ESF II project of the University of West Bohemia in Pilsen

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Carnotization of the thermal cycle and RC cycle with reheat

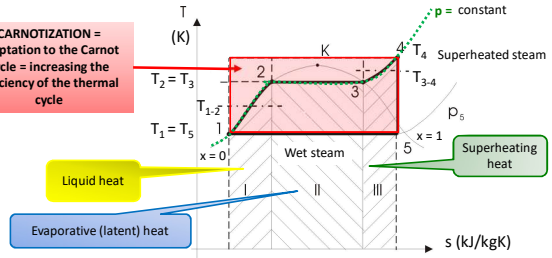
Exercises 4 (KEE/TTE)

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

Carnotization of the RC cycle

- **The thermal efficiency of the RC cycle is relatively low – cca 30 %**
- **The efficiency of the Carnot cycle is about twice the efficiency of the RC cycle**

CARNOTIZATION = adaptation to the Carnot cycle = increasing the efficiency of the thermal cycle



To determine the **effectiveness of individual carnotization treatments**, the partial thermal efficiencies for the thermal cycle in the power plant are determined. Namely for **water heating (I), water evaporation (II) and steam superheating (III),** as if it were Carnot cycles with a mean heat supply temperature between two states on the **basis on the second law of thermodynamics.**

Carnotization of the RC cycle – Water heating

The **heating of water to the boiling point** is in the T-s diagram showing the **course from point 1 to point 2**. The **mean heat supply temperature** between state 1 and 2 is therefore T_{1-2}.

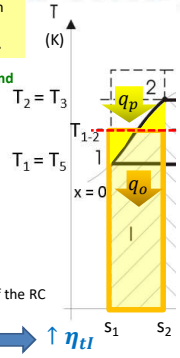
- **Determination of mean temperature - according to the second law of thermodynamics**

$$dq = Tds$$

$$q_{1-2} = i_2 - i_1 = T_{1-2} \cdot (s_2 - s_1)$$

$$T_{1-2} = \frac{i_2 - i_1}{s_2 - s_1}$$

$$\eta_{tI} = \frac{q_p - q_o}{q_p} = \frac{T_{1-2} - T_5}{T_{1-2}}$$



- This part has **the lowest efficiency** of the individual parts of the RC cycle.

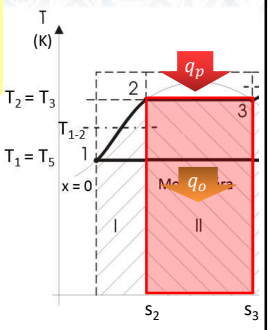
REGENERATIVE HEATING of the feedwater ⇒ ↑ η_{tI}

Carnotization of the RC cycle – Water evaporation

The evaporation of water (transformation of saturated liquid into saturated (dry) steam) is shown in the T-s diagram by the course **from point 2 to point 3. The temperature T_2 is equal to the temperature T_3.**

$$\eta_{tII} = \frac{q_p - q_o}{q_p} = \frac{T_2 - T_5}{T_2}$$

- The **thermal efficiency of this part of the thermal cycle is equal to the thermal efficiency of the Carnot cycle** of this phase, but is not high due to the low temperature T_2.



Increasing steam pressure

Temperature increase T_2 → ↑ η_{tII}

Carnotization of the RC cycle – Steam superheating

The superheating of steam is shown in the T-s diagram by the course **from point 3 to point 4. The mean temperature of the heat supply** between state 3 and 4 is therefore T_{3-4}.

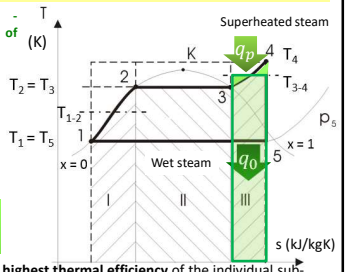
- **Determination of mean temperature - according to the second law of thermodynamics**

$$dq = Tds$$

$$q_{3-4} = i_4 - i_3 = T_{3-4} \cdot (s_4 - s_3)$$

$$T_{3-4} = \frac{i_4 - i_3}{s_4 - s_3}$$

$$\eta_{tIII} = \frac{q_p - q_o}{q_p} = \frac{T_{3-4} - T_5}{T_{3-4}}$$

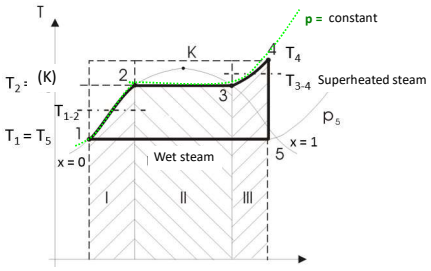


- This part of the thermal cycle **has the highest thermal efficiency** of the individual sub-phases of the RC cycle because of the temperature:
- $T_{3-4} > T_2 > T_{1-2}$

