fluid is insufficient for the needs of cold fluids, so they cool faster than cold fluids warm up. A heat addition Qh is usually necessary, hence this area acts as a heat sink.

The existence of the pinch, shown in Figure 3.2, implies that the composite curves get closer below the pinch and deviate above the pinch. So the slope of the cold composite curve below the pinch is greater than that of the hot composite curve, ie:

$$\dot{m}c_{pc} < \dot{m}c_{ph} \tag{3-2}$$

Conversely above the pinch we get:

$$\dot{m}c_{ph} < \dot{m}c_{pc} \tag{3-3}$$

3.3 Definitions

We will introduce two definitions which we will use later in the document.

Hot utility

The utility is an additional hot heating Qh used to satisfy the need to heat the system at high temperature.

Cold utility

The cold utility is, by definition, an additional cooling fluid used to remove excess heat Qc from the system at low temperature.

Qh and Qc are to be met by appropriate utilities. In the case of a chemical process, it may not be necessary and/or possible to reduce these two quantities: the heat can be available or needed in another part of the plant. In contrast in a power generation system for example, it will be set to zero: you cannot imagine placing a heat backup next to a nuclear reactor or reject excess heat in a well .

3.4 Basic rules

The diagram in Figure 3.2, while being fairly simple to build, is very rich and allows us to give a few general rules for optimizing very large power generation systems:

1) Cancel the hot utility (Qh): In general, in thermodynamic systems such as combined cycles, to cancel Qh, simply adjust the steam flow-rate of the system.

2) Try to cancel the cold utility (Qc): How to cancel Qc depends strongly on the system studied. Depending on the latter, you can change either flow or pressure or temperature. Figure 3.3 shows a simple case where one changes the temperature of flue gas. The pinch method does not say what setting should be changed but it can clearly identify this problem which has to be resolved before proceeding further in the optimization.

3) heat should not be transferred across the pinch. Which consists of:

  3a) Avoid using a hot fluid above the pinch to heat a cold fluid below the pinch.
  3b) Avoid using a cold fluid below the pinch to cool a hot fluid above the pinch.

Indeed, in the case of Figure 3.4, we realize an energy saving by not using the heat that is above the pinch to heat a fluid below the pinch. Avoid taking heat in an area that already lacks some to heat a fluid in an area where there are already too many supplies.

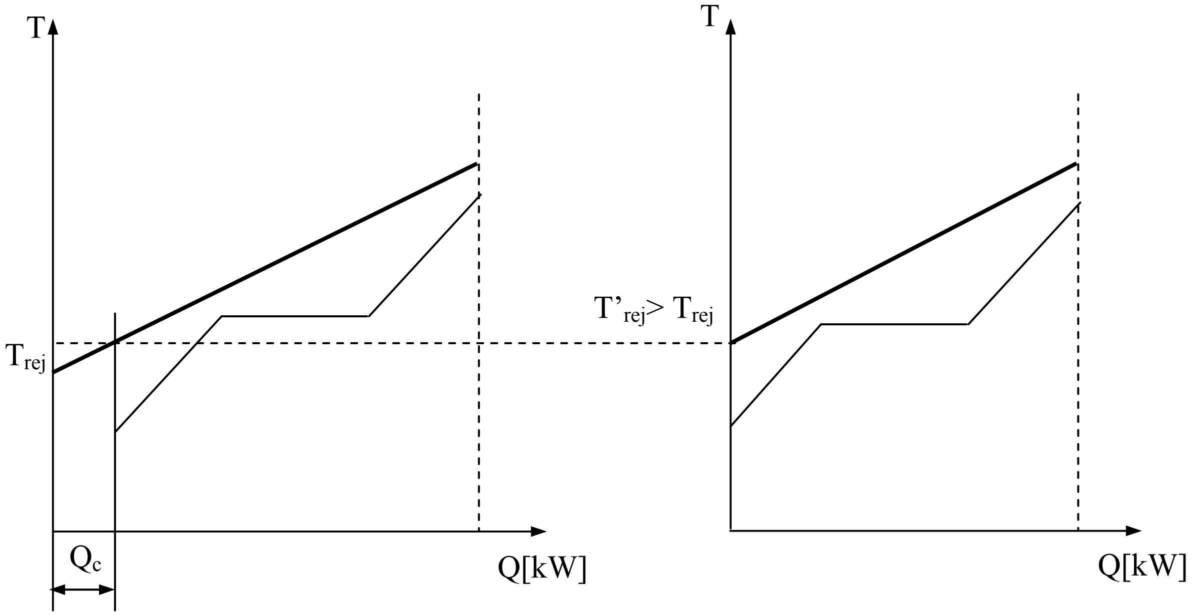
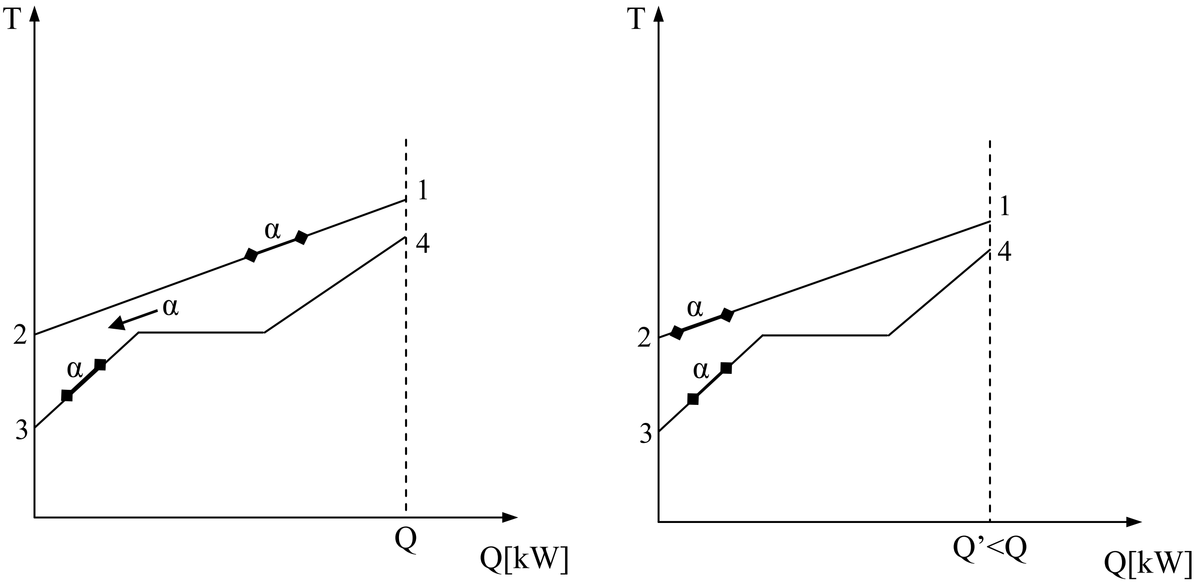


Figure 3.3



(a) (b)

Figure 3.4: Effect of a heat transfer through the pinch

3.5 Method of construction of composite curves

Let us return to the construction method of composite curves. Professor B. Linnhoff proposed an algorithm to determine algebraically the minimum energy consumption and location of the pinch between hot and cold fluids. To explain the method we will take an example from an article by B. Linnhoff. This case falls within the process engineering that is a bit more general than energy conversion because it is not necessary to cancel Qh and Qc.

The thermal data are represented in the following table:

Fluid		$\dot{m}.c_p[kW/K]$	$T_{inf}[°C]$	$T_{sup}[°C]$	$\Delta H[kW]$
N°	type				
1	cold	2	20	135	230
2	hot	3	170	60	-330
3	cold	4	80	140	240
4	hot	1.5	150	30	-180

Table 3.1

- After choosing the value of the pinch, the two curves are shifted so as to bring them closer to each other. The hot composite curve is offset by reducing it by $\frac{\Delta T_{pinc}}{2}$ and the cold composite curve is offset by increasing it by $\frac{\Delta T_{pinc}}{2}$. Choosing a value $\Delta T_{pinc} = 10K$, we obtain the following table with the temperature change:

Fluid		$\dot{m}.c_p[kW/K]$	$T_{inf}[°C]$	$T_{sup}[°C]$	$\Delta H[kW]$
N°	type				
1	cold	2	25	140	230
2	hot	3	165	55	-330
3	cold	4	85	145	240
4	hot	1.5	145	25	-180

***Table 3.2**: Values with shifted temperatures*

- We create the temperature intervals of shifted temperatures by sorting the temperatures from the higher to the lower.

- For each temperature range, locate the fluids involved in the calculation of enthalpy balances. Next, calculate the enthalpy balances of each temperature interval and their difference by checking whether the net balance of the interval results in a lack of energy or excess energy. They are determined by the following formulas:

Where $\sum(\dot{m}.c_p)_c$ and $\sum(\dot{m}.c_p)_h$ represent the sum of the cold and hot fluid heat capacity rates in the interval.

$\Delta \mathrm{Hnet}_i$ represents the net enthalpy balance of interval i.

