

Guidance page for practical work 15: modeling of the secondary circuit of a PWR

1) Objectives of the practical work

The aim is to investigate the potential of Thermoptim in modeling and calculation of energy balances of complex cycles. Therefore, it is assumed that the reader is already a Thermoptim user who is acquainted with the basic functions. If this is not your case, you should start by studying the Diapason sessions on simple steam cycles (S25 and S26En¹).

The example presented here is a secondary circuit of nuclear power plant: the objective is to model it in Thermoptim, calculate its energy balance, and perform some sensitivity analysis on some parameters².

2) References

- [1] GICQUEL R., Energy Systems: A New Approach to Engineering Thermodynamics, CRC Press, 2011.

3) Main practical work

31. Presentation of the system

Pressurized Water nuclear plants are composed of two parts to convert the heat produced by the nuclear reaction in the reactor into mechanic energy, and then in electricity in a generator:

The reactor coolant system is traversed by liquid pressurized water, which is heated in the reactor, then pumped into the steam generator (SG), where it transfers heat to the secondary cooling system.

The secondary cooling system is traversed by water, which is heated and converted into steam in the steam generator. The steam passes through HP and LP turbines and drives the generators, then it is condensed at by a cold source, sent to the feedwater tank, and then pumped again in the steam generator. The cold source is an external element, a river, the sea or the atmosphere by example.

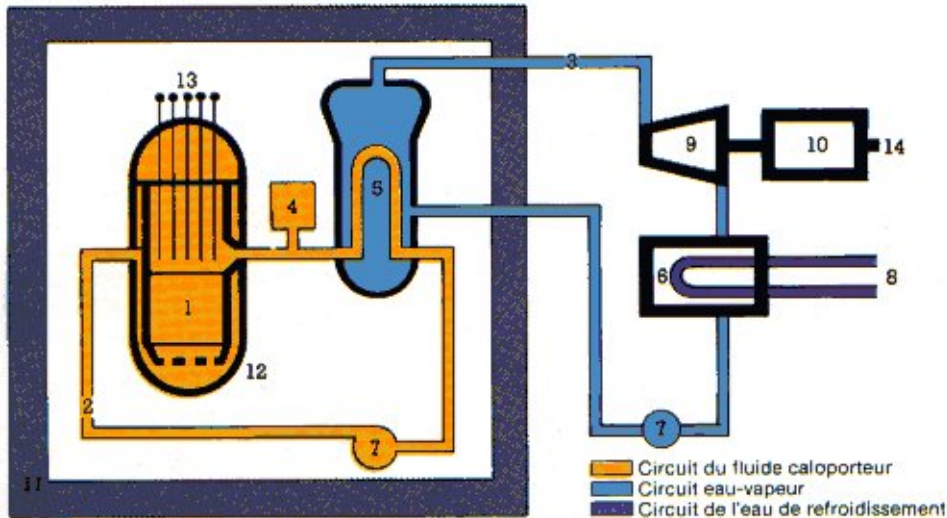
The presence of the two systems is motivated by safety reasons, because the water of the reactor coolant system, in contact with the heart of the reactor, is radioactive. The water of the secondary system is not, because it is not in contact with the first system. It limits the risks of passage of radioactive products outside. Other cooling systems guarantee security and permit to cool the reactor in case of emergency.

¹ Session S25 : <http://www.thermoptim.org/SE/seances/S25/seance.html>

Session S26En : http://www.thermoptim.org/sections/enseignement/cours-en-ligne/seances-diapason/s26_vapor_cycle

² If you are working on an educational or demonstration version, the sensitivity analysis and pressure control functions not being available, you can model the cycle but you cannot achieve as easily the analyzes proposed

The system modeled here is the secondary system of a nuclear power plant "N4" (a type of plant developed by EDF). The secondary system is the "classic" part of the power plant, but its steam cycle is subject to some special constraints, which make it differ from the Hirn cycle of classical thermal power plants.



3.2. Constraints and modeling assumptions

Temperature of the condenser

The temperature of the coolant substance (river, sea, air...) is close to the ambient temperature. In order to increase the rate of thermal transfer, one should keep a pinch of about 15 K, and the temperature in the condenser is taken close to 40°C. This temperature is an important parameter that we will make vary in order to optimize the efficiency.

