Conventional water/steam cycle

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2.1 Introduction

This example relates to the water/steam cycle of a large conventional electricity power station with a design power of 600 MW_e.

For this water/steam cycle a scheme is defined (see Figure 2-1) for both design and off-design cases, although each case is stored in a separate file. It will be explained how a design calculation can be transformed into an off-design calculation, using design data generated by the design calculation.

Calculation results are set out for the design calculation and calculations with 80% part load. The calculations demonstrate in particular a few options of the models for steam turbines, flashed heaters and condensers.

2.2 System description

In the water/steam cycle shown in Figure 2-1 steam of 180 bars and 530 °C expands in the high pressure turbine 2 to a pressure of around 38 bars. The steam is reheated (4) to 530 °C and expanded further in two sections of the intermediate-pressure turbine and in six sections of the low-pressure turbine. The number of parallel sections is not shown, but is specified in the TUCODE for apparatus 5. When using the General Electric procedure in Cycle-Tempo the intermediate- and low-pressure turbines are represented by one turbine (5).

The steam then condenses in condenser 6 at a pressure of 0.027 bar. The condensate is preheated in eight preheaters: five low-pressure and three high pressure preheaters. The last low-pressure preheater (13) is a deaerator, in fact a mixing preheater. The other low-pressure preheaters (8, 10, 11 and 15) are surface preheaters. The surface preheaters, with the exception of the first preheater, are equipped with a subcooler. The condensate of these four preheaters is collected, via any preceding preheaters, in the first preheater (with the lowest extraction pressure). From here the auxiliary condensate pump 19/8 pumps this condensate to the main condensate line. The three high-pressure preheaters (15, 16 and 20) are surface preheaters, each equipped with a desuperheater and a subcooler. The condensate from this is fed into the deaerator, via any preceding preheaters, with the main condensate stream.
Feed pump 14 pumps the feedwater of the deaerator to boiler 1. The feed pump is driven by auxiliary turbine 18. This turbine, like the deaerator, is supplied with extraction steam from the outlet of the intermediate-pressure turbine. In the auxiliary turbine the steam is expanded to a pressure of 0.027 bar. The main and auxiliary condensate pumps (7 and 14) are driven by electro motors.

Apparatus 21 is a dummy. This apparatus is added in order to show separately the pressure drop of the live steam (4% of inlet pressure HP-turbine) (pipe 37) and the throttling losses of the control valves (3% of inlet pressure HP-turbine). This apparatus does in fact form the inlet of turbine 2. The throttling losses of 3% are specified as pressure drop in pipe 1.

