

THERMOPTIM®

Cogeneration Plant

Advanced example

Warning: advanced example.

This document intends to allow a user to go deeper into the capacities of ThermoOptim, in terms of modelling and calculation of complex cycles. Therefore, it is supposed that the reader already knows the basic elements of ThermoOptim. If not, you should start by reading the "Getting Started" documents. To read this example, it is deeply recommended to have read the "Getting Started" examples "Gas Turbine" and "Simple steam cycle".

The example presented here, inspired by a real plant, is a cogeneration plant, which supplies both heat to a district heating network, and mechanical energy converted to electricity by an alternator. The objective of this notice is to model the installation with ThermoOptim, to calculate its balance, and to study some different cases according to the heat network needs.

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I. Presentation of the cogeneration plant

I.1. The installation

The plant modelled in this example produces electricity and supplies in heat the urban heating network of a city of 30 000 inhabitants. It is an installation where heat is the basis product, electricity being a by-product allowing enhancing better the value of the fuel. The heating network is a network of high pressure hot water which temperature is between 90°C and 130°C. The network leaves the plant at its maximum temperature, goes through the city, and feeds sub-stations which role is to heat or reheat potable water for housing, hospitals, schools...

Finally it comes back to the plant at its minimum temperature, where it is reheated. Needs in heat of the city vary during the year, according to climatic conditions. The plant has to adapt itself to these needs and modulate the thermal power it delivers to the network.

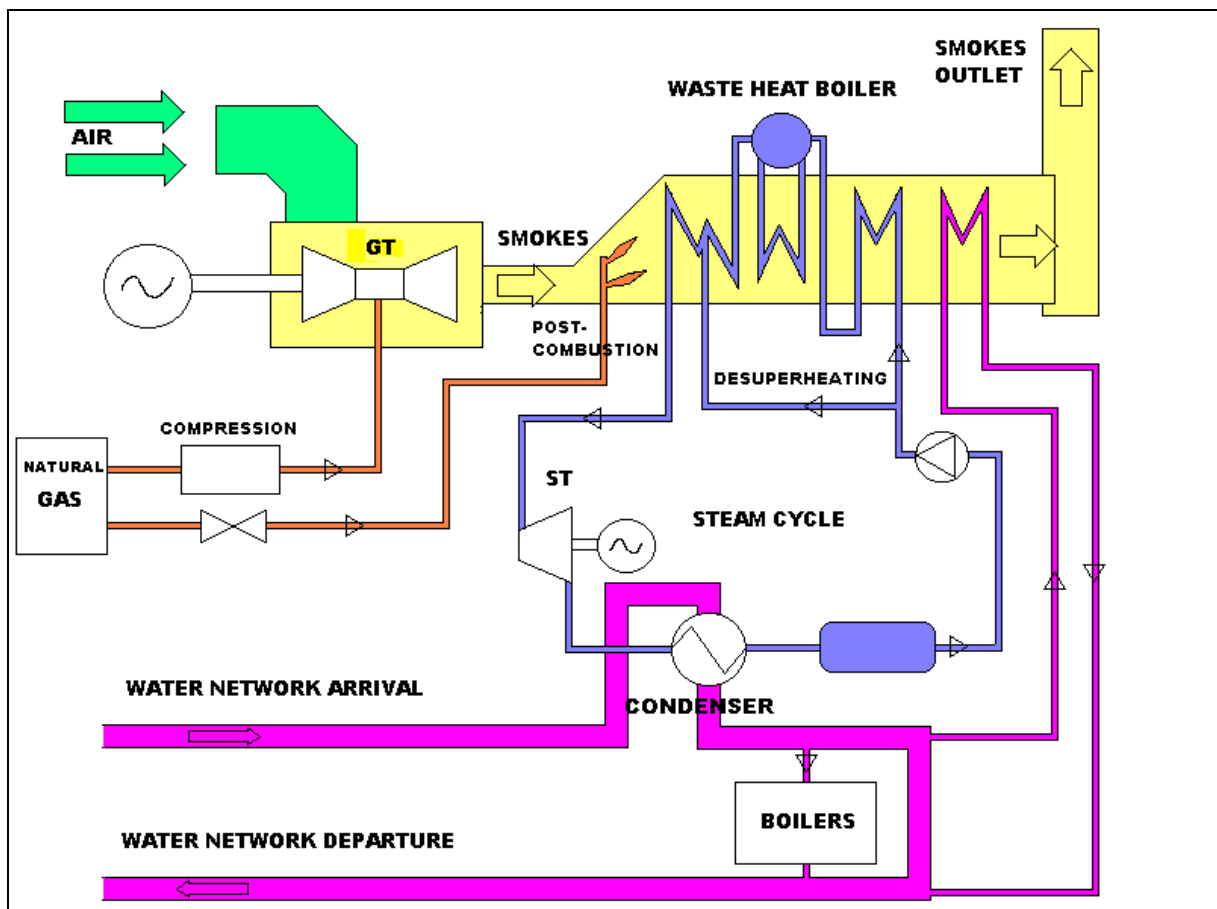


Figure 1: schema of the cogeneration plant

The installation is composed of three independent circuits only exchanging heat together (see Figure 1):

- A gas turbine: connected to an alternator, supplies around 80% of the electricity of the site. Burnt gases leave the gas turbine at about 450°C, and are burnt again with a small supply of fuel. After the post-combustion, (PC), smokes, which temperature is around 600°C, reheat the water of the steam cycle in a waste heat boiler, then reheat water of the urban network. Finally they are rejected to atmosphere at 150°C, through the chimney.

- A steam circuit supply the other 20% of electricity. Water is heated, converted to steam, and superheated in the waste heat boiler by the exhaust smokes of the gas turbine. A desuperheating is made at the middle of the superheater, in order to regulate the steam temperature at the turbine inlet. It is then expanded in a steam turbine connected to an alternator. In the condenser, where pass through both the steam circuit and the urban network, steam condenses and heat the network. Finally, liquid water is sent to the feed water tank, and pumped towards the waste heat boiler.
- The urban heating network is parcouru by high pressure hot water. It returns to the central at its minimum temperature, and is then heated in the condenser, where it plays the role of a cold source. A part of this water is heated in the waste heat boiler, in an exchanger called "pin". The flow in the pin is limited. If the thermal supplies of the condenser and the pin don't cover the needs of the network, boilers bring the complement.

In this example, you will model the whole three circuits and their thermal interactions via heat exchangers. You will calculate the global and detailed balance of the plant, and the different efficiencies of the cogeneration installation: mechanical (or electrical), thermal, global efficiencies, in different cases of operation.