Hot temperature

In the reactor coolant system, the water temperature is limited to 330°C, by the conditions of thermal exchange with the nuclear core. Water is pressurized at 155 bar to avoid boiling. In the steam generator, the temperature of the water of the reactor coolant system is between 300 °C and 320 °C. Due to the small difference of temperature of the reactor coolant water between the inlet and the outlet, the water of the secondary system is vaporized but not superheated. The steam temperature at the outlet of the generator is close to 280 °C.

This temperature is small compared to the ones reached in classic thermal power plants (560 °C), where safety reasons do not impose such a limit to the hot temperature.

The maximal efficiency of a thermal machine working between $T_0 = 313 \text{ K}$ (40 °C) and $T_1 = 553 \text{ K}$ (280 °C) is then rather small, it is given by:

$$\eta_{th} = 1 - \frac{T_0}{T_1} = 1 - \frac{313}{553} = 0.43$$

Pressures in the circuit

A pump pressurizes liquid water to 70 bar, for, if we take into account pressure drops, vaporization in the steam generator takes place close to $P_{sat}(280 \text{ °C}) = 65 \text{ bar}$.

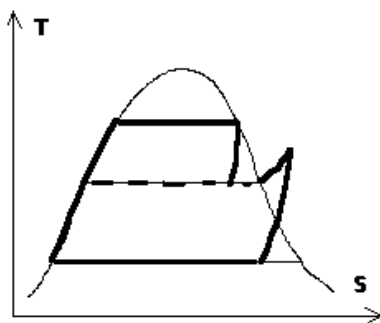
The pressure of the steam at the inlet of the HP turbine is chosen close to 50 bar, in order to better regulate the turbine. Similarly, the steam taken at the outlet of the steam generator for the superheat is expanded at 51.5 bar.

The condensation pressure of the cycle is $P_{\text{sat}}(40\text{ °C}) = 0.07\text{ bar}$.

An intermediate pressure of 11 bar is used, and the expansion of the steam is separated in a HP expansion between 50 and 11 bar, and a LP expansion between 11 and 0.07 bar.

Drying and superheat of the steam at the outlet of the HP turbine

As the steam entering the HP turbine is not superheated, it starts to condense at the beginning of the expansion. Droplets of liquid decrease the turbine efficiency, and are corrosive for the turbine. The quantity of liquid is limited to 25%.