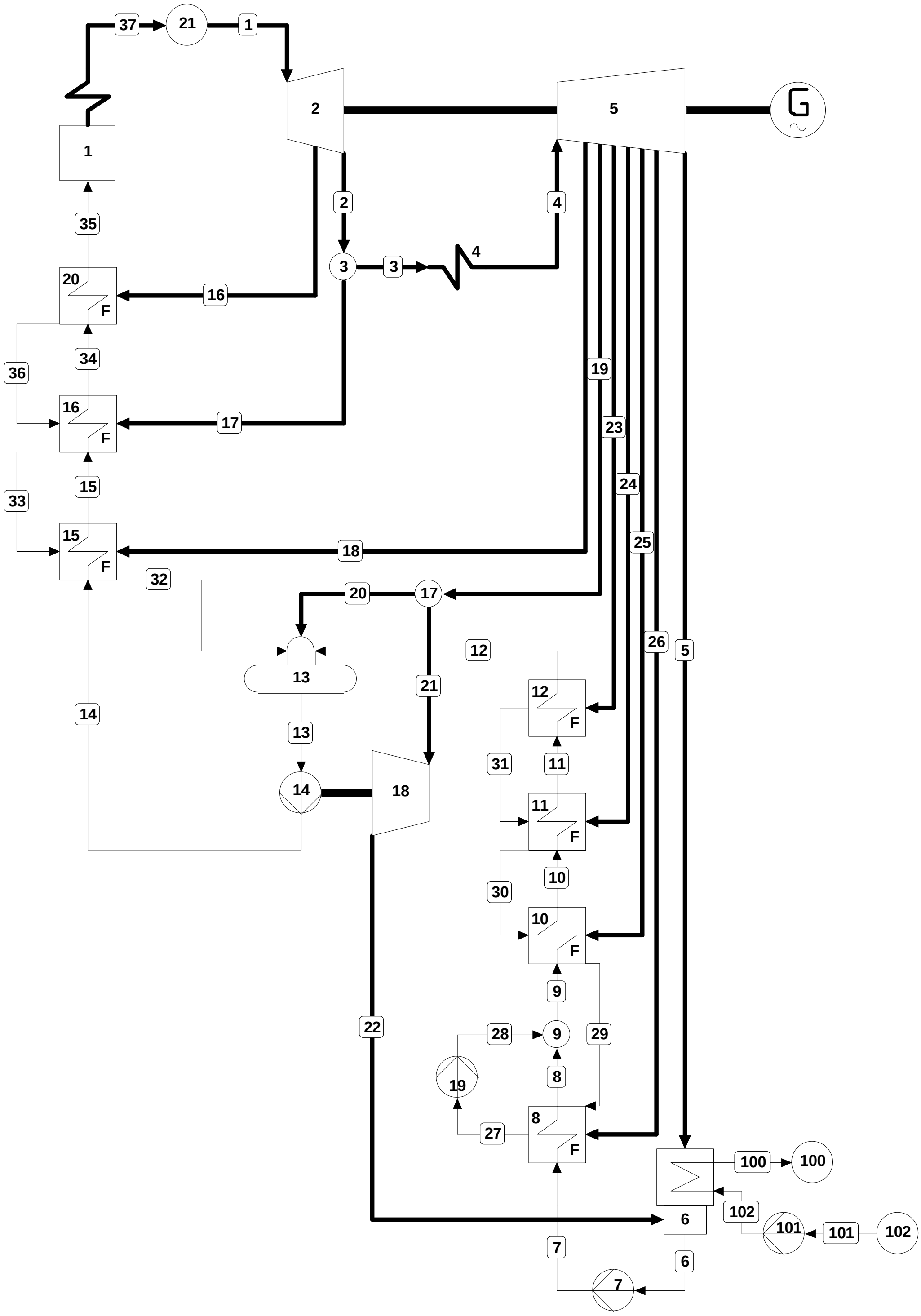

Figure 2-1: conventional water/steam cycle

2.3 Starting points for the calculation

The most important starting points are:

Boiler 1

pressure drop:		30% PIN HP
(specified as extra condition for pipe 35, see below)		

Reheater 4

pressure drop:		10% PIN IP
(specified as extra condition for pipe 4, see below)		

Turbine 2 (see also apparatus 21)

steam conditions inlet:	temperature	TIN = 530 °C
	pressure	PIN = 180 bars
throttling losses control values:		3% PIN HP
(specified as extra condition for pipe 1, see below)		

Turbine 5

steam conditions inlet:	temperature	TIN = 530 °C
	pressure	PIN = 34.02 bars
number parallel streams per section:		IP: 2 streams
		LP: 6 streams
number of revolutions:		n = 3600 min^{-1}
outlet area last stage:		A = 6 * 6.14 m^2

Condenser 6

condenser pressure:	POUT2 = 0.027 bar
geometry data:	NPIPES = 35500
	NEDGE = 3550
	DIAIN = 0.018 m
	DIAOUT = 0.020 m
	PITCH = 0.030 m
	LAMBDW = 0.085 kW/m K
	PRISEC = 1

	RFOUL = 0.045 m^2 K/ kW
	AIRFAC = 1.4

Source/sink 100

cooling water temperature inlet:	TOUT = 12 °C

Turbine 18

isentropic efficiency:	ETHAI = 0.8
mechanical efficiency:	ETHAM = 0.98

Feed pump 14

isentropic efficiency:	ETHAI = 0.82

Main condensate pump 7

isentropic efficiency:	ETHAI = 0.78
efficiency drive:	ETHAE = 0.88

Auxiliary condensate pump 19

isentropic efficiency:	ETHAI = 0.78
efficiency drive:	ETHAE = 0.86

Low-pressure preheater 8

temperature difference at high-temperature side:	DELTH = 3 K
condensate at saturation:	SATCOD = 0
pressure drop primary side:	DELP1 = 0.5 bar

Low-pressure preheaters 10, 11 and 12

temperature difference at high-temperature side:	DELTH = 3 K
temperature difference at low-temperature side:	DELTL = 5 K
pressure drop primary side:	DELP1 = 0.5 bar

Deaerator 13

steam pressure:	PIN = 5.192 bar

High-pressure preheaters 15, 16 and 20

temperature difference at high-temperature side:	DELTH = 0 K
temperature difference at low-temperature side:	DELTL = 7 K
pressure drop primary side:	DELP1 = 1 bar