For each interval, if $\Delta \mathrm{Hnet}_i$ is positive there is excess energy and if $\Delta \mathrm{Hnet}_i$ is negative there is a lack of energy.

$$\Delta T_i = T_i - T_{i+1} \tag{3-4}$$

$$\sum(\dot{m}.c_p)_i = \sum(\dot{m}.c_p)_c - \sum(\dot{m}.c_p)_h \tag{3-5}$$

$$\Delta \mathrm{Hnet}_i = \sum(\dot{m}.c_p)_i . \Delta T_i \tag{3-6}$$

In the case of the previous example we obtain the following table:

Table 3.3: Classification by temperature interval

Intervalle	T_i[°C]	T_{i+1}[°C]	fluides	ΔT_i[K]	$\sum(\dot{m}.c_p)_i$	$\Delta \mathrm{Hnet}_i$[kW]
1	165	145	« 2 »	20	-3	-60
2	145	140	« 2,3,4 »	5	-0.5	-2.5
3	140	85	« 2,3,1,4 »	55	1.5	82.5
4	85	55	« 2,1,4 »	30	-2.5	-75
5	55	25	« 1,4 »	30	0.5	15

For example, for interval 2, $\Delta \mathrm{Hnet}_2$ is negative, meaning that the hot fluids provide more energy than cold fluids need. So this excess energy can be used to heat a cold fluid in interval 3.

Surpluses and deficits of energy are transmitted from one interval to another to form a cascade of energy. This gives the following table:

Intervalle	T_i[°C]	$\Delta \mathrm{Hnet}_i$[kW]	cascade
	165		0
1		-60	
	145		60
2		-2.5	
	140		62.5
3		82.5	
	85		-20
4		-75	
	55		55
5		15	
	25		40

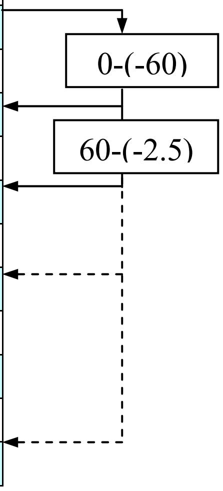


Table 3.4: Energy cascade

From Table 3.4, there is a gap between intervals 3 and 4, which must be compensated by an extra 20 kW. By adding the missing 20 kilowatts at the beginning of the cascade we get the table below:

Intervalle	T_i[°C]	$\Delta Hnet_i$[kW]	cascade
	165		20
1		-60	
	145		80
2		-2.5	
	140		82.5
3		82.5	
	85		0
4		-75	
	55		75
5		15	
	25		60

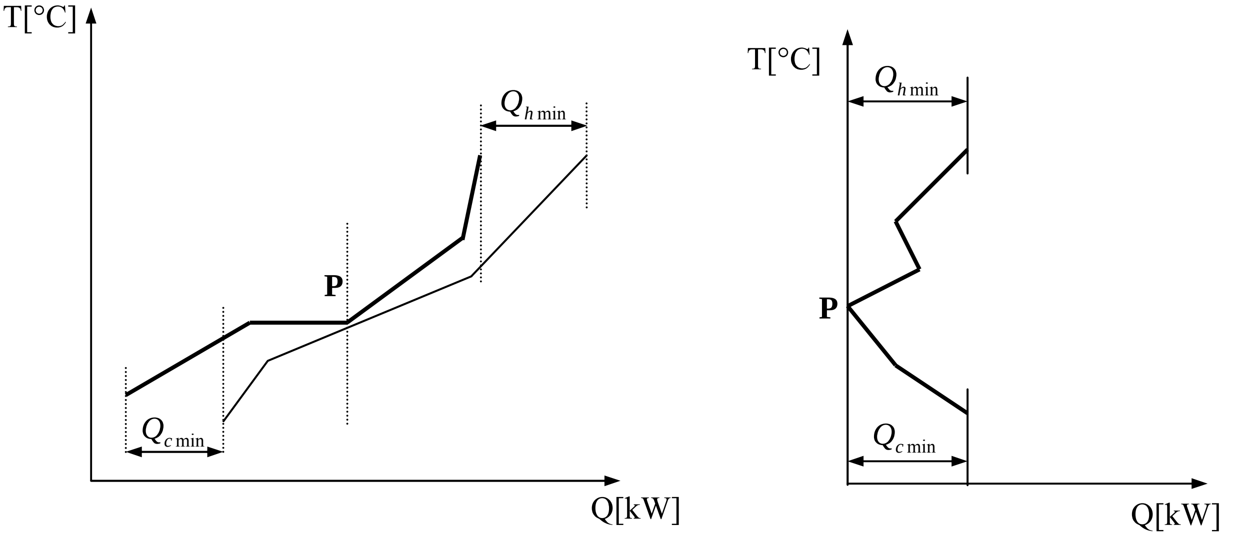
Table 3.5

The table shows that the flow of energy between intervals 3 and 4 is zero. This is the pinch of the system. It is located at 85 °C i.e. 90 °C for hot fluids and 80 °C for cold fluids when you take into account $\Delta T_{pinc} = 10K$.

The minimum hot utility need is equal to $Q_{c\,min} = 20kW$ and the minimum cold utility requirement equals $Q_{f\,min} = 60kW$.

In summary, the method we developed makes it easy to identify the location of the system pinch, and to determine the minimum energy needs to be provided by utilities.

3.6 Grand composite curve



(a) : composite curves C.C

(b) : Grand composite curve G.C.C

Figure 3.5: Diagrams of C.C and G.C.C in shifted temperatures

It represents the change in quantities of heat exchanged in each temperature interval and the energy to be supplied by utilities. In addition, the curve shows that there is no heat flow that passes through the pinch. In Figure 3.5 (b), the pinch is the intersection of the large composite curve with the y-axis T. It is built directly from the Linnhoff algorithm.

3.7 Exergy composite curves

The exergy composite curves are plotted in the same way as the composite curves, but replacing the temperature T by the Carnot factor $\theta = 1 - \frac{T_0}{T}$.

Consider Figure 3.6 showing the variation of Carnot factors for hot fluids θ_h (bold) and for cold fluids θ_c depending on the heat exchanged Q.

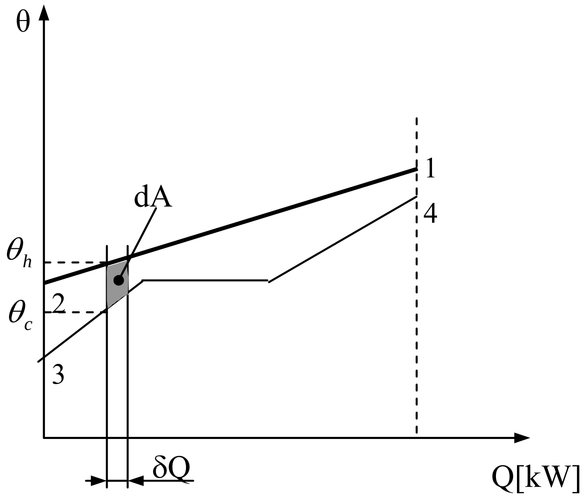


Figure 3.6: Diagram of exergy composite curves

From the figure, the surface element can be expressed by the following equation:

$$dA = (\theta_h - \theta_c).dQ = \left[\frac{1}{T_c} - \frac{1}{T_h}\right].T_0.dQ \qquad (3\text{-}7)$$

On the other hand, the total change of entropy is given by:

$$dS = \left[-\frac{1}{T_h} + \frac{1}{T_c}\right].dQ \qquad (3\text{-}8)$$

Comparing equations (3-7) and (3-8) we have:

$$\mathrm{dS.T_0} = \mathrm{dA} \qquad (3\text{-}9)$$

The latter relation shows that the surface element dA is proportional to the exergy destruction during the heat transfer. So the area between the two composite curves is proportional to irreversibilities in the heat exchanger.

To summarize this graph allows one to directly view irreversibilities within the system studied. Therefore, it indicates the area where we should focus our efforts if we are to improve system performance.

3.8 Basic optimization rule

The heat integration method makes it possible to highlight the irreversibilities by construction of the composite curves. The optimization is therefore to seek to minimize the area between these two curves by varying the key parameters of the system (flow, temperature and pressure) or by changing the overall system configuration.

The method is called graphic because it provides visual information which allows the designer to easily identify areas where there are many irreversibilities.

3.9 Heat exchanger network design

So far, we used the heat integration method to highlight the pinch and to determine the minimum energy to be supplied to the system. Once the system is optimized, we will proceed to the construction of heat exchangers.

This phase is to find the network of heat exchangers that can achieve the minimum energy consumption.

To design the network of heat exchangers corresponding to the configuration where the energy is minimal, we use a grid on which fluids are displayed (Figure 3.7). To illustrate this, we will take the process engineering case shown in figure below:

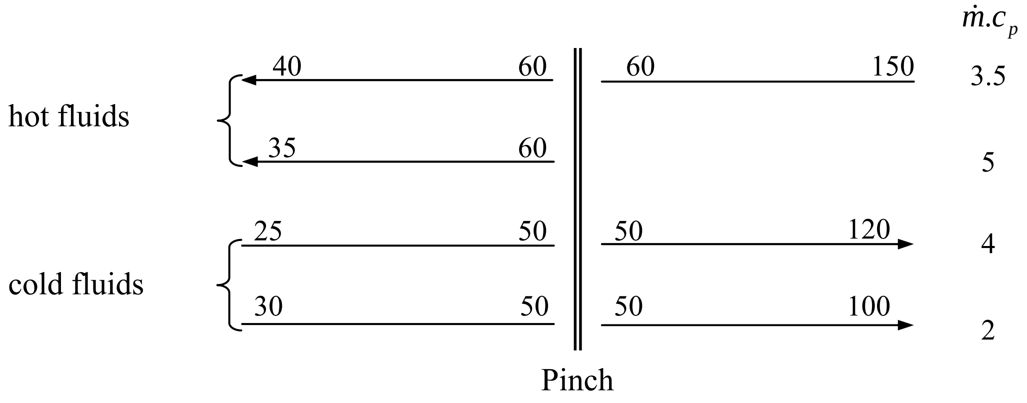


Figure 3.7: Grid of heat exchanger network

The fluids are represented by horizontal lines. The cold fluids are directed from left to right and the hot fluid from right to left. At the far right of the figure ($\dot{m}.c_p$) represents the heat capacity rate of each fluid. The pinch separates the system into two independent areas.