RC cycle with reheat → ↑ η_{tIII}

Example 1

- Calculate the partial thermal efficiencies of the Carnot cycle of individual phases of steam production in a thermal power plant operating according to the RC cycle (water heating to boiling point - I, water evaporation - II, steam superheating - III). The power of the power plant unit is **P_e = 55 MW**. The steam parameters at the turbine input are: **p_a = 10 MPa, t_a = 510 °C**. The steam temperature at the turbine output is **t_e = 35 °C**.



Example 1 - Solution

- **Calculation of mean temperatures of individual phases of the thermal cycle**

We replace the thermal cycle with partial Carnot cycles with heat supply at constant temperature:

- I - water heating to boiling point
- II - water evaporation
- III - steam overheating

The heat value for isobaric and isothermal supply must be the same:

$$dq_{p=konst} = di = c_p dt = dq_{T=konst} = Tds$$

1. From steam tables or i-s diagram we determine values of enthalpies and entropies

2. Mean **water heating** temperature

$$T_{1-2} = \frac{i_2 - i_1}{s_2 - s_1}$$

3. The **water evaporation** temperature is constant during heat supply

$$T_2 = T_3$$

4. Mean **steam superheating** temperature

$$T_{3-4} = \frac{i_4 - i_3}{s_4 - s_3}$$

7

Example 1 - Solution

- **Calculation of mean temperatures of individual phases**

1. From steam tables or i-s diagram we determine values of enthalpies and entropies

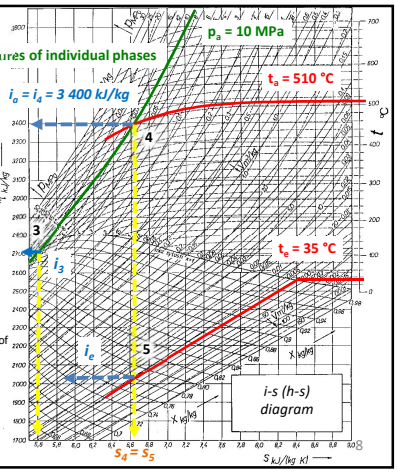
Given:
p_a = 10 MPa, t_a = 510 °C
t_e = 35 °C

Admission steam parameters

- from the i-s diagram: the intersection of t_a a p_a → *$i_a = i_4$ = 3 400 kJ/kg*
- perpendicular to the entropy axis → *$s_a = s_4$ = 6.63 kJ/kgK*

Saturated steam parameters (dry steam)

- from the i-s diagram: the intersection of the saturation curve (x = 1) and p_a → *i_3 = 2 725 kJ/kg*
- perpendicular to the entropy axis → *s_3 = 5.6 kJ/kgK*



9

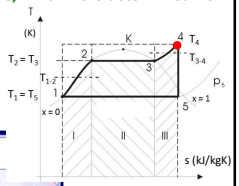
Example 1 - Solution

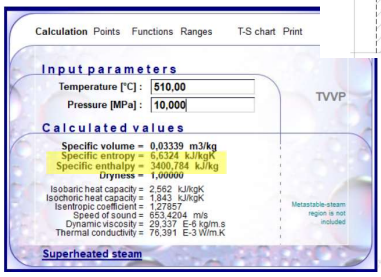
- **Verification of values of quantities using software, which were determined from the i-s diagram**

  - **Point 4**

  Values from the i-s (h-s) diagram:

  i_4 = 3 400 kJ/kg s_4 = 6.63 kJ/kgK



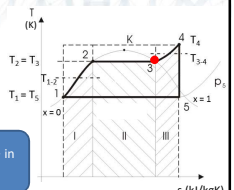


Example 1 - Solution

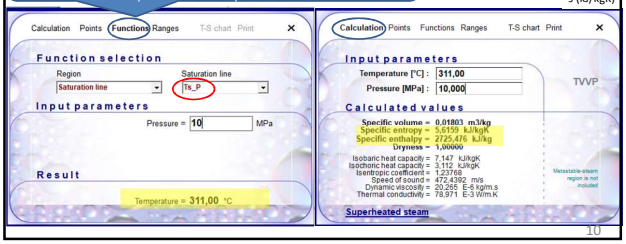
- Verification of values of quantities using software, which were determined from the i-s diagram
  - Point 3