Steam pressures in the preheaters

preheater 8:	PIN2 = 0.082 bar
preheater 10:	PIN2 = 0.236 bar
preheater 11:	PIN2 = 0.676 bar
preheater 12:	PIN2 = 1.895 bar
preheater 15:	PIN2 = 13.919 bar
preheater 20:	PIN2 = 71.472 bar

Generator

design power (production function):	POWER = 600 MWe
capacity:	GENMVA = 750 MVA
power factor:	COSPHI = 0.85

Pipes

Pressure losses

live steam pipe 37:	4% PIN HP
(extra condition:	DELPR = 0.0384 (= 0.04/1.04))
pipe 1:	3%
(extra condition:	DELPR = 0.03)
extraction steam pipe 17:	3%
(extra condition:	DELPR = 0.03)
extraction steam pipes 16, 18, 19, 23-26:	6%
(extra condition:	DELPR = 0.06)
boiler feed water pipe 35:	30% PIN HP
(extra condition:	DELPR = 0.2239 (= 0.3/1.34))

reheated steam pipe 4:	10% PIN HP
(extra condition:	DELPR = 0.0909 (= 0.1/1.01))

As a reference for the caculation of exergies the environment according to the definition of Baehr at 15°C is used.

2.4 Off-design calculations

2.4.1 Changes in the input

For an off-design calculation the input data, as set up for the design calculation, must be altered in a number of points. These alterations may, for example, relate to a more detailed specification of the design of apparatuses or of the control of the system.
In this example the input data are altered for an off-design calculation representing a 80% part load situation.

For the design calculation the assumption has been made of a power to be produced by the steam turbine of 600 MWe. The specification for this is:

- Production functions for turbines 2 and 5: POWER = 600

In the case of an off-design calculation for 80% part load one must then specify:

- Production functions for turbines 2 and 5: POWER = 480

For the conversion of the design case into the required off-design case the changes described below must also be made.

For the turbine

For the turbine the design data as generated by the design calculation, must be added to the input. These data can be imported from the appriopriate PLD-file using the “Paste” button which will appear after pressing the “Off-design input data” button in the input window of the apparatus. The following design data will be copied in the different fields:

- the volume flow at the inlet of the relevant turbine (DESVOL);
- the numbers of the pipes connected to the turbine, first of all the outlet pipes from low to high pressure, then the inlet pipe (LBLEED);
- the pressures in these pipes in the design situation, specified in the same order, hence from low to high pressure (PBLEED);
- the specific volumes in these pipes in the design situation, specified in the same order (VBLEED);
- the mass flows in these pipes in the design situation, specified in the same order (MBLEED).

If GDCODE = 1 (no governing stage present), which is the case for turbines 2 and 5, the turbine-inlet pressure can be calculated with Traupel’s formula. The extraction pressures of the turbine can also be calculated with Traupel’s formula. A condition for this is that the pressure at the outlet of the turbine is known. The outlet pressure of turbine 5 is established by the condenser pressure, see the data for the condenser. The outlet pressure of turbine 2 is established by the inlet pressure of turbine 5, see above.

This results in the following changes for the input:

- As the turbine inlet pressure of turbine 2 is calculated, for apparatus 21 the pressure PIN = 180 may no longer be specified. This pressure would otherwise be transmitted to the turbine inlet.
- As the turbine inlet pressure of turbine 5 is calculated, PIN = 34.02 may no longer be specified for the turbine.
- As the extraction pressure of turbine 2 is calculated, PIN2 = 71.472 of flashed heater 20 may no longer be specified. This pressure would otherwise, taking into account the pressure drop in pipe 16, be transmitted to the extraction of turbine 2.
- As the extraction pressures of turbine 5 are calculated, PIN2 = 13.919 of flashed heater 15 may no longer be specified. This pressure would otherwise, taking into account the pressure drop in pipe 18, be transmitted to the extraction of turbine 5.

- For the same reason PIN2 may no longer be specified for the preheaters 8, 10, 11 and 12. The same goes for PIN specified for deaerator 13.

For the condenser

The design data for the condenser can be imported as off-design input data in the input window in the same way as described for the turbine. For a condenser for which geometry data have been specified, this will be:
- the size of the heat exchanging area (m^2)

In the design calculation the cooling water temperatures at the inlet and outlet of the condenser are specified. The quantity of cooling water necessary to absorb the heat of condensation is then to be calculated from the energy balance. If this option is used, the Energy EQuation CODe (EEQCOD) must be set to 1.