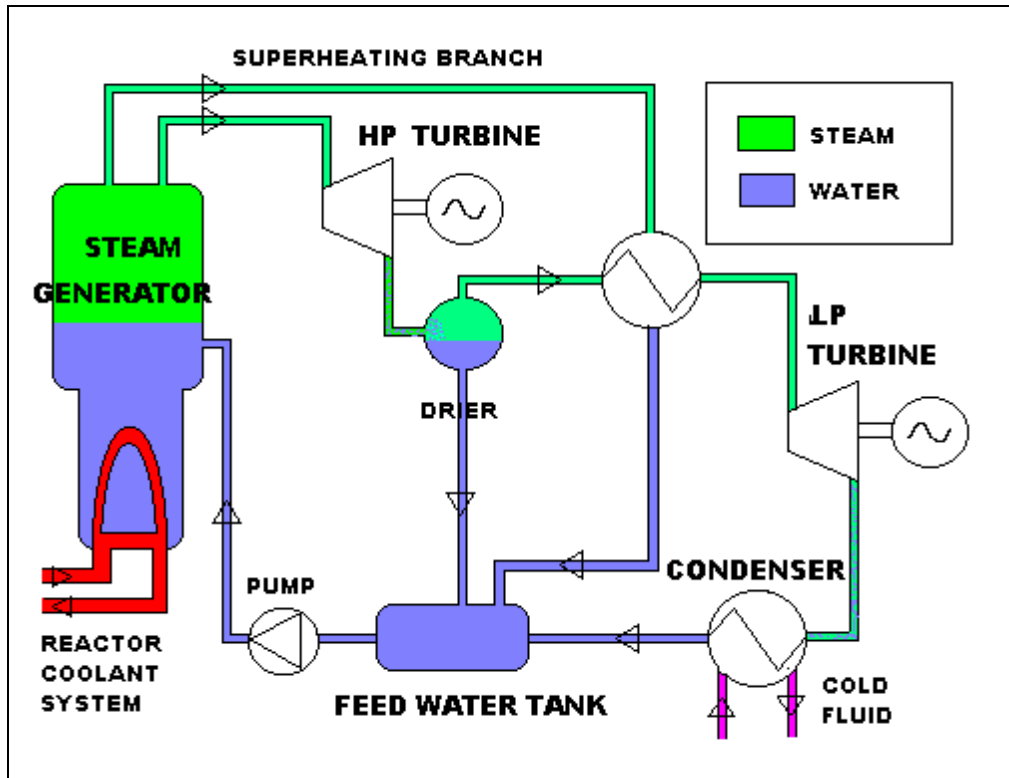


At the outlet of the HP turbine, the liquid-steam mix is separated, liquid is sent to the feed water tank, whereas steam is superheated before being entering the LP turbine. Superheating can be done at low energy cost with an extraction of steam at the outlet of the steam generator. The gain is high because steam condenses only at the end of the LP expansion.

3.3. Diagram and description of the cycle

The steam cycle in the secondary cooling system (Rankine cycle) is shown on the (T,s) chart:

The diagram of the system is as follows:



The feedwater tank is kept at a pressure of 11 bar. Temperatures of the different condensates mixed determine water temperature at the outlet. At the outlet, the feedwater pump pressurizes the water at 70 bar.

It is then heated in the economizer and converted into steam in the steam generator. Pressure drops make pressure decrease to 65 bar at the outlet of the economizer and 56 bar at the outlet of the steam generator. Steam is not superheated.

The main part of steam is expanded at 50 bar in a valve before being expanded in the HP turbine at 11 bar. At the turbine outlet, the two phase fluid is separated in a dryer. Liquid is sent to the feedwater tank, whereas steam is superheated, then expanded in the LP turbine at 0.07 bar. Fluid is then condensed in the condenser, compressed again to 15 bar, and sent to feedwater tank.

Superheating at the outlet of the dryer is made with an extraction at the outlet of the steam generator. Steam extracted is expanded at 51.5 bar, then it releases heat while condensing completely. The condensate is then sent to the feedwater tank.

Efficiencies of pumps and turbines

Isentropic efficiencies are given by manufacturers:

HP turbine: isentropic efficiency = 0.816, small because steam is very humid in the turbine.

LP turbine: isentropic efficiency = 0.85

pumps: isentropic efficiency = 0.9

Remark:

A real circuit has in addition different extractions, which for reasons of simplicity, were not modeled here. You should refer to the steam plant example to study the influence of these extractions³.

4. Modeling with ThermoOptim

Now you are going to model the cycle with ThermoOptim, calculate its efficiency, and understand how the different parameters you can adjust influence the cycle performance: the flow of the steam extraction, the intermediate pressure and the condenser temperature.