Here we must recall the basic rules to respect in order to minimize the hot energy to provide to the system, which are slightly different or a process than those used for energy systems:

- Do not transfer heat across the pinch.
- Do not use hot utility to warm a cold fluid below the pinch.
- Do not use cold utility to cool a hot fluid above the pinch.

We will now create the network of heat exchangers. As the pinch divides the system into two zones, heat exchangers above the pinch and below the pinch must be created separately. Furthermore, we must start construction at the pinch, and deviate gradually, allowing us to recognize important fluids in the most constrained area.

Figure 3.7 shows two hot fluids and two cold fluids below the pinch but there is only one hot fluid and two cold fluids above the pinch.

The second rule implies that the level of the interval located just above the pinch, the whole hot fluid must be cooled by the cold fluids, without any cold utility. To observe this rule, the number of cold fluids must be greater than or equal to the number of hot fluids to create the heat exchangers.

Similarly for the third rule, below the pinch, all cold fluids must be heated by hot fluids with no hot utility. That is to say that the number of hot fluids must be greater than or equal to the number of cold fluids (Figure 3.8 (a)). Heat exchangers are represented by vertical lines connecting two circles that form the matched pair of fluids (Figure 3.8).

In the case of Figure 3.8 (b) these rules are not complied with (number of hot fluids <number of cold fluids), in which case we will divide the hot fluid in two parallel veins.

(a) (b)

Figure 3.8: Pairing the streams at the pinch

Moreover, the figure below shows that to optimize the coupling of fluids in the case of an energy system condition $\dot{m}.c_{ph} \le \dot{m}.c_{pc}$ above the pinch (respectively $\dot{m}.c_{pc} \le \dot{m}.c_{ph}$ below the pinch), which is also true in general for the case of optimizing a process, must be verified exchanger by exchanger that is to say by pair of matched fluids.

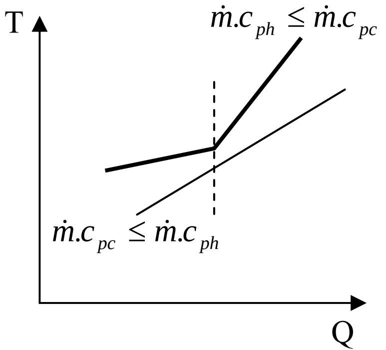
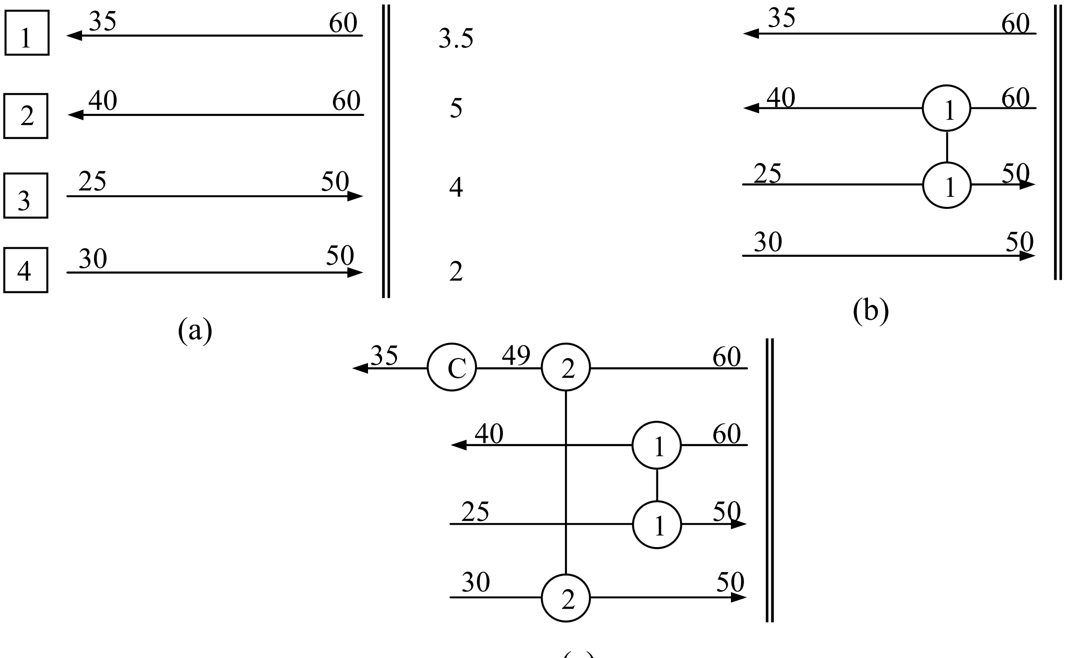


Figure 3.9

Using the example in Figure 3.7, the fluids that are below the pinch are shown in Figure 3.10 (a). From this figure, to respect the rules on heat capacity rates, fluids 2 and 3 must be matched, which creates heat exchanger 1 (Figure 3.10 (b)). Similarly, these rules are always checked when fluids 1 and 4 are matched, so we can create heat exchanger 2. Figure 3.10 (c) shows the exchanger network structure below the pinch. Note that the fluid 4 could not exhaust all the available heat in fluid 1, so that excess heat must be removed by a cold utility. Utilities are represented by a circle with a "C" if they are cold and a "H" if they are hot.



(a)

(b)

(c)

Figure 3.10: Exchanger network below the pinch

Figure 3.11 (a) shows the fluid above the pinch. There is only one hot fluid and two cold fluids. As the heat capacity rate of fluid 1 is greater than the heat capacity rate of fluid 4, only fluids 1 and 3 meet the constraint on capacity rates $\dot{m}.c_{ph} \le \dot{m}.c_{pc}$. We must create the heat exchanger 3 (Figure 3.11 (b)).

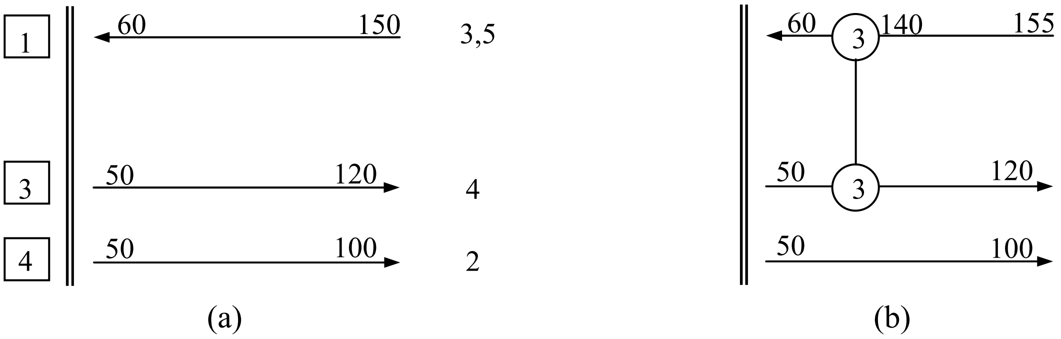


Figure 3.11: Beginning of the heat exchanger network

The rules on maximum heat only concern for heat exchangers "pinched", i.e. one of the bounds has a temperature difference equal to ΔT_{pinc}. Take for example the case of the figure below, the heat exchanger (a) is a "pinched" heat exchanger, but the heat exchanger (b) is not.

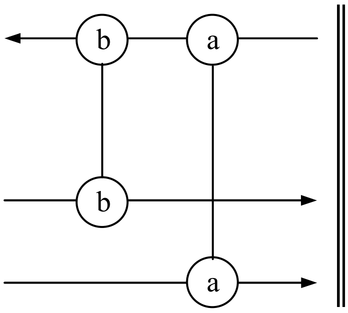
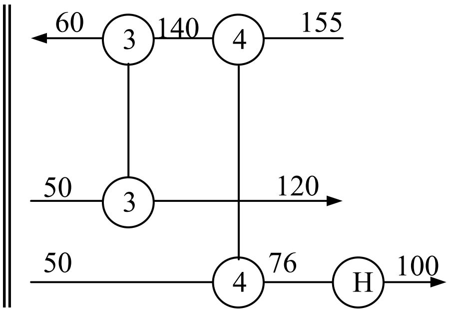


Figure 3.12

In our example, to exhaust all the heat available in fluid 1, heat exchanger 4 can be created even if it does not respect the rules on the flows as shown in Figure 3.11 (c).



(c)

Figure 3.11: Heat exchanger network above the pinch

The complete structure of the heat exchanger network is represented by figure 3.13.