In the off-design calculation the heating of the cooling water is kept the same as that of the design calculation. The energy balance is again used to calculate the quantity of cooling water necessary to absorb the now smaller quantity of heat of condensation. In the off-design calculation in addition to the energy balance the heat transfer equation is now available for calculating an unknown temperature. This equation is used to calculate the condensation temperature in the condenser. See also part “Reference Guide” of the manual.
In the input the following then changes:
- the condenser pressure POUT2 = 0.027 may no longer be specified, as this pressure is directly coupled with the condensation temperature. This temperature is determined in the off-design calculation using the heat transfer equation.

For the preheaters

For the preheaters in the system flashed heaters (type 5) are used. For a heat exchanger apparatus of type 5 the U*A value can usually not be defined because of the phase change of the extraction steam. For this reason for a heat exchanger of apparatus type 5 the U*A value is not stored in the file containing design data. For the off-design calculation of a flashed heater only the value of either DSMAS1 or DSMAS2 must be specified. The value of

DSMAS1 as calculated in the design calculation can be imported via the “Paste” button as described above.
In the input data for the preheaters no further changes need to be made. For apparatus type 5 with an off-design calculation the inlet and outlet temperature differences, which are specified in the input (DELTH and DELTL), are altered. This alteration is a function of the mass flow ratio off-design, as indicated in Figure 2-3 in paragraph 2.6 of part “Reference Guide” of the manual.

2.4.2 Results of the 80% part load calculation

For the calculated part load situation the results are set out below. The quantity of boiler feedwater/steam, circulating in the system, falls as the demand for power drops. The consequences of this on the various apparatuses are set out below.

Changes for the turbine

For the turbines the extraction pressures and inlet pressure are calculated using Traupel’s formula. Table 2-1 indicates how the pressures and mass flows change in the 80% part load situation for the high-pressure turbine 2.

Table 2-1: Design/off-design calculation high-pressure turbine 2

Turbine 2	Pipe no	Mass flow [kg/s]		Pressure [bar]	
		Design	Off-design	Design	Off-design
inlet	37	519.1	401.0	180.0	141.7
extraction	16	51.6	35.4	76.0	60.5
outlet	2	467.5	365.6	37.4	29.7

For the intermediate- and low-pressure turbine 5 the data are set out in Table 2-2.

Table 2-1: Design/off-design calculation intermediate- and low-pressure turbine 5

Turbine 5	Pipe no.	Mass flow [kg/s]		Pressure [bar]	
		Design	Off-design	Design	Off-design
inlet	4	418.6	331.0	34.02	27.00
extraction	18	25.8	19.5	14.81	11.81
	19	46.5	31.8	5.523	4.480
	23	18.6	14.1	2.016	1.641
	24	15.5	11.9	0.719	0.587
	25	12.7	9.7	0.251	0.205
	26	9.6	6.7	0.087	0.073
outlet	5	289.9	237.4	0.027	0.026

The extraction pressures fall because of the reduced mass flow through the turbines.

Changes for the condenser

The quantity of heat which must be transferred in the condenser is proportionate to the quantity of steam passing through the condenser. The heat of condensation is virtually independent of the steam pressure/steam temperature. The heating of the cooling water is kept the same as that in the design situation. From the energy balance it then follows that less cooling water, primary medium, is necessary to absorb the heat of condensation. If the quantity of cooling water falls, the turbulence in the flow is reduced, as a result of which the overall heat transfer coefficient of the condenser deteriorates. This fall is however less than the fall in the quantity of heat to be transferred. From the heat transfer equation it then also follows that the log mean temperature difference must fall. The off-design value of T_{cond} is then also lower than the design value. Table 2-3 sets out the results for the design and off-design calculation.

Table 2-2: Design/off-design calculation condenser

Condenser 6		Pipe no.	Mass flow [kg/s]		Temperature [°C]	
			Design	**Off-design**	**Design**	**Off-design**
primary	in:	102	22787	18409	12.00	12.00
	out:	100	22787	18409	19.36	19.36
secondary	in:	5	289.90	237.36	22.36	21.75
		22	24.23	15.02	22.36	21.75
	out:	6	314.13	252.39	22.36	21.75

Changes for the preheaters

In the preheaters the inlet and outlet temperature differences specified are altered. The off-design values of these differences are dependent on the design values of ΔT_H and ΔT_L specified. In addition the difference is a function of the ratio between the off-design and the design value of the mass flow. In Table 2-4 the data and results for the preheaters are presented. The temperature difference ΔT_L for apparatus 8 is not specified (see input data) and is thus also not altered.