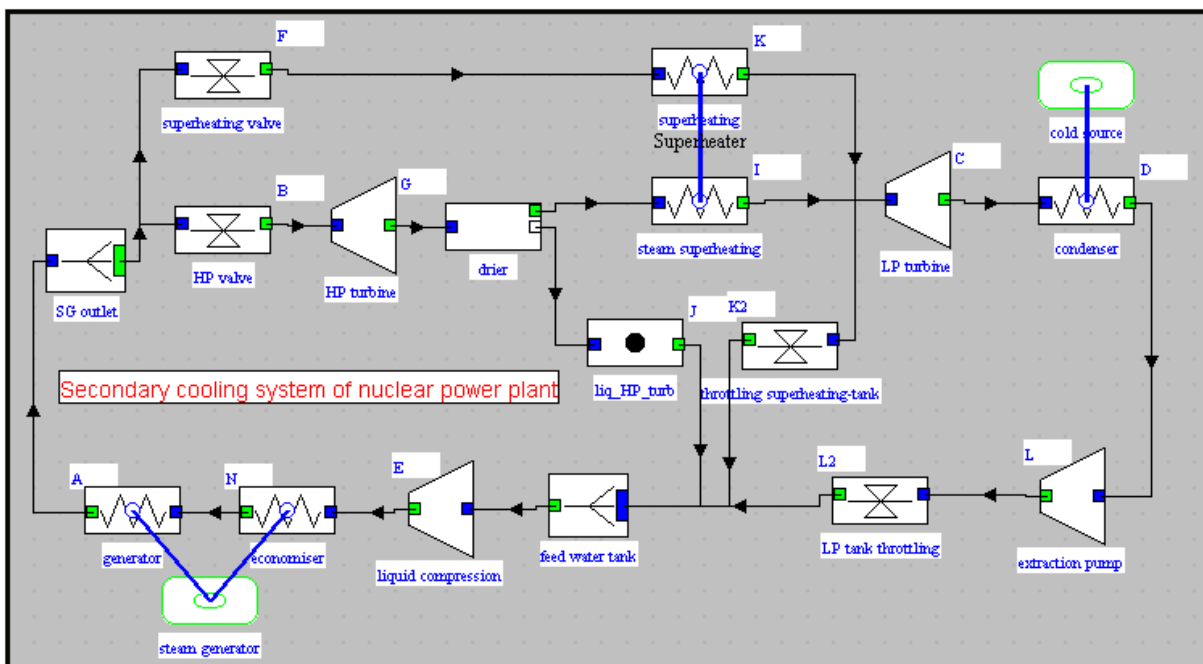
4.1. Creation of the diagram

In the Diagram Editor, create the different processes of the cycle and connect them.

Don't forget the valves at the outlet of the steam generator: one to expand the steam before the HP turbine, and one before the superheater. You should insert throttlings in two of the three veins going to the feedwater tank, in order to expand the fluids to the tank pressure (11 bar).

The process-point inserted between the dryer and the feedwater tank is obligatory because ThermoOptim cannot directly connect two nodes.

The cold source is also materialized on the condenser and the hot source on the steam generator.



4.2. Definition of the points and processes.

Set the parameters of the different points and processes according to the data, and calculate the processes in order to obtain a first balance. To do it, 5% of the steam generator flow is extracted for

³ Session S27En : <http://www.thermooptim.org/sections/enseignement/cours-en-ligne/seances-diapason/session-s27en-extraction>

the superheating (you will better adjust this rate later). If your version of Thermoptim has the Pressure Settings, create a IP pressure set to 11 bar (for the moment), and a BP pressure set to 0.07 bar.

You can start by point N (economizer outlet), which is *a priori* known:

Point N: set $P = 65$ bar, $T = T_{\text{sat}}$, quality = 0. Calculate and save.

Point A: $P = 56$ bar, $T = T_{\text{sat}}$, quality = 1. Calculate and save.

Process generator: choose "energy type = purchased", calculate, save.

Node SG outlet: this divider allows you to set the rate of steam extracted for superheating at the outlet of the HP turbine. The screen of the divider shows the two branches "HP valve" and "superheating valve". You may set the two flows by two different methods :

Use the mouse to select one of the veins, then click on "flow setting". Indicate the flow rate (95 for the main branch and 5 for the superheating branch). Calculate.

Set flow in one of the branches. To do it, open the screen of the process "HP valve", check the box "set flow", and indicate the value of the flow (real and not relative)(0.95). Save and come back to the divider screen. Simply click on "Calculate" and the flow value in the other branch is given. The message "set flow" appears in red.

Set flow in the "HP valve" process

process name	m abs	m rel	T (°C)	H
HP valve	0.95	0.95	271.09	2,788.99
superheating ...	0.05	0.05	271.09	2,788.99

Set flow in the divider

The second method can be used only when the divider has exactly two branches. Here, it is better to choose this method, because it allows making sensitivity analyses on these flows.

Set the parameters and calculate now the points and processes of the main HP branch up to the heat exchanger "steam superheating".