1.2. The different cases of operation

The plant has to adapt itself to the needs of the urban network: it must supply to the hot water circuit the thermal power dissipated by the city. This power depends on climatic conditions, and, on average, on the outside temperature; needs in heat of the network according to the outside temperature are given in the following table :

Outside T (°C)	-5	-4	-3	-2	-1	0	1	2	3	4	5
Needs in P (MW)	61,1	58,6	56,2	53,8	51,4	49,0	46,6	44,2	41,7	39,3	36,3
Network flow (t/h)	1372	1318	1264	1210	1155	1128	1128	1128	1128	1128	1128
Return T (°C)	90	90	90	90	90	90	90	90	90	90	90
Departure T (°C)	130	130	130	130	130	129	127	125	123	121	119

The plant can supply heat to the hot water circuit by three means: via the condenser of the steam circuit, the pin, and the boilers. The maximal flow in the steam circuit is 70 tons/hour. For small needs, boilers are not used, and the flow in the steam circuit is smaller. Water needs then a smaller supply in heat to be converted in superheated steam in the waste heat boiler (steam temperature must always be the same at the turbine inlet: 485°C). To do it, varying the flow of fuel for the post-combustion modulates smokes temperature. Direct heating of the hot water network is then less important. When the needs in heat of the urban network increase, the flow in the steam circuit must increase, and also the flow of fuel for post-combustion, until reaching the maximal flow of 70 t/h in the steam circuit. When thermal needs of the urban network can't no more be assumed by the condenser and the pin, boilers are turned on.

Two cases of operation and their borderline case can then be distinguished:

Important thermal needs $T_{ext} < T_{lim}$:

The flow in the steam circuit is maximal, 70 t/h. Post-combustion is at its maximum. Thermal energy given by the condenser and the pin is maximal. Boilers are turned on and supply the complement needed to assume the thermal needs of the network.

Less important thermal needs $T_{ext} > T_{lim}$:

Boilers are turned off. Thermal energy given by the condenser and the pin are not maximal. The flow in the steam circuit is less than 70 t/h, and post-combustion is not maximal.

Borderline case corresponds to a maximal post-combustion and a steam flow of 70 t/h. Thermal power of the condenser is then 43.9 MW, and the one of the pin, 7.4 MW. Total thermal power transmitted to the urban network is then 51.3 MW. It corresponds to $T = T_{lim} = -1^{\circ}\text{C}$.

You will begin by modelling the borderline case at -1°C , using the values of the operation points given by the manager of the plant and the constructors of the different elements of the circuits. Then you will adapt the model for cases where thermal needs are greater ($T < -1^{\circ}\text{C}$) or less important

1.3. Points of operation

The manager of the plant and the constructors of the different machines give the following points of operation :

Gas turbine

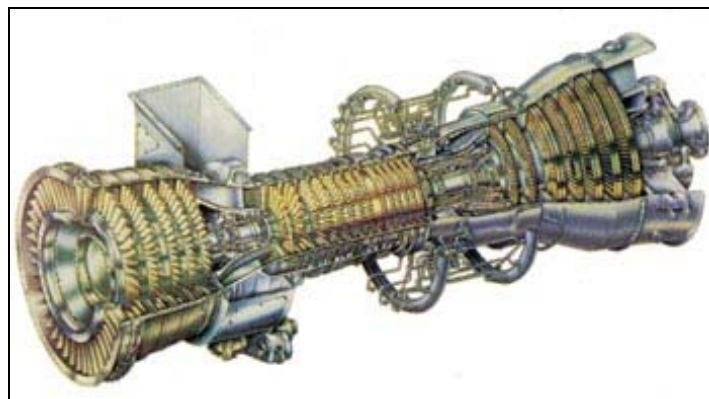


Figure 2 : gas turbine LM6000

The gas turbine used in the installation is a LM 6000 from General Electrics. It is composed of a compressor which compresses the ambient air, of a combustion room burning the fuel (here natural gas) with air, and of a turbine. The data given by GE are, for an ambient air at -1°C :

Mechanical power	47,5 MW
Efficiency	42 %
Exhaust gases temperature	448 °C
Exhaust gases flow	129,7 kg/s
Compression rate	29,6

The fuel used by the plant is natural gas from Fos at 45 bars and around 10°C , which average composition is given :

CH ₄	91,2 %
C ₂ H ₆	6,5 %
C ₃ H ₈	1,1 %
C ₄ H ₁₀	0,2 %
N ₂	1,0 %

Waste heat boiler with Post-combustion

The waste heat boiler is composed of a first block where the turbine exhaust gases are burnt again with some new fuel if post-combustion is activated (in cases you are going to model, PC will always be activated), and of 5 blocks of heat exchangers (see Figure 1). The first 4 blocks are heat exchangers with the steam circuit. The first one is a high temperature superheater (HTS), the second a low temperature superheater (LTS). The superheating block is divided in two parts because a

desuperheating is made between the two in order to control the steam temperature at the boiler outlet, which must be equal to 485°C to obtain the best efficiency on the steam turbine. The two following blocks are the evaporator (EVAP) and the economiser (ECO). The fifth block is the "pin", where water from the urban network is heated directly by the smokes.

The constructor gives the following point of operation, for a maximal flow in the steam circuit (70 t/h), and maximal post-combustion :

Smokes

P = 1 bar (atmosphere reject)

Gas turbine outlet flow	129,7 kg/s
Post-combustion temperature	591°C
HTS inlet smokes temperature	591°C
HTS outlet smokes temperature	567°C
LTS outlet smokes temperature	490°C
EVAP outlet smokes temperature	287°C
ECO outlet smokes temperature	204°C
Pin outlet smokes temperature	147°C

Steam / Water

Steam flow	70 t/h	
Flow in the desuperheating branch	4,3 t/h	
HTS outlet steam temperature	485°C	57 bars
HTS inlet steam temperature	423°C	59 bars
LTS outlet steam temperature	495°C	59 bars
LTS inlet steam temperature	279°C	62,5 bars
EVAP inlet water temperature	265°C	62,5 bars
ECO inlet water temperature	125°C	62,5 bars

Urban Network

Pressure	20 bars
Pin inlet water temperature	120°C
Pin outlet water temperature	145,5°C

Steam circuit

In the feed water tank, water is kept at 2.5 bars and 125°C. It is compressed to 62.5 bars by the feed water pump. The main part of water is converted to steam in the waste heat boiler, but a sampling of 4.3 t/h is made here for desuperheating. The sampling is mixed with steam at the outlet of LTS. The steam produced by the boiler is at 485°C and 57 bars. It is expanded in the steam turbine, then condensed at 2.5 bars ($T_{\text{sat}} = 127,5^\circ\text{C}$), and cooled until 125°C in the condenser.

The manager of the plant gives the value of the turbine outlet temperature according to the flow: for 70 t/h of steam, its temperature at the turbine outlet is 160°C.

Hot water network

In the borderline case at $T_{\text{ext}} = -1^\circ\text{C}$, the flow in the urban heating network is 1155 t/h, the network return temperature is 90°C and the departure temperature must be 130°C. The flow in the boilers is equal to 0 because they are not activated, the flow in the pin is 270 t/h, the maximal flow possible in the pin. Water pressure is 20 bars.