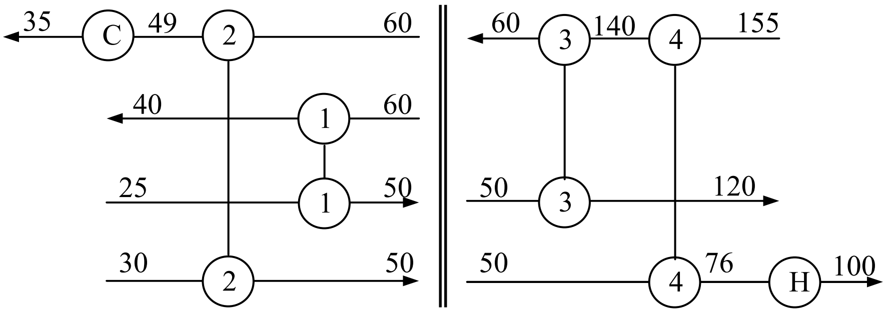


Figure 3.13 : Structure of the exchanger network

3.10 Conclusion

In conclusion, the optimization method we have presented is an effective method if you want to optimize a thermodynamic system in order to reduce energy consumption. This optimization step is done without knowing a priori the network configuration of heat exchangers. It is based on rules simple to express using the composite curves.

The method provides a graphical representation that allows direct visualization of the irreversibilities of the system studied. It does not give the optimal solution but it automatically guides the designer to identify areas to improve in order to reduce the irreversibilities.

After optimizing the system, heat integration also allows to build the network of heat exchangers, and thus to find a practical solution corresponding to the optimal point obtained.

In the rest of our work, we will apply this method to a heat recovery system on the exhaust gases of a gas turbine to provide heat to a steam cycle. As optimization tool, we will of course use the Thermoptim pinch method.

4 Application of the method with Thermoptim

4.1 Steps to follow

The application of the Thermoptim optimization method can be divided into two main steps:

1 - Describe the system without making a priori assumptions about the matches between heat exchangers, and reduce energy consumption for the best performance.

Procedure:

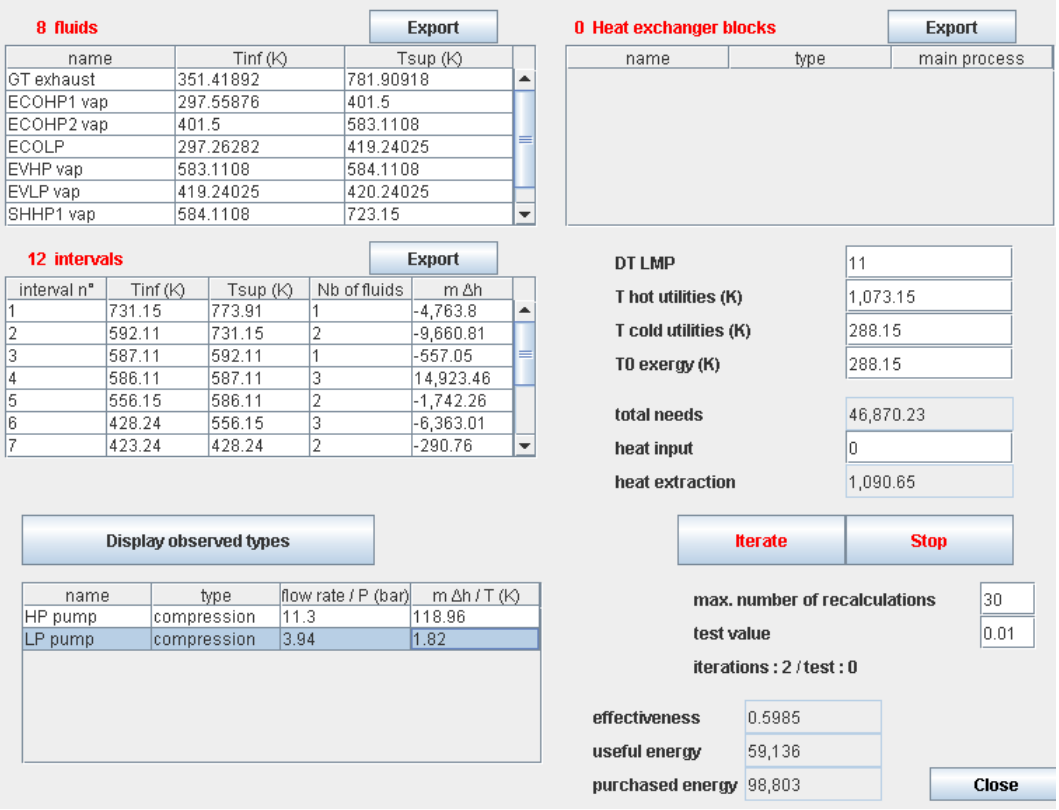
- Vary by simulation key parameters of the system (flow, temperature, pressure level) to improve performance.
- Check by the pinch method that one does not introduce additional high-temperature heat requirements and that the rejection at low temperatures is minimized.
- Graphical tools such as composite curves, the exergy composite curves and the Carnot factor difference curve (CFDC) allow one to visualize the position of the pinch and the irreversibilities that exist within the system.

2 - Once the system is optimized, establish the configuration of the exchanger network by matching fluids in the system.

Procedure:

- Perform fluid matching starting from the area most constrainted i.e. the pinch, and respect the rules
- Continue the study with the rest of the system deviating from the pinch.

4.2 OPTIMIZATION FRAME



8 fluids

name	Tinf (K)	Tsup (K)
GT exhaust	351.41892	781.90918
ECOHP1 vap	297.55876	401.5
ECOHP2 vap	401.5	583.1108
ECOLP	297.26282	419.24025
EVHP vap	583.1108	584.1108
EVLP vap	419.24025	420.24025
SHHP1 vap	584.1108	723.15

0 Heat exchanger blocks

name	type	main process

12 intervals

interval n°	Tinf (K)	Tsup (K)	Nb of fluids	m Δh
1	731.15	773.91	1	-4,763.8
2	592.11	731.15	2	-9,660.81
3	587.11	592.11	1	-557.05
4	586.11	587.11	3	14,923.46
5	556.15	586.11	2	-1,742.26
6	428.24	556.15	3	-6,363.01
7	423.24	428.24	2	-290.76

DT LMP: 11
T hot utilities (K): 1,073.15
T cold utilities (K): 288.15
T0 exergy (K): 288.15

total needs: 46,870.23
heat input: 0
heat extraction: 1,090.65

name	type	flow rate / P (bar)	m Δh / T (K)
HP pump	compression	11.3	118.96
LP pump	compression	3.94	1.82

max. number of recalculations: 30
test value: 0.01
iterations : 2 / test : 0

effectiveness: 0.5985
useful energy: 59,136
purchased energy: 98,803

Figure 4.1: Optimization screen

All functions specific to optimization are accessible from the optimization frame (figure 4.1). They work in close coordination with the simulator, so you can easily modify the system parameters but are separated, however, mainly to simplify Thermoptim use for those who do not need them.

To get access to the optimization screen, type Ctrl M or select "Optimization tools" in the "Special" menu of Thermoptim professional version.

It is comprised of three main tables:

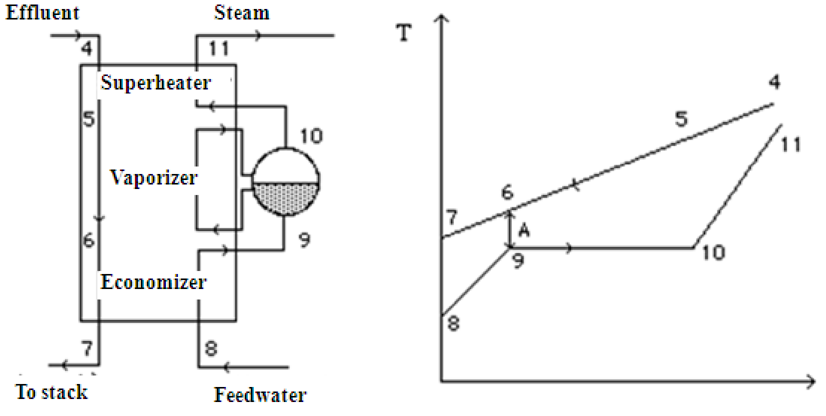
- the fluid table contains all the exchange streams in which the "pinch method fluid" option is selected. These are fluids which are processed by the variant of the Problem Table Algorithm implemented in Thermoptim;
- the interval table contains the list of intervals which are built by the PTA variant;
- the heat exchanger block table contains the exchange blocks which can be defined in order to facilitate stream matching in heat exchangers.

4.3 Example data

We call steam generators (SG) devices where heat is not provided by combustion. Among them, we will focus here particularly on devices for recovering heat in thermal effluents, including gas (the heat recovery steam generators (HRSG) are sometimes called recovery boilers).

A steam generator has three successive functions:

- heat pressurized feedwater (in the economizer) to the vaporization temperature corresponding to the pressure;
- vaporize steam;
- and finally superheat steam at the desired temperature.

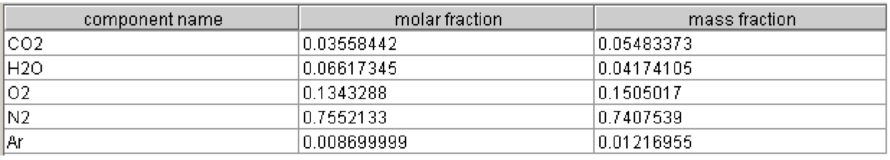


Heat recovery steam generator **Temperature-enthalpy diagram**

Figure 4.2: Steam generator exchange configuration

Most HRSGs are variations of water tube boilers. The main differences come from the fact on the one hand that the temperature levels of effluents are much lower than those achieved in a boiler, and on the other hand that heat exchange takes place only by convection. Nothing in these conditions prevents the superheater being positioned upstream of the vaporizer, and the HRSG operating sketch and enthalpy diagram become as shown in Figure 4.2. A is the pinch.