Throttling "HP valve": display the outlet point B, set $P = 50$ bar. Calculate and save.

HP turbine : isentropic efficiency = 0.816. Set the outlet pressure: it is the intermediate 11 bar pressure, on which one wants to make sensitivity analyses. If you don't have the "Pressure Settings" in your Thermoptim version, just indicate 11 bar in the field for pressure, else:

Start by creating a set pressure: in the main screen of Thermoptim, click on the table of Pressure Settings. A screen "pressure settings" appears. Indicate the name of the pressure (IP) and its value (11), and save. In the main screen, table of set pressures has now one element.

Open the screen of point G (turbine outlet). To set its pressure, check "set P controlled", double-click on the blank field under, and choose "IP". Save the point, calculate and save the expansion.

1 PRESSURE SETTINGS

name	value
IP	11

Pressure settings
(Simulator screen)

Open system (T,P,h) Closed system (T,v,u) Water vapor/gas mixtures

P (bar) 11 h (kJ/kg) 2,562.80466628

set P controlled P and h known

IP P and T known

correction factor 1 exergy (kJ/kg) 812.1376

Controlled pressure for the point G.

Node "dryer": to calculate this separator, you must indicate what is the outlet branch for the liquid and for the steam. Open the screens of the inlet points of the processes "steam superheating" and "HP_turb_liq", and indicate their quality, respectively 1 and 0. Come back to the dryer and calculate it.

Exchange process "steam superheating": you cannot calculate now the temperature of the outlet point, but you must indicate a temperature higher than the inlet temperature and calculate the enthalpy involved in the process (positive), in order to prepare the calculation of the heat exchanger, which must obligatory distinguish the cold and the hot fluid.

Set the parameters and calculate now the branch of steam extraction for superheating.

Throttling "superheating valve": outlet pressure = 51.5 bar.

Exchange process "superheating": one wants the hot fluid in the exchanger to be two-phase; at the inlet, it is already at T_{sat} , and quality ≈ 1 . At the outlet, set quality = 0, but let the box "set Tsat" unchecked, so that the exchanger doesn't find in its calculations a constraint on the outlet temperature of this fluid. Calculate the enthalpy variation (negative) of the process and save. During the calculation of the exchanger, the outlet temperature of the hot fluid is calculated according to the other constraints, in particular the effectiveness of the exchanger. It can be lower than the temperature of condensation.

You can now set the parameters of the exchanger in order to calculate the outlet temperatures of the fluids. Set the exchanger effectiveness to 0.8, and the inlet temperatures and flows of the two fluids: there are 5 constraints, the exchanger can be calculated.

Heat exchanger

name Superheater type counterflow

links Suppress Close

hot fluid superheating display

cold fluid steam superheating display

Calculate

Tce (°C) 265.76398414	<input checked="" type="checkbox"/> set calculated	Tfe (°C) 184.0674	<input checked="" type="checkbox"/> set calculated
Tcs (°C) 200.40671683	<input checked="" type="checkbox"/> set calculated	Tfs (°C) 230.24222541	<input type="checkbox"/> set calculated
mc 0.05	<input checked="" type="checkbox"/> set calculated	mf 0.846907477	<input checked="" type="checkbox"/> set calculated
Cpc 29.58053954		Cpf 2.47188779	
DHc -96.66516148		DHf 96.66516148	

unconstrained

minimum pinch DTmin 0

set efficiency epsilon 0.8

UA 3.91333784

R 0.706498715

NTU 2.64588672

LMTD 24.70146085

design non nominal

Finish setting the parameters and calculating the last elements:

Throttling "throttling superheating-tank": at 11 bar.

LP turbine: expansion at 0.07 bar (create a LP set pressure of value 0.07 bar), isentropic efficiency 0.85.

Condenser at 0.07 bar.