II. Modelling with ThermoOptim

You are now going to model the installation with ThermoOptim and calculate its energy balance in the borderline case at $T_{\text{ext}} = -1^\circ\text{C}$.

II.1. Creation of the diagram and definition of the points and processes

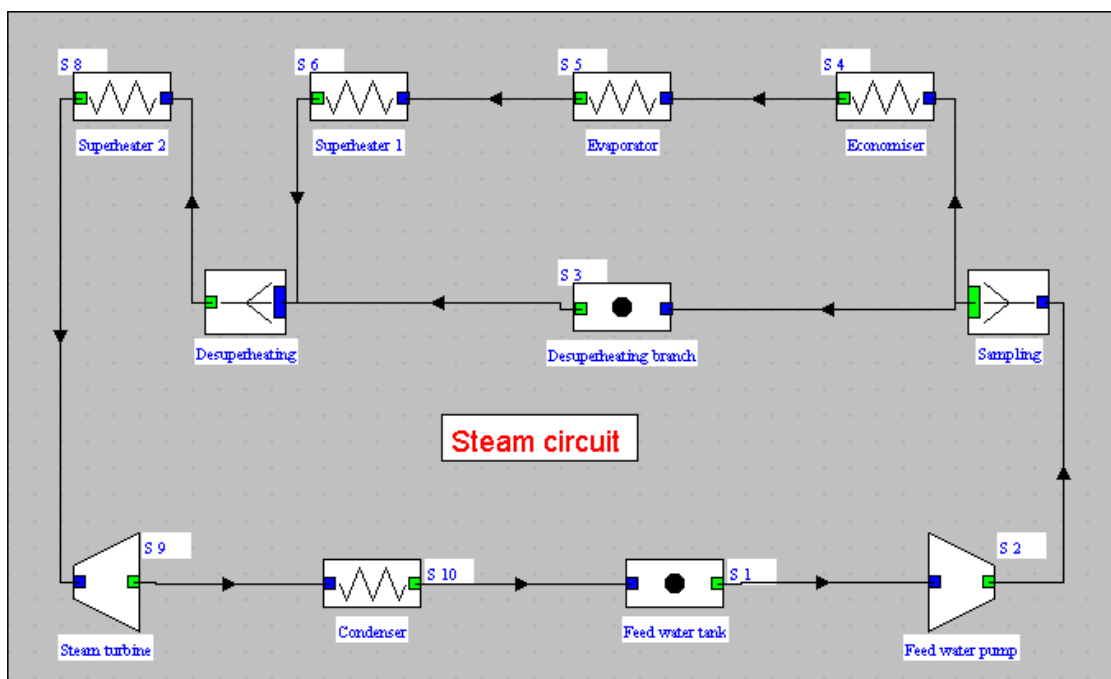
As the project you are going to model has an important weight, you should create the diagrams, define and test one after the other the different parts of the installation. Open a new project, give it a name, and save it regularly.

The entire diagrams are given at the end of this part.

Steam circuit

The steam circuit is very classic, except the branch of desuperheating, sampled before the waste heat boiler and mixed with steam between the two superheaters.

In ThermoOptim's Diagram Editor, create the different processes of the steam circuit, and connect them. Then define the cycle according to the data given in the first part of this document.



Comments:

The feed water tank was represented by a process-point, which is not obligatory but enhance the readability of the diagram.

On the contrary, the process-point "Desuperheating branch" inserted between the divider "Sampling" and the mixer "Desuperheating", is obligatory because ThermoOptim can't connect directly two nodes.

When you create the process "Superheater 2", edit its properties again (select the component in the Diagram Editor, then press F4) ; click on the "Inlet port" tab, and give a name (S 7 for example) at the inlet point and enter the substance name (water). This operation is necessary because the inlet port of "Superheater 2" is connected to a mixer, which doesn't correspond to an outlet point well defined. Same comment about the process "Economiser", name the inlet point S 2 bis.

Once the diagram created in the Diagram Editor, transfer the elements of the diagram to the simulator, using the "Interface Diagram/Simulator" of the menu "Special". Now define and calculate the processes :

- *Process-point Feed water tank* : set $P = 2.5$ bars, $T = 125^{\circ}\text{C}$ for the point V 1, and set in the process-point a value of the flow of 19.4 kg/s ($=70$ t/h.). Calculate and save.
- *Feed water pump* : set $P = 62.5$ bars for the outlet point. As you don't know the isentropic efficiency of the pump, let it to 1 ; the energy used by the pump is all the way really small in front of the energies needed for heating water, and the energy of the expanse. Choose "energy type = purchased", because the pump is fed by electricity. Calculate and save. The water temperature raises less than 1°C .
- *Node Sampling* : set the flows ; select the branche "Desuperheating branch", then click on "flow setting". A window asks for the flow rate, that is to say the relative flow in the branch. Enter the value 4.3. For the main branch, enter the value $70 - 4.3 = 65.7$. Calculate and save.
- *Desuperheating branch* : set the presure of the point S 3 to 62.5 bars.

For all the exchange processes of the waste heat boiler, choose (for the moment) "energy type = purchased", in order to calculate the balance of the steam cycle alone.

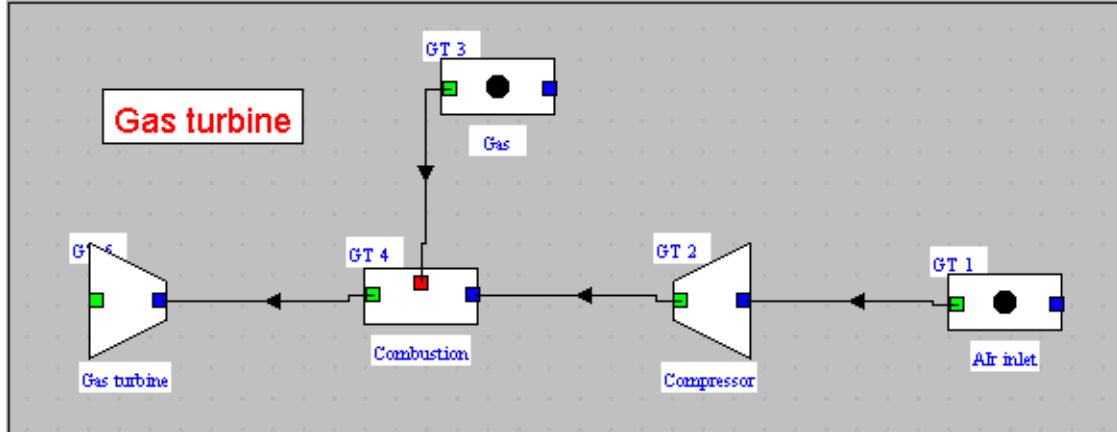
- *Economiser* : set the pressure of the inlet and outlet points to 62.5 bars (no loss of head in this exchanger), and the outlet point temperature to 265°C . Calculate and save.
- *Evaporator* : Set the outlet point pressure to 62.5 bars, and the temperature to 279°C . ($T_{\text{sat}} = 278,2^{\circ}\text{C}$).
- *Superheater 1* : set for the outlet point : $P = 59$ bars (losses of head), $T = 495^{\circ}\text{C}$.
- *Mixer Desuperheater* : Calculate and save. The mixture temperature is 421.6°C , which corresponds less than 1.5°C to the temperature given by the plant manager.
- *Superheater 2* : set for the outlet point $P = 57$ bars (losses of head), $T = 485^{\circ}\text{C}$.
- *Steam turbine* : one knows the turbine outlet temperature but not the isentropic efficiency. Set the outlet point to $P = 2,5$ bars, $T = 160^{\circ}\text{C}$. Choose a polytropic expanse, because the turbine is composed of several floors of expanses. Finally, calculate the efficiency and the mechanical power by checking the box "Calculate the efficiency, the outlet point being known". One finds an isentropic efficiency equal to 0.75. Choose "energy type = useful".
- *Condenser* : set the outlet point to $P = 2.5$ bars et $T = 125^{\circ}\text{C}$. ($T_{\text{sat}} = 127.4^{\circ}\text{C}$). Calculate and save. You should find the value already given : the maximal thermal power of the condenser is 43.9 MW.
- The steam cycle is now calculated. Show the balance :