The problem is defined as follows: a gas turbine whose compressor and turbine polytropic efficiencies are equal to 0.9, whose compression ratio is 20 and whose turbine inlet temperature is equal to 1,220 °C sucks 100 kg/s of air at 10 °C. We wish to design a dual pressure HRSG capable of powering a cycle with two steam turbines whose isentropic efficiencies are equal to 0.85. The pressure and condensing temperature are respectively 0.03 bar and 24.1 °C. The cycle maximum temperature and pressure are set at 450 °C and 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 75 °C.



component name	molar fraction	mass fraction
CO2	0.03558442	0.05483373
H2O	0.06617345	0.04174105
O2	0.1343288	0.1505017
N2	0.7552133	0.7407539
Ar	0.008699999	0.01216955

Table 4.1: Flue gas composition

The net power produced is 43,690 kW; the efficiency is 44.2% and about 102 kg/s of exhaust gas exit at 509 °C. Their composition is given in Table 4.1.

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 75 °C;
- set up two simple steam cycles with HP and LP pressure settings;
- select all exchange fluids (the gas turbine flue gas, the economizers, the vaporizers and the superheaters) 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;
- set the HP and LP pump flow rates; as the other cycle processes are located downstream from them, their flow rates will automatically be updated;
- select the "observed" checkbox in the HP and LP pump processes; they will thus directly appear in the Optimization screen.

5 Single pressure HRSG

The sketch of a single pressure combined cycle is given Figure 5.1.

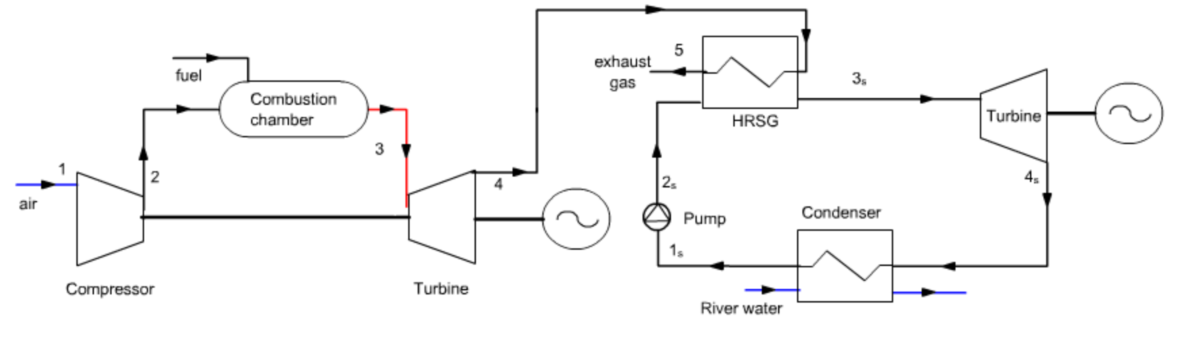
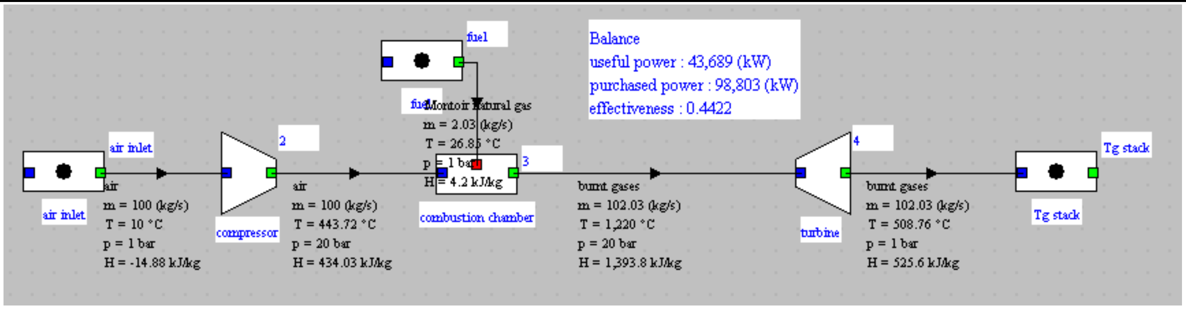


Figure 5.1: Sketch of the combined cycle

Start by building the gas turbine model and set it as indicated above. If you do not know how to build such a model, study Diapason Session S24En[1]. You get the synoptic view shown in Figure 5.2.



Balance
useful power : 43,689 (kW)
purchased power : 98,803 (kW)
effectiveness : 0.4422

Montoir natural gas
m = 2.03 (kg/s)
T = 26.85 °C
p = 1 bar
H = 4.2 kJ/kg

air
m = 100 (kg/s)
T = 10 °C
p = 1 bar
H = -14.88 kJ/kg

air
m = 100 (kg/s)
T = 443.72 °C
p = 20 bar
H = 434.03 kJ/kg

burnt gases
m = 102.03 (kg/s)
T = 1,220 °C
p = 20 bar
H = 1,393.8 kJ/kg

burnt gases
m = 102.03 (kg/s)
T = 508.76 °C
p = 1 bar
H = 525.6 kJ/kg

Figure 5.2: Synoptic view of the gas turbine

Now build below the gas turbine a model of a simple steam cycle. If you do not know how to build such a model, study Diapason Session S26En[2].

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[1] http://www.thermoptim.org/sections/enseignement/cours-en-ligne/seances-diapason/session-s24en-simple-gas

[2] http://www.thermoptim.org/sections/enseignement/cours-en-ligne/seances-diapason/s26_vapor_cycle

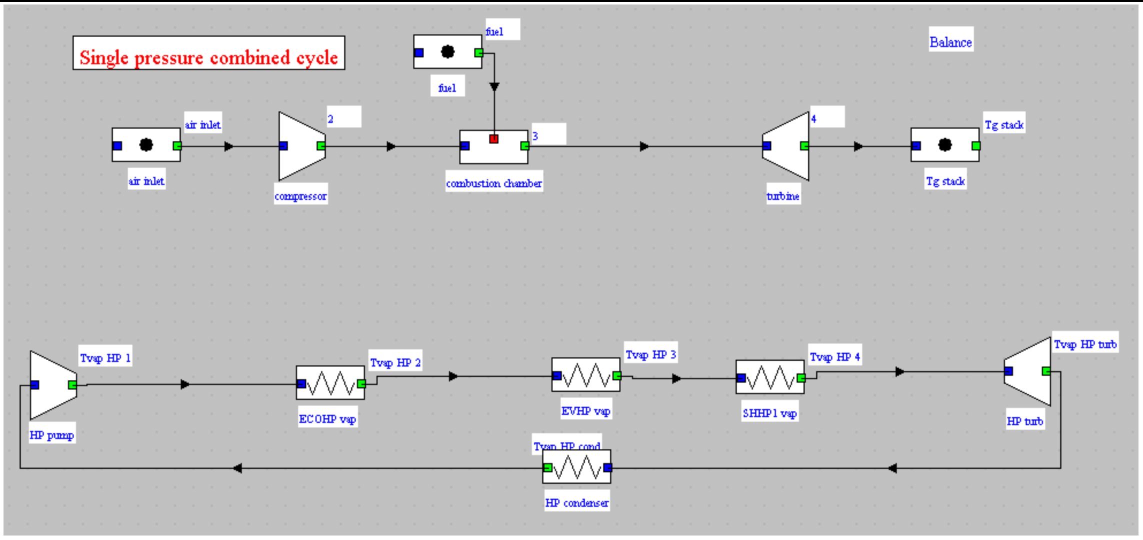


Figure 5.3: Diagram of the combined cycle

The diagram you get is as shown in Figure 5.3.

Now, we will add an exchange process downstream the gas turbine to model the cooling of the exhaust gases, setting the stack temperature to 75 °C. The diagram becomes as shown in Figure 5.4, for a steam flow-rate of 5 kg/s.

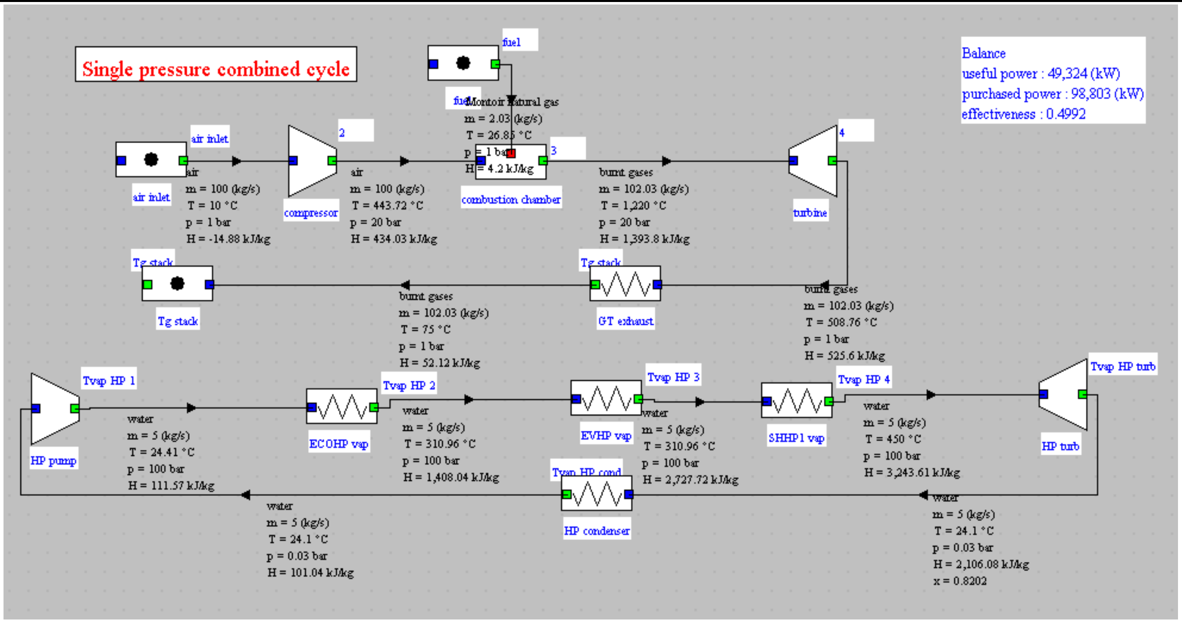
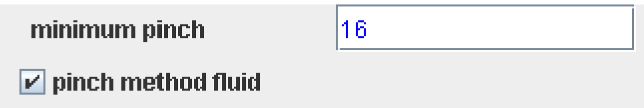