Extraction pump: liquid compression at 15 bar, isentropic efficiency 0.9

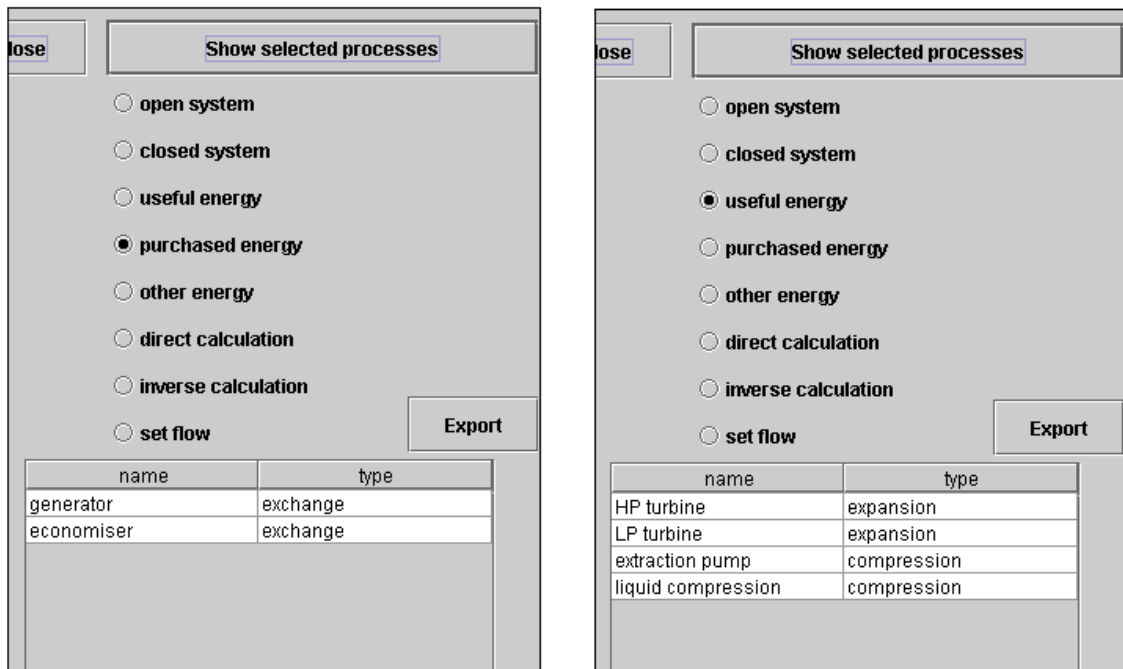
Throttling "LP tank": expansion at 11 bar.

Feedwater tank: don't forget to indicate the outlet pressure, 11 bar (Thermoptim doesn't do it alone).

Liquid compression: at 70 bar, isentropic efficiency 0.9.

Economizer.

The cycle is now entirely calculated. Check (with "Diagnosis tools" of menu "Special" for example, if your version of Thermoptim allows it) the "useful" and "purchased" energies:



Diagnosis tools: show purchased and useful energies

Calculate the balance:

Balance	
efficiency	0.308658
useful energy	772.51
purchased energy	2,519.12

The efficiency of this cycle is 30.7%, to compare with the 43% of the Carnot cycle. You can now vary the values of the extraction flow, of the intermediate pressure, and of the condenser temperature, in order to understand their influence on the global efficiency of the cycle.

4.3. Influence of the different parameters

Steam extraction flow

One can see, by making a sensitivity analysis on the flow, or by calculating the balance for some different values of the flow, that the variation of the flow between 1% and 10% doesn't change the global efficiency of more than 0.5%. One can then think that this flow doesn't have any influence, but this is because Thermoptim doesn't take into account the variation of the isentropic efficiency of the turbines with humidity of steam which passes through.

Indeed, the lower the superheating is, the more humid steam will be in the LP turbine, and the lower its isentropic efficiency, as well as the global efficiency. Furthermore droplets of water have an abrasive effect on the turbine blades.

It is then better to set the extraction flow to a value where superheating is important. A 8% extraction leads to a steam temperature of 250 °C at the inlet of the BP turbine (but 230 °C for a 5% extraction for example). Higher extraction does not increase this temperature a lot, but decreases the flow in the main branch.

Intermediate Pressure

With constant isentropic efficiency of the HP turbine, variation of the intermediate pressure doesn't induce significant variations of the global efficiency (no more that 1%).