Balance	
efficiency	0.211119
useful energy	11,736.03
purchased energy	55,589.53

The 21% efficiency is poor for the steam cycle alone, it is due to the desuperheating branch. But one must not forget that when the entire plant works, first the energy one qualified from "purchased" comes in fact from the heat of the turbine exhaust gases (burnt again in post-combustion). The real energetic cost of this heat is in fact only the one of post-combustion. Second, the heat freed by the condensation of steam is used to heat the urban network.

Gas turbine

In Thermoptim's Diagram Editor (over the steam circuit for example), create the diagram of a simple gas turbine¹, then parameterise it in order to find the data supplied by the constructor. Create and use a fuel "natural gas", which composition is the one given in the first part of this document.



Comments :

When you create the processes "Air inlet" and "Compressor", enter the substance "air". For the process-point "Gas", enter the name "natural gas" for the substance, that you will define later. After the combustion, enter the substance "exhaust gases", which will be defined by the combustion.

Transfer the elements of the diagram in the simulator using the "Interface Diagram/Simulator" of the "Special" menu.

Start by creating the gas : open the screen of the point GT 3, then click on the "display" button, near the field of the substance "natural gas".

point	GT 3
substance	natural gas display

Gas composition natural gas		
The first figure column from the left selects the input values from among molar and mass fractions		
component name	molar fraction	mass fraction
CH4 ` methane	0.912	0.8376373
C2H6 ` ethane	0.065	0.1118997
C3H8 ` propane	0.011	0.02776988
C4H10 ` n-butane	0.002	0.006655185
N2	0.01	0.01603792

A window "Gas composition natural gas" opens. If you double-click on the lines in the column of the component name, a list of pure gases appears. Enter the molar fraction (between 0 and 1) of each pure gas for create the composed gas. Validate the composition by saving the gas. The sum of molar fractions must obligatory be equal to 1.

¹ If you don't know how to do it, see the detailed example in the "Getting Started" document "Simple Gas Turbine".

Parameterise now the processes in order to find the data given by the constructor :

Mechanical power	46 MW
Efficiency	42 %
Exhaust gas temperature	448 °C
Exhaust gas flow	129,7 kg/s
Compression rate	29,6

The definition of the points and processes is not so immediate that for the steam circuit, because one should grope along in order to find the parameters that conduct to this data. A possible set of parameters is :

- the compression and expand rate of the compressor and turbine (given)
- the isentropic efficiency of the compressor (polytopic compression)
- the isentropic efficiency of the turbine (polytopic expand)
- the combustion temperature
- the inlet air flow

One must set, then, 4 parameters to find 4 constraints. Try yo set them yourself. To see the mechanical power and the efficiency of the gas turbine, set in all the processes of the steam circuit "energy type = other", the combustion "purchased" and the compression and expand "useful".

A solution :

Parameters

Inlet air flow :	127,5 kg/s
Compression/expand rate	29,6
Compressor isentropic efficiency	0,86
Combustion temperature	1200°C
Turbine isentropic efficiency	0,87

Results :

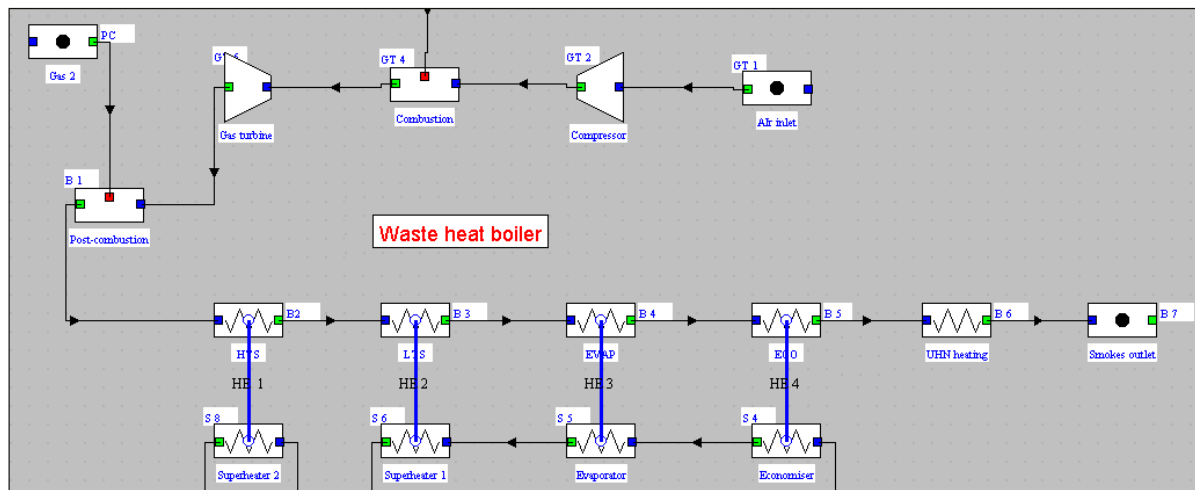
Gas turbine efficiency	42,5 %
Mechanical power	45,9 MW
Exhaust gas temperature	446°C
Exhaust gas flow	129,71 kg/s
Natural gas flow	2,21 kg/s
Combustion	107,8 MW

Comments on the gas turbine

One has to remark that this modelling of the gas turbine is the simplest possible, and it is adapted only for these conditions of temperature and flow. Indeed, the real gas turbine is more complex, in particular, the inlet air flow and the exhaust gases temperature depend on the inlet air temperature. These phenomenons are due to the fact that a part of inlet air is used for ventilating the turbine. Modelling this effect would give more precise resultsfor other points of operation but, for simplicity reasons, one will keep using this model of the turbine.