Figure 5.4: Synoptic view of the combined cycle

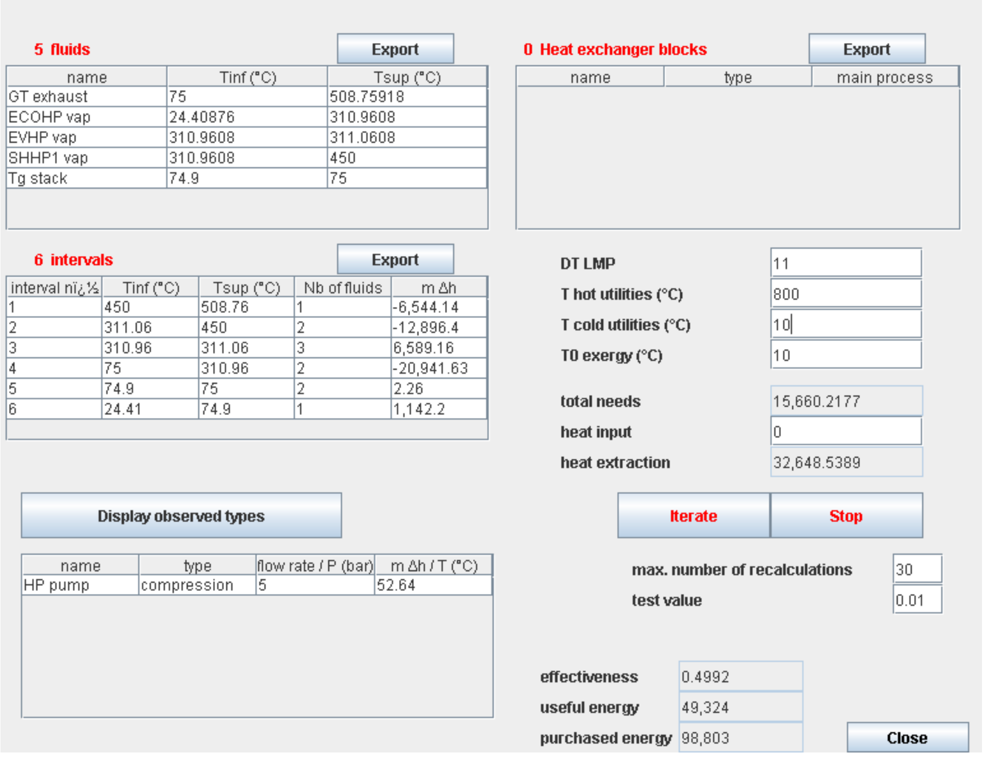
In the exchange processes, enter the values of the minimum pinch (16 K for the exhaust gas, 8 K for the economizer, 6 K for the vaporizer, 16 K for the superheater), and check option « pinch method fluid », except for the condenser.



minimum pinch 16

☑ pinch method fluid

Open now the optimization frame (Figure 5.5).



5 fluids

name	Tinf (°C)	Tsup (°C)
GT exhaust	75	508.75918
ECOHP vap	24.40876	310.9608
EVHP vap	310.9608	311.0608
SHHP1 vap	310.9608	450
Tg stack	74.9	75

0 Heat exchanger blocks

name	type	main process

6 intervals

interval nï¿½	Tinf (°C)	Tsup (°C)	Nb of fluids	m Δh
1	450	508.76	1	-6,544.14
2	311.06	450	2	-12,896.4
3	310.96	311.06	3	6,589.16
4	75	310.96	2	-20,941.63
5	74.9	75	2	2.26
6	24.41	74.9	1	1,142.2

DT LMP: 11
T hot utilities (°C): 800
T cold utilities (°C): 10
T0 exergy (°C): 10
total needs: 15,660.2177
heat input: 0
heat extraction: 32,648.5389

name	type	flow rate / P (bar)	m Δh / T (°C)
HP pump	compression	5	52.64

max. number of recalculations: 30
test value: 0.01

effectiveness: 0.4992
useful energy: 49,324
purchased energy: 98,803

Figure 5.5: Optimization frame

Draw then the exergy composite (menu Charts), which provides an immediate synthesis of the whole cycle (Figure 5.6). The pinch is very large.

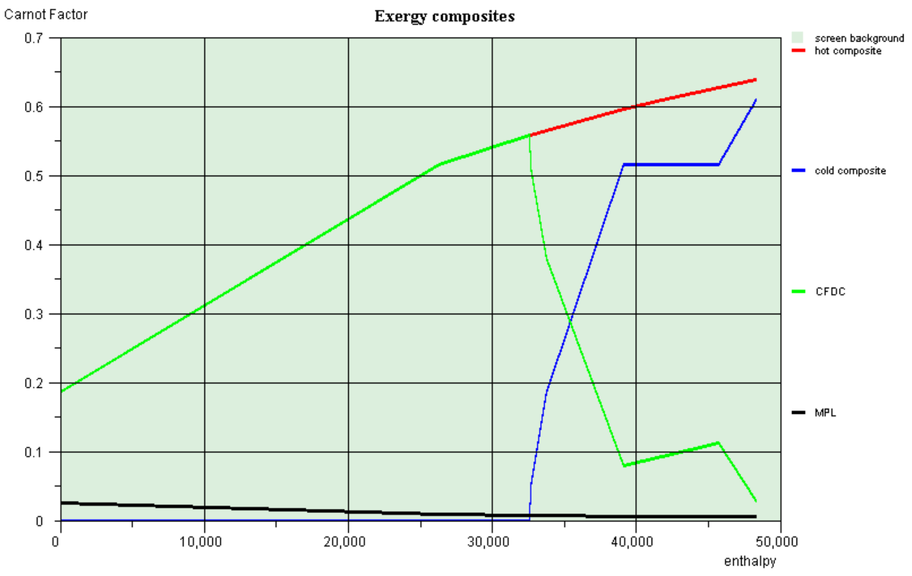


Figure 5.6: Exergy composites

The steam cycle flow-rate being quite low, an important part of the heat available in the exhaust gas is not used. We can therefore increase it significantly.

Double-click on the line that appears in the « observed types » table in the bottom left of the optimization frame (the pump process), enter a flox-rate of 10 and calculate the process.

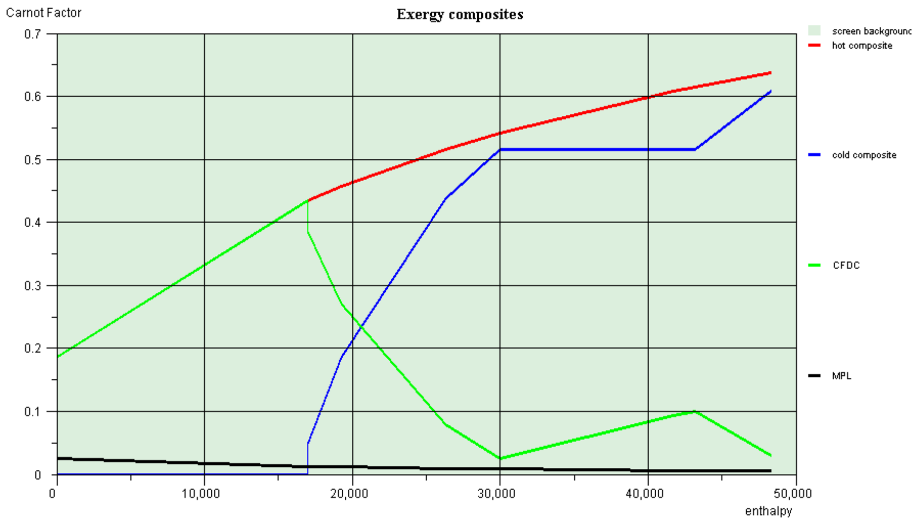


Figure 5.7: Exergy composites

Go back to the optimization frame and click on Iterate, then update the optimization frame (Ctrl U or « Update and minimize target » of menu « Optimization method ») and plot the new curves (Figure 5.7). The pinch is reduced, but there is still place for improving the cycle. Repeat the previous steps increasing the steam flow-rate. If it becomes too large, a message warns you that there is a need for a heat input. After a few trials, you find a flow-rate of about 11.3 kg/s (Figure 5.8).