Values from the i-s (h-s) diagram:

$i_3 = 2\ 725\ kJ/kg$ $s_3 = 5.6\ kJ/kgK$

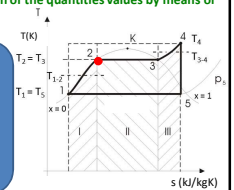


We know that we are at the saturation point → according to the entered pressure we find the temperature in the "Functions" tab → in the "Calculation" tab we find the entropy and enthalpy from the pressure and temperature.



Example 1 - Solution

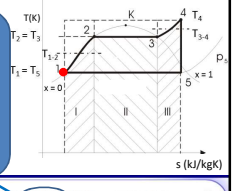
- Point 2
- Determination of the quantities values by means of the software



We know that we are on the left limit curve of saturation → according to the entered pressure we find the temperature in the tab "Function" → in the tab "Function" we find the entropy and enthalpy from the temperature.

Example 1 - Solution

- Point 1
- Determination of the quantities values by means of the software

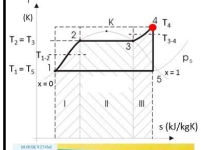


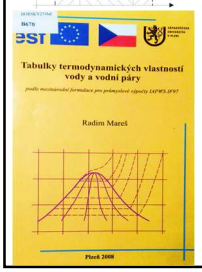
We know that we are on the left saturation limit curve → according to the entered temperature we find the pressure in the "Functions" tab → in the "Functions" tab we find the entropy and enthalpy from the temperature.