Post-combustion and waste heat boiler

In the diagram editor, represent the post-combustion of the turbine exhaust gases, and the waste heat boiler, where smokes pass through, like a suit of exchange processes linked to the ones of the steam circuit by exchangers. Parameterise the whole thing, and check that the smokes temperatures obtained after each exchanger correspond to the ones given by the operation point



Comments :

When you create the "HTS" process, enter the substance "smokes", which will be defined by the post-combustion.

Before creating the exchangers, you must define the cold fluid and the hot one, that is to say indicate if each exchange process has a enthalpy variation positive or negative. The cold fluids of the exchangers are already defined, they are the fluids of the steam circuit. Indicate that exchange processes of the smokes circuit are the hot fluids by setting the temperatures of outlet points lower than the ones of inlet points. Once this is done, you can create the heat exchangers.

Don't forget the fifth exchange process "UHN heating", which represents the "pin" where water from the urban network is heated directly by smokes.

Transfer the new elements from the diagram to the simulator, and define :

- *post-combustion* : set $T_{\text{combustion}} = 591^{\circ}\text{C}$, calculate, save. You find the fuel flow equal to 0.46 kg/s.
- *the exchangers* : you are going to calculate the smokes temperature at the outlet of each exchanger, and design them. Open the screen of HE 1 exchanger. Set the two flows, the inlet temperatures and the steam outlet temperature. There are 5 constraints, the exchanger can then be calculated. Calculate (you should have to click several times on "calculate", until the two enthalpy variations are opposed, because the calculation of an exchanger is iterative), and save. Do the same thing with the three others exchangers.

The screenshot shows a software window titled "Heat exchanger" with the following data:

Parameter	Value	Unit	Notes
name	HE 1		
type	counterflow		
hot fluid	HTS		
cold fluid	Superheater 2		
Tce (°C)	591		set calculated
Tcs (°C)	571.07621568		set calculated
mc	130.16854475		set calculated
Cpc	1.16560631		
DHc	-3,022.9416861		
Tfe (°C)	421.09900231		set calculated
Tfs (°C)	485		set calculated
mf	19.4		set calculated
Cpf	2.43848675		
DHf	3,022.9416861		
UA	23.85541359		
R	0.311791444		
NTU	0.50427196		
LMTD	126.71931569		
DTmin	0		
epsilon	0.376107254		
Design	design		checked
Non nominal	non nominal		unchecked

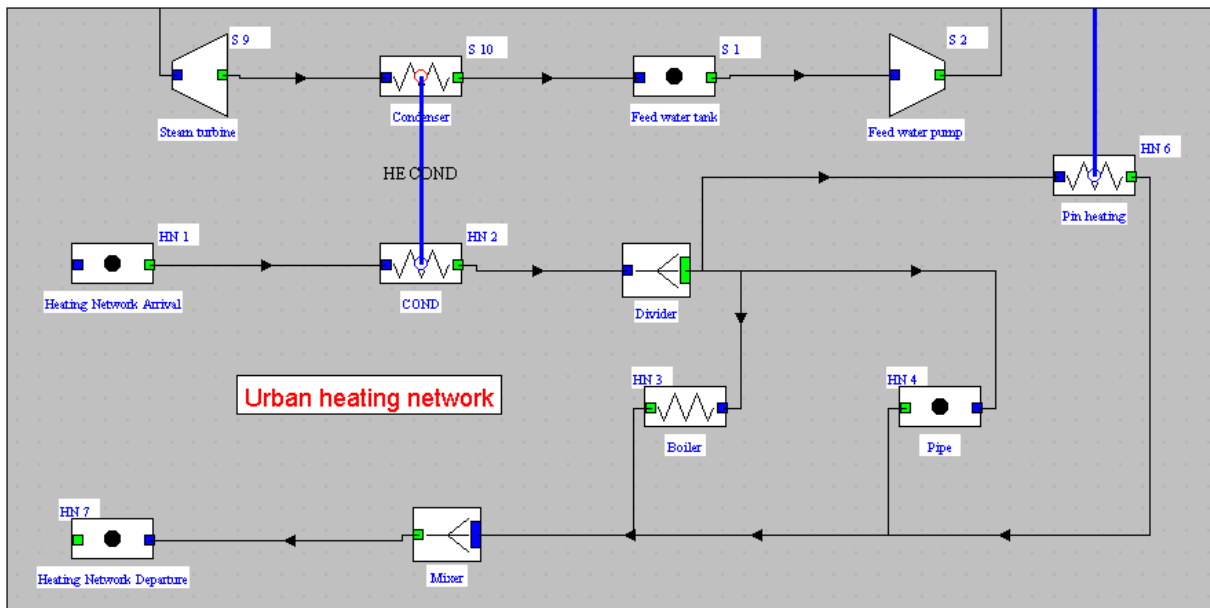
You find the following temperatures :

- B 1 591°C
- B 2 571°C
- B 3 495°C
- B 4 292°C
- B 5 210°C

The value given for B 5 by the plant manager is 204°C. The difference is 6°C, compared to a temperature decrease of 380°C, that is to say 1.5%.

Urban heating network

Represent the last elements in the Diagram Editor; the high-pressure hot water network for urban heating. Show the boilers in deviation, even if the flow is equal to 0 in the case you are modelling now, and the pin, which passes in the waste heat boiler.



Comments :