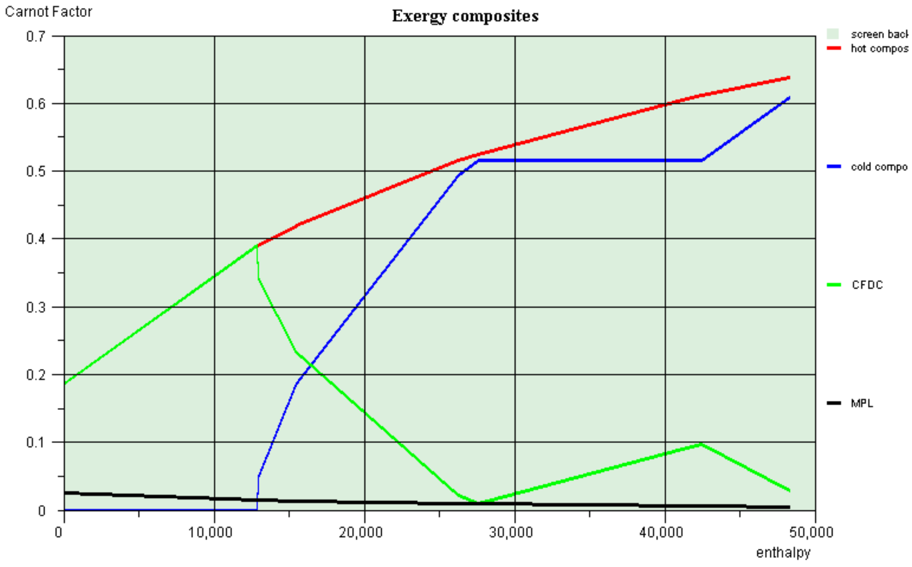


Figure 5.8: Exergy composites

The pinch is now appropriate, where the black and green curves meet. The synoptic view is given Figure 5.9.

At this stage, it may be interesting to make a sensitivity analysis on the value of the steam cycle pressure.

If we choose a pressure of 30 bar and seek the maximum flow for this new pressure, we find a value of 12.5 kg/s. The performance of the cycle is slightly improved as shown by the synoptic view of Figure 5.10.

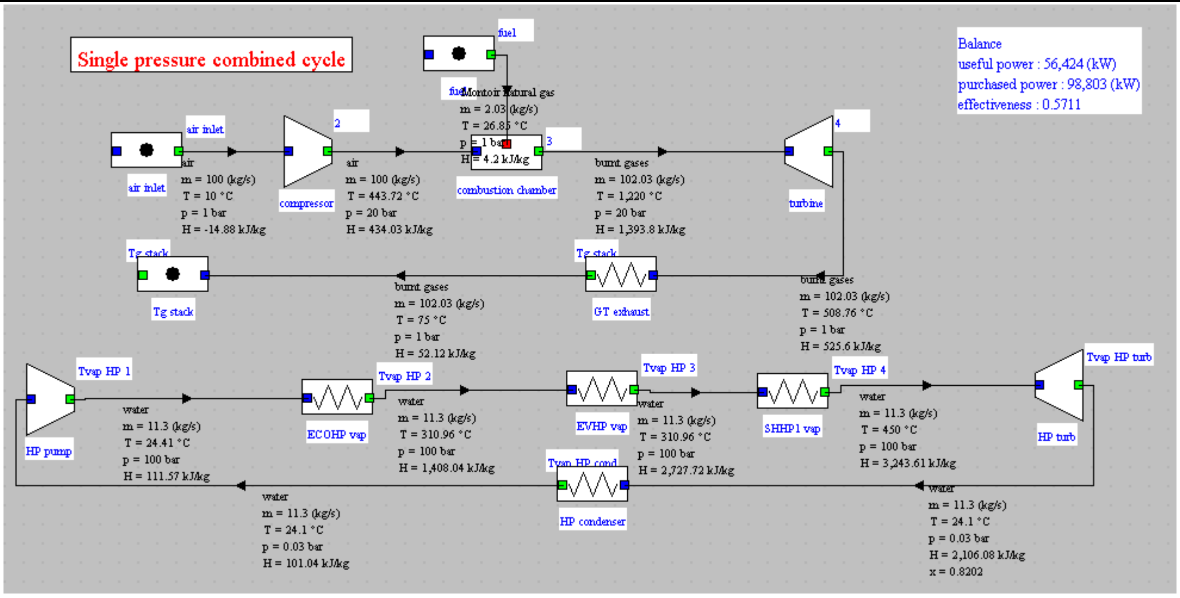


Figure 5.9: Synoptic view of the combined cycle

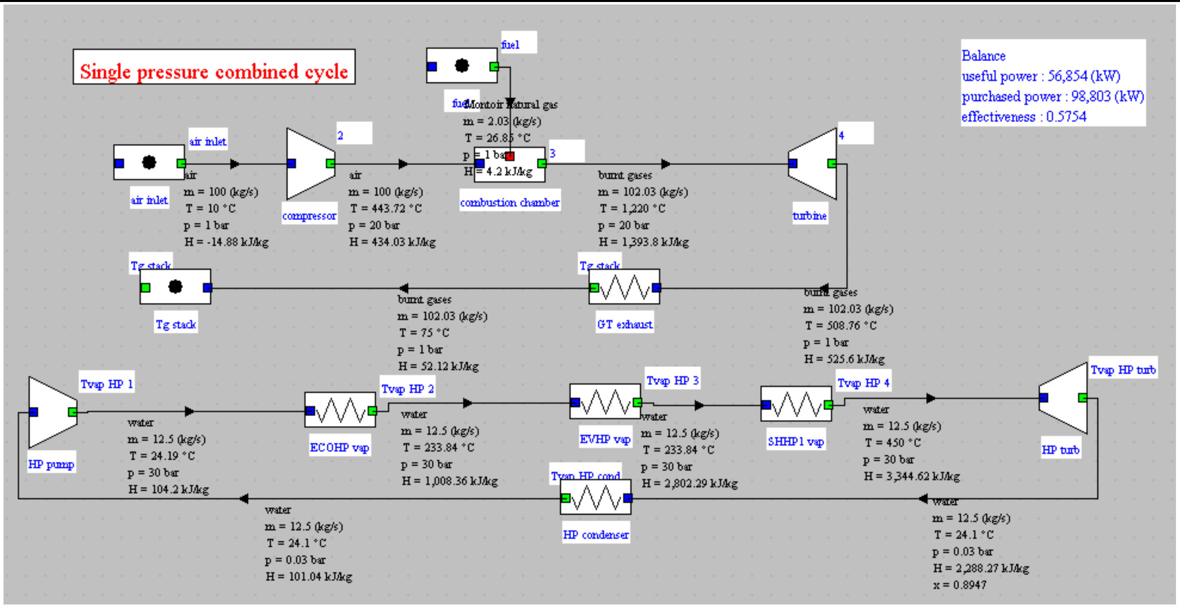


Figure 5.10: Synoptic view of the combined cycle

In both cases, there is still much heat available in the exhaust gas, but a single pressure HRSG cannot recover it.

6 Dual pressure HRSG

We will now study a dual pressure HRSG. Start from the diagram of Figure 5.3 and add a second LP steam cycle, which gives the diagram of Figure 6.1.

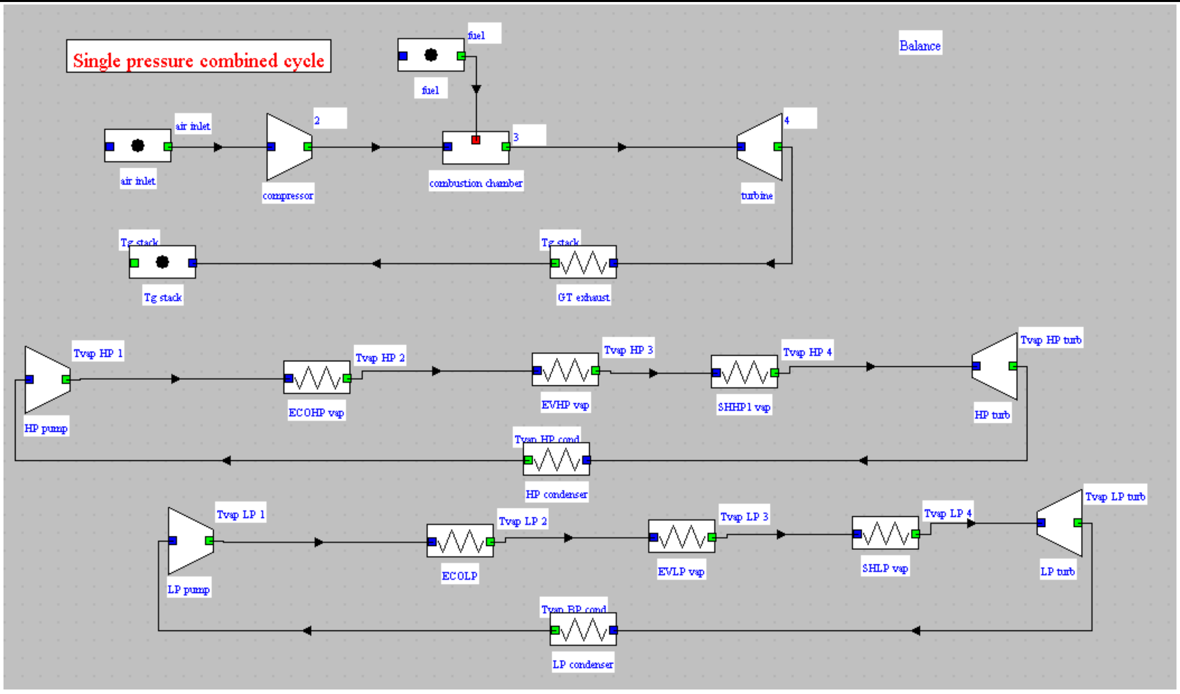


Figure 6.1: Diagram of the dual pressure combined cycle

For the HP steam cycle, we keep a pressure of 100 bar and a flow-rate of 11.3 kg/s, and we set the LP cycle as follows : pressure of 6 bar, superheating temperature of 275 °C.