Example 1 - Solution

- Point 4

Subtraction of enthalpy and entropy values in the Steam Tables



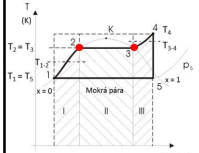


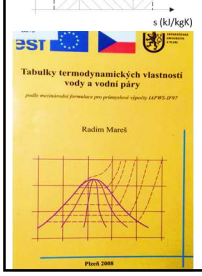
9,85MPa				10,00MPa				10,15MPa			
v	h	s		v	h	s		v	h	s	
0,0009954	51,8	0,1501	0,0003	0,0009952	10,1	0,0003		0,0009950	10,6	0,0006	
0,0009956	51,8	0,1501	0,0009957	51,8	0,1501	0,0009956	51,7	0,1501	0,0009954	52,2	0,1500
0,0009975	92,9	0,2945	0,0009974	93,1	0,2944	0,0009973	93,3	0,2944	0,0009971	93,8	0,2943
0,0010007	134,5	0,4338	0,0010001	134,6	0,4338	0,0010000	134,8	0,4337	0,0009998	135,3	0,4336
0,0010037	176,0	0,5687	0,0010036	176,2	0,5686	0,0010035	176,4	0,5685	0,0010033	176,8	0,5684
⋮											
0,0013998	1343,6	3,2501	0,0013989	1343,3	3,2493	0,0013980	1343,1	3,2484	0,0013959	1342,5	3,2462
0,011926	2745,9	5,6636	0,01856	2732,4	5,6341	0,0014471	1401,8	3,3498	0,0014443	1400,9	3,3471
0,02058	2804,1	5,7427	0,01992	2793,6	5,7381	0,01927	2782,7	5,7131	0,01773	2753,5	5,6694
0,02173	2853,6	5,8454	0,02108	2844,7	5,8236	0,02045	2835,7	5,8017	0,01895	2811,9	5,7460
0,02275	2897,5	5,9176	0,02211	2889,9	5,8978	0,02149	2882,1	5,8760	0,02002	2861,8	5,8261
0,02371	2937,6	5,9825	0,02307	2930,8	5,9641	0,02244	2924,0	5,9458	0,02098	2906,3	5,9000
0,02460	2974,8	6,0418	0,02395	2968,8	6,0245	0,02333	2962,6	6,0073	0,02186	2946,9	5,9646
0,02545	3009,9	6,0967	0,02479	3004,4	6,0803	0,02416	2998,8	6,0641	0,02268	2984,6	6,0236
0,02625	3043,2	6,1482	0,02559	3038,2	6,1325	0,02495	3033,1	6,1170	0,02346	3020,2	6,0786
0,02702	3075,2	6,1967	0,02635	3070,6	6,1817	0,02571	3065,9	6,1668	0,02421	3054,0	6,1300
0,02776	3106,0	6,2429	0,02709	3101,7	6,2283	0,02644	3097,4	6,2139	0,02492	3086,4	6,1785
0,02848	3135,9	6,2869	0,02780	3131,9	6,2728	0,02714	3127,8	6,2589	0,02561	3117,6	6,2246
0,02918	3165,0	6,3292	0,02849	3161,2	6,3155	0,02783	3157,5	6,3019	0,02628	3147,9	6,2686
0,02987	3193,4	6,3699	0,02917	3189,9	6,3565	0,02850	3186,3	6,3432	0,02693	3177,3	6,3108
0,03053	3221,2	6,4092	0,02983	3217,9	6,3961	0,02915	3214,6	6,3831	0,02756	3206,1	6,3514
0,03119	3248,6	6,4473	0,03047	3245,4	6,4344	0,02978	3242,3	6,4217	0,02818	3234,3	6,3907
0,03183	3275,5	6,4843	0,03111	3272,5	6,4716	0,03041	3269,5	6,4591	0,02878	3262,0	6,4287
0,03246	3302,1	6,5203	0,03173	3299,2	6,5078	0,03102	3296,4	6,4955	0,02938	3289,2	6,4656
0,03309	3328,3	6,5553	0,03234	3325,6	6,5431	0,03163	3322,9	6,5310	0,02996	3316,1	6,5015
0,03370	3354,3	6,5896	0,03295	3351,7	6,5775	0,03223	3349,1	6,5655	0,03054	3342,6	6,5365
0,03431	3380,0	6,6230	0,03354	3377,5	6,6111	0,03281	3375,1	6,5993	0,03110	3368,9	6,5706
0,03491	3405,5	6,6556	0,03413	3403,1	6,6440	0,03339	3400,8	6,6326	0,03166	3394,9	6,6041
0,03550	3430,8	6,6880	0,03472	3428,6	6,6763	0,03397	3426,3	6,6648	0,03222	3420,6	6,6368
0,03608	3456,0	6,7195	0,03529	3453,8	6,7079	0,03454	3451,7	6,6965	0,03276	3446,2	6,6688
0,03667	3481,0	6,7505	0,03587	3479,0	6,7390	0,03510	3476,9	6,7277	0,03331	3471,6	6,7003