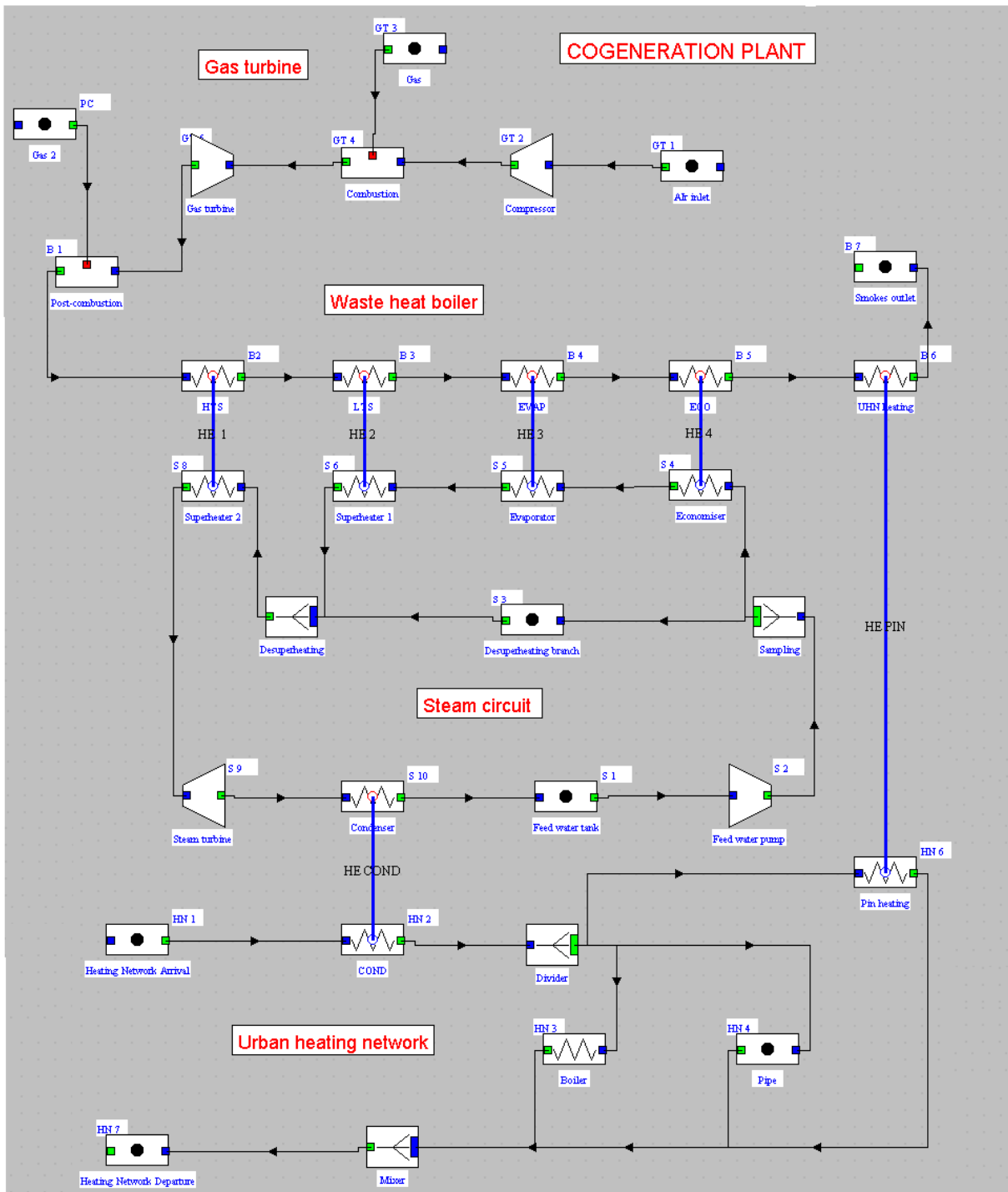
The exchanger of "Pin heating" links this process to the fifth exchange process of the waste heat boiler, "UHN heating".

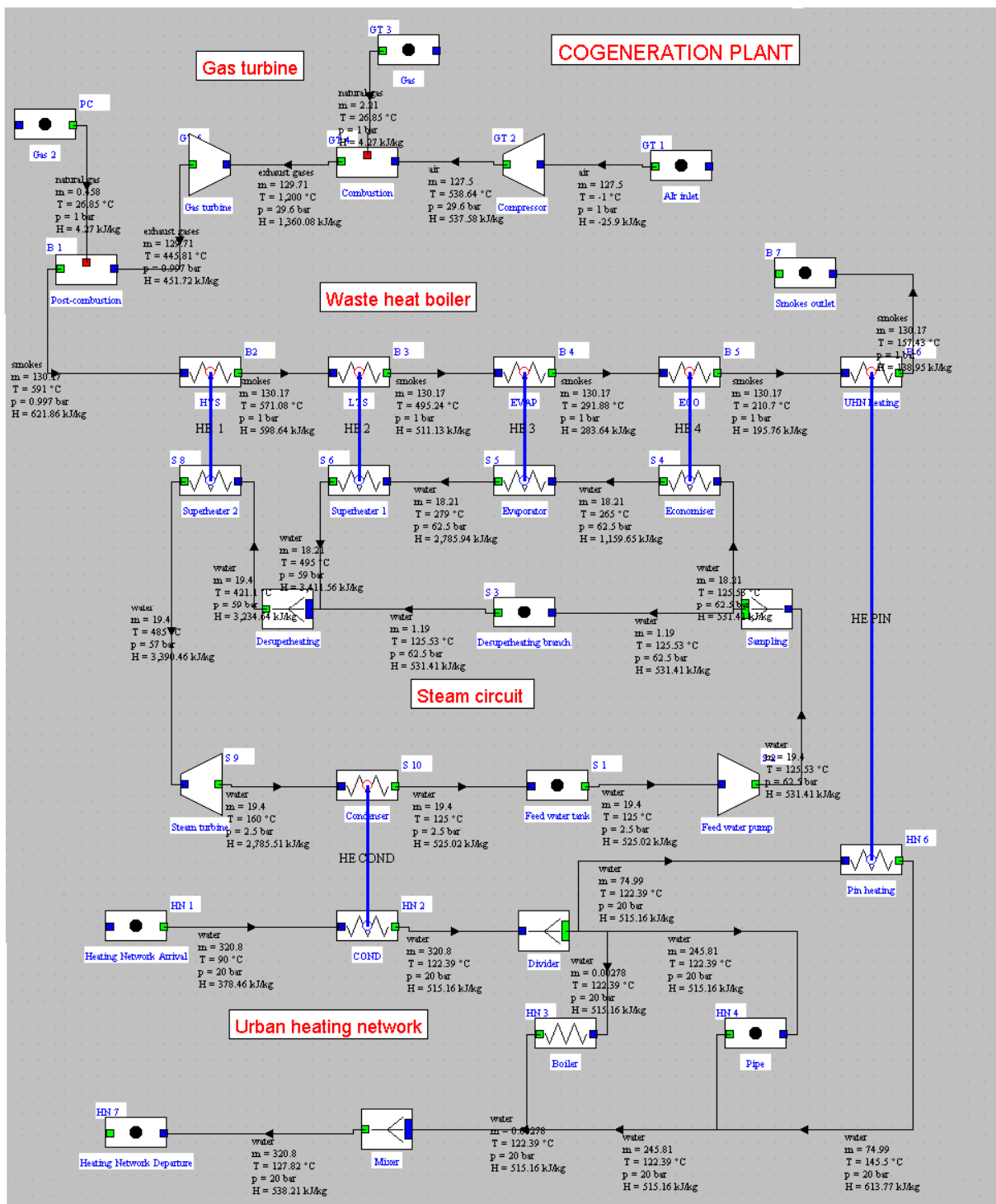
Enter the substance (water) in the process-point HN 6 because it is connected to the outlet of a mixer.