We can now proceed similarly as for the HP flow-rate, seeking the value of the maximum LP flow-rate which can be obtained without heat input.

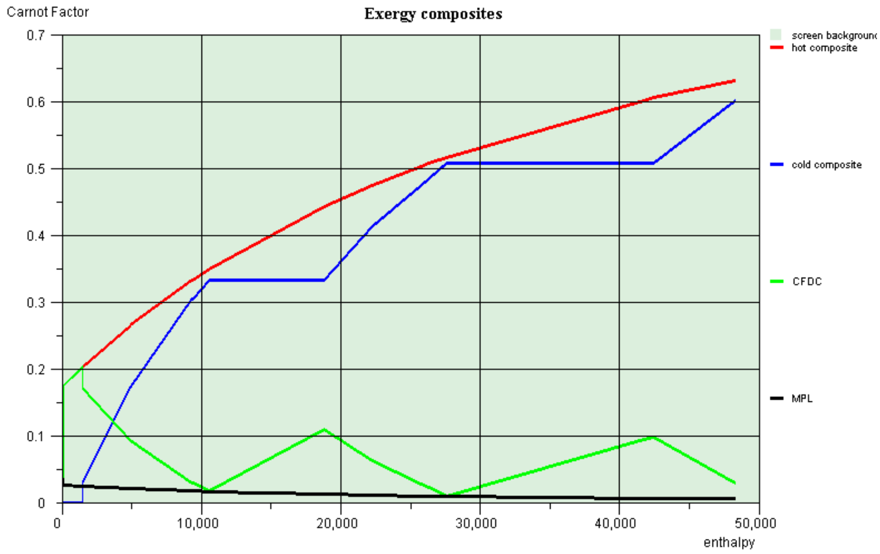


Figure 5.8: Exergy composites

The exergy composites that we get are shown in Figure 6.2, and the synoptic view in Figure 6.3. With a flow rate of 3.94 kg/s, the overall efficiency is now 59.9%. The net power output is 59.1 MW, which corresponds to almost 5% increase compared to single pressure HRSG.

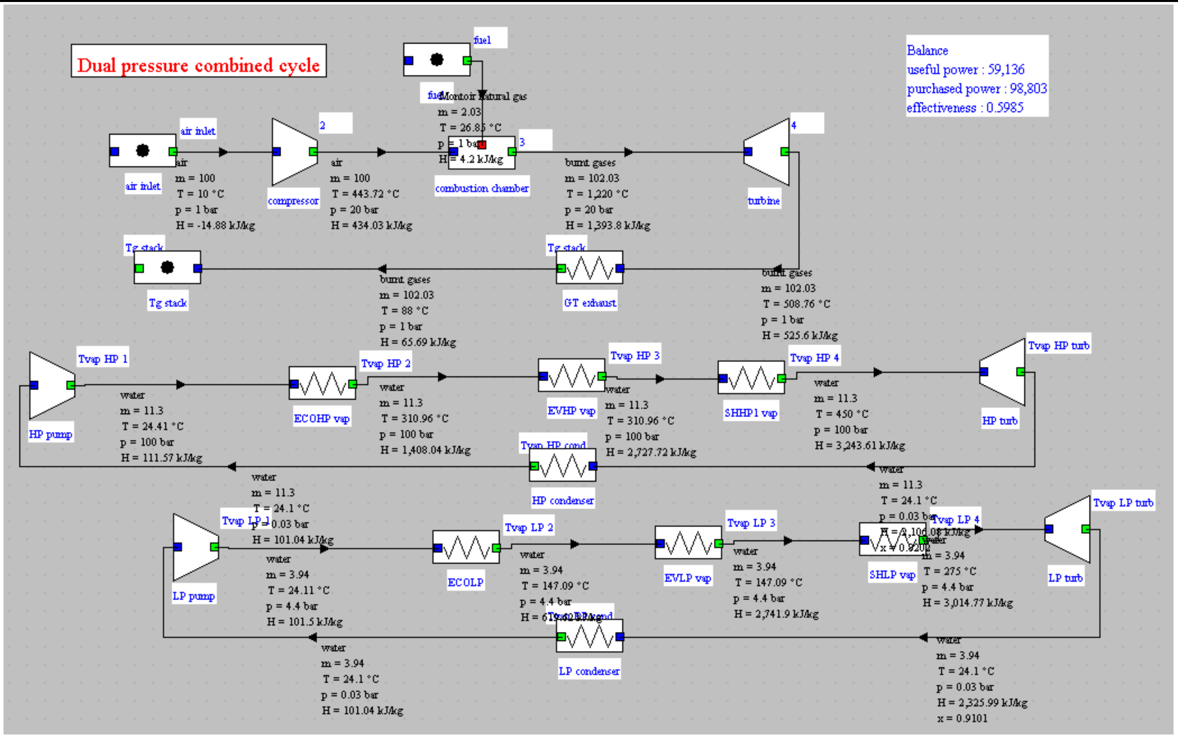


Figure 6.3: Synoptic view of the dual pressure combined cycle

You can now make sensitivity studies to find the best low pressure.

7 Construction of the heat exchanger network

The construction of the heat exchanger network is explained in section 12.6.2 of the book Energy Systems, to which you should refer.

Figure 7.1 shows the synoptic view that is obtained.

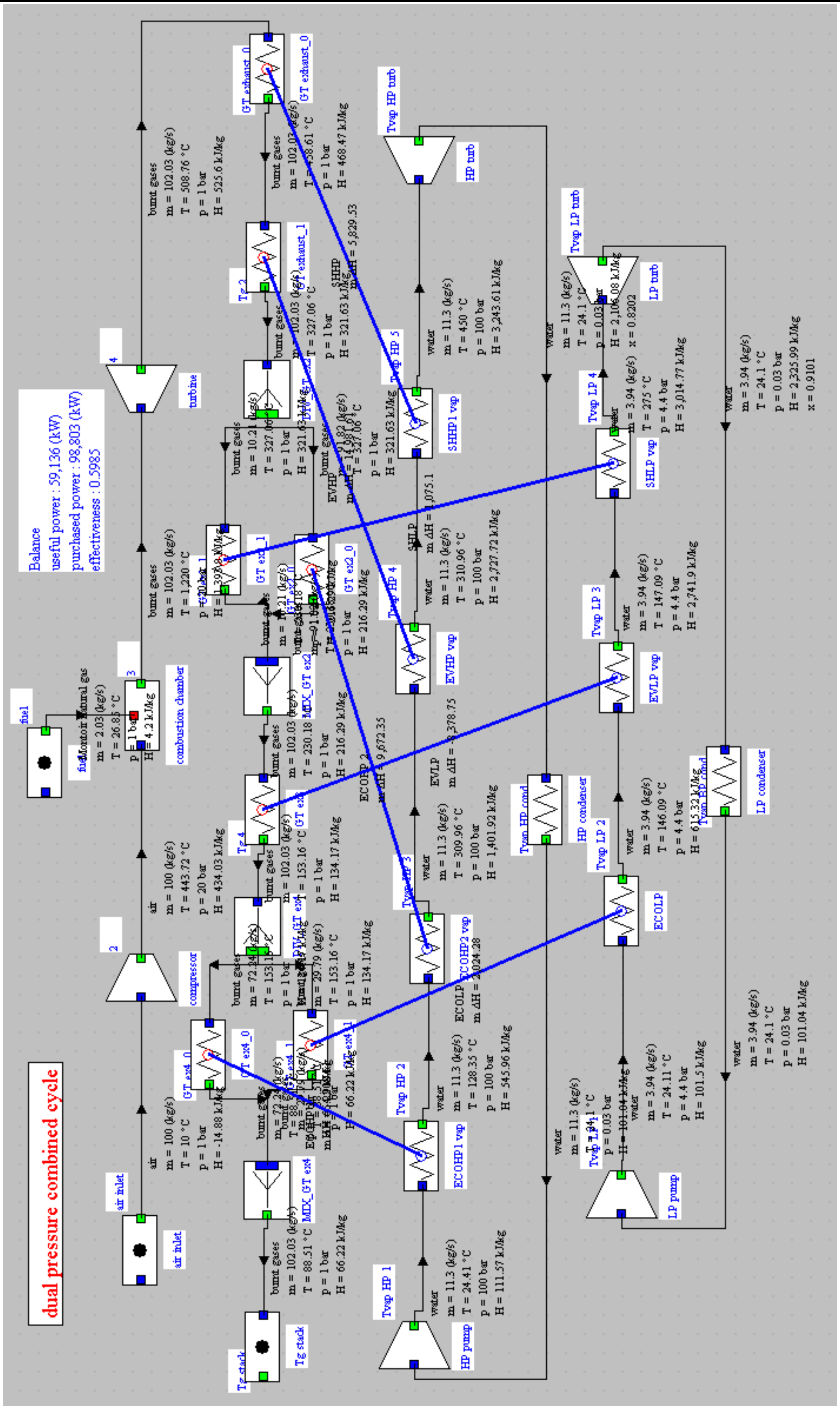


Figure 7.1: Synoptic view of the combined cycle with heat exchangers