Table 2-3: Design/off-design calculation preheaters (d = design, od = off-design)

Apparatus-number	Pipe, primary in/out	$\Phi_{m,prim,d}$ [kg/s]	$\Phi_{m,prim,od}$ [kg/s]	$\Delta T_{H,d}$ [K]	$\Delta T_{H,od}$ [K]	$\Delta T_{L,d}$ [K]	$\Delta T_{L,od}$ [K]
8	7/8	314.18	252.39	3	2.14	-	-
10	9/10	370.58	294.70	3	2.11	5	3.7
11	10/11	370.58	294.70	3	2.11	5	3.7
12	11/12	370.58	294.70	3	2.11	5	3.7
15	14/15	519.16	401.04	0	-0.51	7	5.1
16	15/34	519.16	401.04	0	-0.51	7	5.1
20	34/35	519.16	401.04	0	-0.51	7	5.1

2.4.3 Other use of the condenser model

In the example shown above the heating of the cooling water is established by specifying the outlet temperature of the cooling water. The energy equation is then used to calculate the mass flow of cooling water (EEQCOD = 1).

It is however also possible to prescribe the mass flow of cooling water, where then the outlet temperature of the cooling water is calculated (EEQCOD = 2). This can be used when as the load falls the cooling water mass flow remains unchanged. For source 102 the mass flow is then specified, as calculated for the design situation (DELM = -22787).
In this case too the heat transfer equation is used to calculate the condensation temperature/ condensation pressure.

The results of this calculation (see Table 2-5) differ in a number of points from those of the preceding calculation. The quantity of heat of condensation falls in proportion to the mass flow of steam. From the energy balance it then follows that as the cooling water mass flow does not change, the outlet temperature of the cooling water falls with respect to the design situation. The overall heat transfer coefficient remains more or less unchanged. From the heat transfer equation it then follows that the log mean temperature difference falls. This means that the condensation temperature falls more than in the preceding calculation (see Table 2-5 below).

Table 2-4: Results other use condenser model

Condenser 6		**Pipe no.**	**Mass flow [kg/s]**		**Temperature [°C]**	
			Design	**Off-design**	**Design**	**Off-design**
primary	in:	102	22787	22787	12.00	12.00
	out:	100	22787	22787	19.36	17.94
secondary	in:	5	289.90	236.85	22.36	20.38
		22	24.23	14.83	22.36	20.38
	out:	6	314.13	251.68	22.36	20.38

The lower condenser pressure also affects the mass flow through the turbine and the extraction pressures. As a result this produces different temperatures and pressures virtually throughout the system.

The higher fall of the condenser temperature is also shown in Figure 2-2.

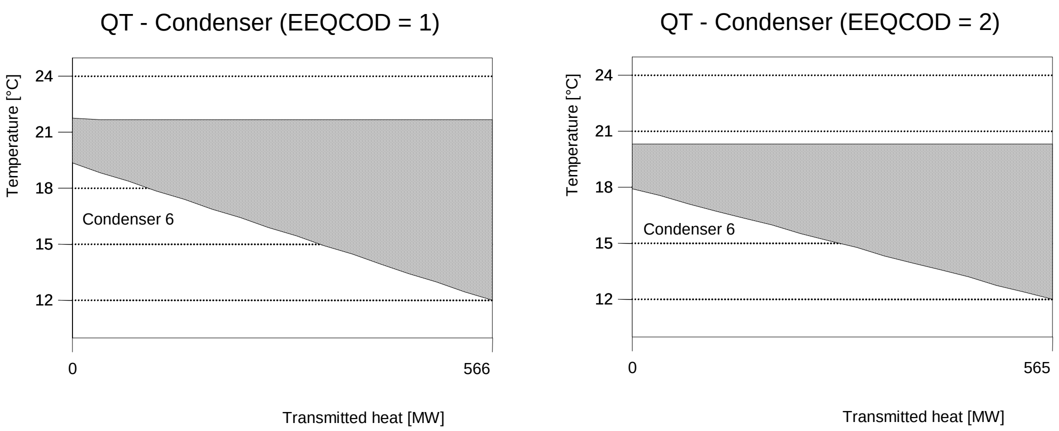

Figure 2-2: Q, T – diagram condenser