Transfer the new (and last) elements of the diagram in the simulator, and define :

- *Heating network return* : P = 20 bars, T = 90°C, set flow to 320,8 kg/s (= 1155 t/h).
- *COND* : preset the outlet point at 20 bars, and a temperature greater than 90°C (for the moment), in order to indicate to ThermoOptim that COND is the cold fluid of the exchanger. Open the screen of the exchanger, set the two inlet temperatures and flows, and the outlet temperature of the condenser. Calculate the exchanger, you find T = 122.4°C.
- *Divider* : set the flow rates of the three branches : boiler : 0.01 (you can't put 0), Pin heating: 270, and the last branch : 1155-270 = 885. Calculate and save.
- *Pin heating* : Set the outlet point at 145.5°C, and do like for COND, to find the smokes outlet temperature. You find 157°C.
- *Boiler and third branch* : set HN 3 and HN 4 to 20 bars. Set $\Delta H = 0$.
- *Mixer* : edit first the main branch (process-point Network departure) and set its pressure to 20 bars. Then come back to the mixer screen, calculate and save. You find $T_{\text{network_departure}} = 127.8^\circ\text{C}$.

On the two following sheets : complete diagram of the installation, and diagram with values.





II.2. Energy balance

As an installation of cogeneration products both heat and electricity, one introduces the following definitions of efficiencies to qualify its performances:

- *mechanical efficiency* :
$$\eta_m = \frac{\tau}{Q_c}$$

where τ is the mechanic work supplied by the turbines and Q_c the heat supplied to the installation by combustion and post-combustion.

- *global efficiency* :
$$\eta_g = \frac{\tau + Q_u}{Q_c}$$

where Q_u is the useful heat, taken by the hot water network at the level of the condenser and the pin.

- *heat-force ratio* :
$$HF = \frac{Q_u}{\tau}$$

One can calculate these different efficiencies in ThermoOptim's simulator. Choose the combustion and post-combustion as purchased energies, and the turbine and compressor of the gas turbine, and also the steam turbine, as useful energies, to obtain the **mechanical efficiency** :

Balance	
efficiency	0.443189
useful energy	57,716
purchased energy	130,228.84

Set also the condenser and UHN heating as useful energies to obtain the **global efficiency** :

Balance	
efficiency	0.836714
useful energy	108,964.24
purchased energy	130,228.84

To obtain the heat-force ratio, you can define the condenser and UHN heating as useful energies, and the gas turbine and steam turbine as purchased ones. These energies don't have the meaning "purchased" and "useful" here, but their ratio give the **HF ratio** :

Balance	
efficiency	0.887938
useful energy	51,248.24
purchased energy	57,716

As the project modelled here is complex, one should want to present a more detailed energy balance, doing the synthesis of all the energies implicated in the processes, and the different efficiencies characterising the cogeneration installation. To do it, it is possible to export the results of the calculations made by ThermoOptim in a text file, readable in a solver ; in the menu "result files", choose "Export results". ThermoOptim asks the name of the file where results would be exported ; choose a name with .txt extension, or the extension of the solver you use. Open your favorite solver, and load the file.

	A	B	C	D	E	F
1	THERMOPTIM	Copyright R. Gicquel 1999-2001				
2	EXPORTATION	September 7, 2001 12:17:45 o'clock PM CEST				
3	lang=en					
4	Project name	Cogeneration				
5						
6	Balance					
7	efficiency	purchased en	useful energy			
8	0.887938	57716	51248.24			
9						
10						
11	POINTS	30				
12	name	substance na	T (K)	P (bar)	quality	h (kJ/kg)
13	S 10	water	398.15	2.5	0	525.022846
14	S 1	water	398.15	2.5	0	525.022846
15	S 2	water	398.67733	62.5	0	531.409606
16	S 3	water	398.67733	62.5	0	531.409606
17	S 2 bis	water	398.67733	62.5	0	531.409606
18	S 4	water	538.15	62.5	0	1,159.65
19	S 5	water	552.15	62.5	1	2,785.94
20	S 6	water	768.15	59	1	3,411.56

You can then work on this data with your solver, and, for example, make a detailed energy balance of the project:

Cogeneration Energetic Balance

Process	Power (MW)
GT combustion	107.9
Post-combustion	22.4
TOTAL Purchased Power	130.2
GT turbine	117.8
GT compressor	71.8
GT mechanical power	46.0
ST mechanical power	11.7
TOTAL Mechanical Power	57.7
Condenser	43.9
Pin heating	7.4
TOTAL Useful Thermal Power	51.2
TOTAL Useful Power	109.0
<i>Mechanical efficiency</i>	<i>44.3%</i>
<i>Global efficiency</i>	<i>83.7%</i>
<i>Heat-Force ratio</i>	<i>0.89</i>

III. Other cases of operation

You are now going to see how you can modify the model you have made with ThermoOptim in order to model other cases of operation of the plant.

III.1. Important thermal needs

This case of operation is really simple to model from the borderline case you studied. Indeed, when needs in heat are more important than in this case, the post-combustion and steam cycle stay maximal, and the extra heat is brought by boilers in deviation.

One has only to pass a non-zero flow by boilers, and to supply the extra thermal power with it.

To know the value of this extra power, use a trick; model the case where ambient temperature is -5°C , you have : (see paragraph I.2.) :

- Network flow : $1\,372\text{ t/h} = 381\text{ kg/s}$
- $T_{\text{return}} = 90^{\circ}\text{C}$
- $T_{\text{departure}} = 130^{\circ}\text{C}$

Parameterise the heating network with this new flow (the return network temperature stays the same), and calculate the temperature of departure obtained, without boilers supply for the moment :

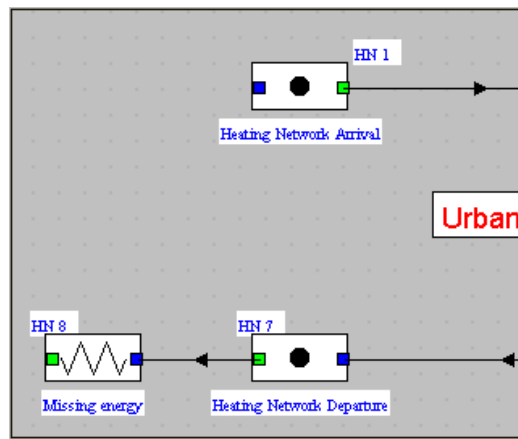
- *Network return:* set the flow to 381 kg/s . Don't change anything else. Calculate and save.

- *Exchanger COND:* : to calculate the water temperature at the outlet of the condenser of the steam circuit, one must recalculate the exchanger. Open it. You are going to calculate the ΔT of water, but not redesign the exchanger, because one wants it to "physically" stay the same exchanger. To do it, check the box "non nominal".

- In order to calculate the water temperature at the outlet of the exchanger with the condenser of the steam circuit, one must re-calculate the exchanger. Open it. You are going to calculate the water temperature elevation, but not re-design the exchanger, because you want it to represent physically the same exchanger. To do it, check the box "non nominal". This option permits to conserve the design defined previously: the UA coefficient, product of the exchange surface by the exchange coefficient, stays the same. Once this option checked, one can give five or four constants.
- Calculate the end of the hot water network, this time with a non-zero flow in the boiler, but still with $\Delta h = 0$.