However, for the real turbine, the quality of steam at the end of expansion must be the highest possible. The choice of intermediate pressure is done according to the turbine parameters, which is not modeled in Thermoptim. The value taken for it is 11 bar.

Condensation temperature

The temperature (or pressure) of the condenser is on the contrary a very important parameter, which can vary the global efficiency in an important way. The impact of the LP pressure (and then, of the condensation temperature) can be analyzed with the "Sensitivity analyses" function, of the "Special" menu.

Open the "Sensitivity analyses" screen, click on "Show mutable elements"; a list of mutable parameters of the cycle appears. These are:

set pressures.

points with temperature set by the user, and that you can modify.

Processes with the "set flow" box checked.

Select the LP pressure line. On the left, the message "pressure setting | P / pressure P | initial value: 0.07" appears. In order to analyze the influence of this pressure between the values 0.01 and 0.07 bar, indicate the value 0.01 in the field "minimum value", 0.07 in the field "maximum value", and 0.01 in the field "increment". Click "Iterate"; Thermoptim calculates and shows the useful and purchased energies for all the values of pressure selected.

Sensitivity analyses

Show mutable elements

pressure setting | LP

pressure P | initial value : 0.07

name	type
IP	pressure setting
LP	pressure setting
N	point
A	point
I	point
K	point
HP valve	throttling

minimum value: 0.01
maximum value: 0.07
increment: 0.01
maximum number of recalculations: 10
test value: 0.01

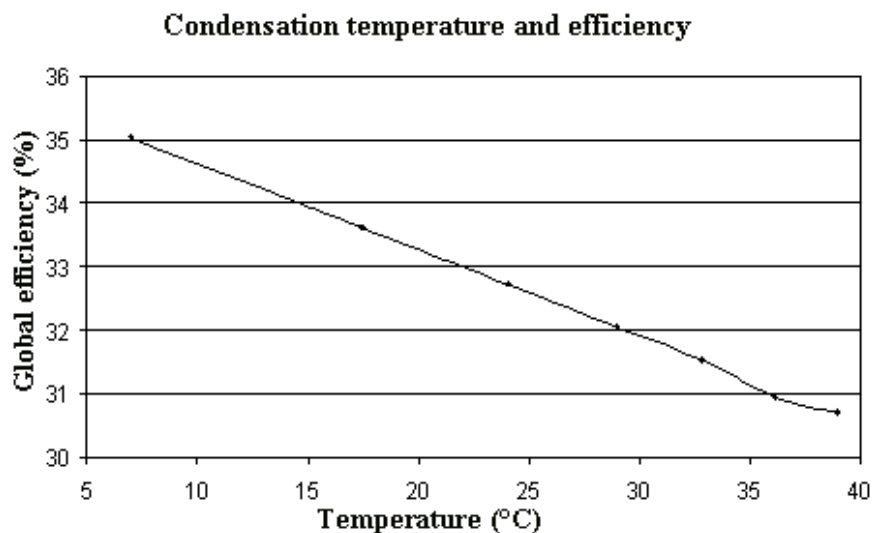
SENSITIVITY ANALYSIS
project: Nuclear power plant
September 5, 2001 3:56:54 o'clock PM CEST

pressure setting | LP

pressure P	useful	purchased	iterations	accuracy
0.01	921.68	2633.06	2	0.000000414465
0.02	871.22	2595.27	3	0.0000000756552
0.03	840.59	2572.03	3	0
0.04	817.95	2554.6	3	0.0000000286859
0.05	799.96	2540.61	3	0
0.06	785.08	2528.97	3	0.0000000287052
0.07	772.51	2519.12	3	0

Iterate Close

You can then continue to process these values in a spreadsheet; select the table of results, copy and paste it in a spreadsheet. Here it is for example the curve showing the global efficiency according to the condenser temperature.



The efficiency of the cycle increases significantly when the temperature of the condenser is reduced by 10 °C. This parameter seems to be the one on which one should pay more attention, but to model precisely the influence of the other parameters, one should know how the efficiencies of turbines vary with the steam quality.

5) Work files

The project and diagram files of the ThermoOptim model are in the archive PWR_N4.zip.