The temperature obtained at the departure of the hot water network is 122.8°C.

You are now going to introduce a new exchange process, in order to calculate the energy the boiler must furnish to raise the water temperature to 130°C. In the Diagram Editor, create an exchange process named "Missing energy", and link it to the point HN 7, at the outlet of the circuit.



Open the screen of the process, then the one of the outlet point. Set its temperature to 130°C, and calculate Δh of the process.

Exchange Process

process: Missing energy type: exchange links: < > Save

energy type: other set flow flow rate: 381 closed system observed Suppress Close

inlet point: HN 7 display Delta_H: 11,533.44 open system Calculate

T (°C): 122.88 P (bar): 20 h (kJ/kg): 517.23 quality: 0 minimum pinch: 0

outlet point: HN 8 display pinch method fluid

T (°C): 130 P (bar): 20 h (kJ/kg): 547.5 quality: 0

Calculate Delta H, the outlet point being known
 Set Delta H and modify the outlet point

You see that the energy the boiler must bring to the water is 11 538 kW. Suppress the "Missing energy" process, and parameterise the boiler, check "Set Delta H and modify the outlet point", and set this value for Δh . Recalculate now the mixer: you find the outlet temperature wanted!

III.2. Less important thermal needs

When thermal needs are less important than in the borderline case at -1°C , boilers are turned off, and the flow in the steam circuit is less important, so heat brought by the condenser also. Post-combustion is set to a lower level. Setting the temperature of post-combustion is difficult because, everywhere in the exchangers, there must be a difference of temperature of at least 10°C between the hot fluid (smokes) and the cold one (water/steam). Places where this difference of temperature is locally minimal are called the pinches of the system. These pinches can be found at the extremities of the boiler or in the evaporator. The lowest pinch stresses the whole system because it mustn't become smaller than about 10°C .

If the minimal pinch is in the evaporator, one should take the maximum heat from the smokes after the evaporator to reject them to the atmosphere at the lowest temperature possible. The heating of the water network should be done more in the pin.

On the contrary, if the pinch is at the end of the boiler, at the place where smokes are rejected, one should take heat from smokes before the reject, so one should have the flow in the steam circuit the highest possible. The condenser gives more heat to the water network.

These few arguments let see that it is very difficult to optimise globally the whole plant, because one needs to set simultaneously the post-combustion temperature, the flow in the steam circuit, the power of the pin exchanger...

Your objective here will be simpler: it is to find a solution, not necessarily the best one, to heat the hot water network while respecting the pinches constraints.

Model, by example, the case where outside temperature is 5°C , that is to say (see table in paragraph I.2):

- network flow : $1\,128\text{ t/h} = 313\text{ kg/s}$
- $T_{\text{arrival}} = 90^{\circ}\text{C}$
- $T_{\text{departure}} = 119^{\circ}\text{C}$
- Needs in heat = 44.2 MW.

One must drain off around 7.5 MW in the pin exchanger to refresh smokes before their reject in the atmosphere. One must then take around $44.2 - 7.5 = \mathbf{36.7\text{ MW}}$ in the condenser.

In the steam cycle, steam enters the condenser at 160°C and 2.5 bars, and leaves it liquid at 125°C . In these conditions, Thermoptim calculates that for 1 kg/s, power drained is 2260.5 kW. The flow necessary is then $36\,700 / 2\,260 = \mathbf{16.23\text{ ks/s}} \approx 58.4\text{ t/h}$.

Exchange Process

process: Condenser type: exchange

energy type: useful set flow flow rate: 1

inlet point: S 9 Delta_H: -2,260.49

T (°C): 160 P (bar): 2.5 h (kJ/kg): 2,785.51 quality: 1

outlet point: S 10

T (°C): 125 P (bar): 2.5 h (kJ/kg): 525.02 quality: 0

minimum pinch: 0 pinch method fluid

Calculate Delta H, the outlet point being known
 Set Delta H and modify the outlet point

Buttons: Save, links, Suppress, Close, Calculate, display, display

- Set this flow and recalculate the whole steam cycle. Set the flow 1 kg/s in the desuperheating branch. In the first superheater, don't go to 495°C but only to 450°C.
- Calculate now the minimal temperatures of the smokes in the waste heat boiler: begin by calculate (in "non nominal" mode) the exchanger where is located a priori the pinch, that is to say in the evaporator. Set a pinch of 10 K, calculate the inlet and outlet temperatures of the cold fluid. You find 458 and 287°C.

Heat exchanger

name: HE 3 type: counterflow

hot fluid: EVAP cold fluid: Evaporator

Tce (°C): 458.29643925 set calculated
Tcs (°C): 287.73681272 set calculated

mc: 130.16854475 set calculated

Cpc: 1.11342265 DHc: -24,719.65109037

Tfe (°C): 265 set calculated
Tfs (°C): 279 set calculated

mf: 15.2 set calculated

Cpf: 116.16377391 DHf: 24,719.65108767

UA: 326.05752368 R: 0.0820827313
NTU: 2.24971822 LMTD: 75.81377301

unconstrained minimum pinch DTmin: 10 set efficiency epsilon: 0.882373349

design non nominal

Buttons: Save, links, Suppress, Close, Calculate, display, display

- Calculate now the smokes temperatures at the other points of the waste heat boiler: begin by HE 2, set smokes outlet temperature (485°C) and calculate the inlet temperature. Then calculate HE 1, by the same method. Calculate then HE 4 and HE PIN in setting inlet temperature and calculating outlet temperature. You find the following smokes temperatures:

B 1	539°C
B 2	511°C
B 3	458°C
B 4	287°C
B 5	220°C
B 6	166°C

- End by calculating the urban heating network, with flow = 313 kg/s.

This case of operation is simulated in the file Coge2.prj.

You can compare the energetic balances obtained at -1°C, -5°C et 2°C:

Outside Temperature	-5°C	-1°C	2°C
Process	Power (MW)	Power (MW)	Power (MW)
GT combustion	107.9	107.9	107.9
Post-combustion	22.4	22.4	14.3
Boilers	11.5	0.0	0.0
TOTAL Purchased Power	141.7	130.2	122.2
GT turbine	117.8	117.8	117.8
GT compressor	71.8	71.8	71.8
GT mechanical power	46.0	46.0	46.0
ST mechanical power	11.7	11.7	9.8
TOTAL Mechanical Power	57.7	57.7	55.8
Condenser	43.9	43.9	36.7
Pin heating	7.4	7.4	7.5
Boilers	11.5	0.0	0.0
TOTAL Useful Thermal Power	62.7	51.2	44.2
TOTAL Useful Power	120.5	109.0	100.0
Mechanical efficiency	40.7%	44.3%	45.7%
Global efficiency	85.0%	83.7%	81.8%
Heat-Force ratio	1.09	0.89	0.79