Example 1 - Solution

- Point 2 and Point 3

Subtraction of enthalpy and entropy values in the Steam Tables



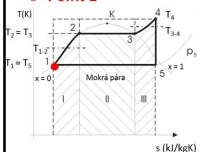


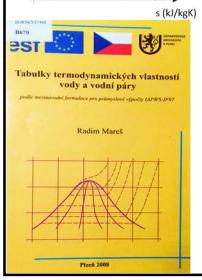
p MPa	t °C	v' m³/kg	v'' m³/kg	h' kJ/kg	h'' kJ/kg	s' kJ/kgK	s'' kJ/kgK
6,50	280,86	0,0013356	0,02973	1241,2	2778,5	3,0760	5,8515
6,60	281,88	0,0013388	0,02923	1246,5	2777,6	3,0854	5,8440
6,70	282,88	0,0013421	0,02875	1251,8	2776,4	3,0947	5,8366
6,80	283,88	0,0013453	0,02828	1257,1	2775,1	3,1039	5,8292
6,90	284,86	0,0013486	0,02782	1262,3	2773,9	3,1130	5,8219
9,00	303,35	0,0014181	0,02049	1363,7	2742,9	3,2866	5,6790
9,10	304,14	0,0014215	0,02022	1368,2	2741,2	3,2942	5,6726
9,20	304,93	0,0014249	0,01996	1372,7	2739,5	3,3017	5,6662
9,30	305,71	0,0014283	0,01970	1377,1	2737,8	3,3092	5,6598
9,40	306,48	0,0014318	0,01945	1381,6	2736,1	3,3166	5,6535
9,50	307,25	0,0014352	0,01920	1386,0	2734,4	3,3240	5,6472
9,60	308,01	0,0014387	0,01896	1390,4	2732,6	3,3313	5,6409
9,70	308,77	0,0014421	0,01872	1394,8	2730,9	3,3386	5,6346
9,80	309,52	0,0014456	0,01849	1399,2	2729,1	3,3459	5,6283
9,90	310,26	0,0014491	0,01826	1403,5	2727,3	3,3531	5,6221
10,0	311,00	0,0014526	0,01803	1407,9	2725,5	3,3603	5,6159
10,2	312,46	0,0014597	0,01760	1416,5	2721,8	3,3745	5,6035
10,4	313,90	0,0014668	0,01717	1425,0	2718,0	3,3886	5,5912
10,6	315,31	0,0014740	0,01677	1433,5	2714,2	3,4025	5,5789
10,8	316,71	0,0014812	0,01637	1441,9	2710,3	3,4163	5,5667
11,0	318,08	0,0014885	0,01599	1450,3	2706,4	3,4300	5,5545
11,2	319,44	0,0014959	0,01563	1458,6	2702,4	3,4435	5,5424
11,4	320,77	0,0015034	0,01527	1466,8	2698,3	3,4569	5,5303
11,6	322,09	0,0015110	0,01493	1475,0	2694,1	3,4702	5,5182
11,8	323,39	0,0015186	0,01459	1483,2	2689,9	3,4834	5,5062
12,0	324,68	0,0015263	0,01427	1491,3	2685,6	3,4965	5,4941
12,2	325,95	0,0015342	0,01395	1499,4	2681,2	3,5095	5,4821
12,4	327,20	0,0015421	0,01365	1507,5	2676,7	3,5224	5,4700
12,6	328,43	0,0015501	0,01335	1515,5	2672,2	3,5352	5,4580
12,8	329,65	0,0015582	0,01307	1523,4	2667,6	3,5479	5,4459
13,0	330,86	0,0015665	0,01279	1531,4	2662,9	3,5606	5,4339
13,2	332,05	0,0015749	0,01251	1539,3	2658,1	3,5732	5,4218
13,4	333,22	0,0015834	0,01225	1547,2	2653,2	3,5857	5,4097
13,6	334,39	0,0015920	0,01199	1555,1	2648,3	3,5982	5,3975
13,8	335,53	0,0016008	0,01174	1563,0	2643,2	3,6106	5,3853

Example 1 - Solution

- Point 1

Subtraction of enthalpy and entropy values in the Steam Tables





t °C	p MPa	v' m³/kg	v'' m³/kg	h' kJ/kg	h'' kJ/kg	s' kJ/kgK	s'' kJ/kgK
0,00	0,0006112	0,0010002	206,1	-0,04	2500,9	-0,0002	9,1558
0,01	0,0006117	0,0010002	206,0	0,00	2500,9	0,0000	9,1555
1	0,0006571	0,0010001	192,4	4,18	2502,7	0,0153	9,1291
2	0,0007060	0,0010001	179,8	8,39	2504,6	0,0306	9,1027
3	0,0007581	0,0010001	168,0	12,60	2506,4	0,0459	9,0765
4	0,0008135	0,0010001	157,1	16,81	2508,2	0,0611	9,0506
5	0,0008726	0,0010001	147,0	21,02	2510,1	0,0763	9,0249
6	0,0009354	0,0010001	137,6	25,22	2511,9	0,0913	8,9994
7	0,0010021	0,0010001	128,9	29,43	2513,7	0,1064	8,9742
8	0,0010730	0,0010002	120,8	33,63	2515,6	0,1213	8,9492
9	0,0011483	0,0010003	113,3	37,82	2517,4	0,1362	8,9244
⋮							
30	0,004247	0,0010044	32,88	125,75	2555,6	0,4368	8,4521
31	0,004497	0,0010047	31,15	129,93	2557,4	0,4506	8,4317
32	0,004759	0,0010050	29,53	134,11	2559,2	0,4643	8,4115
33	0,005035	0,0010054	28,00	138,29	2561,0	0,4780	8,3914
34	0,005325	0,0010057	26,56	142,47	2562,8	0,4916	8,3715
35	0,005629	0,0010060	25,21	146,64	2564,6	0,5052	8,3518
36	0,005947	0,0010064	23,93	150,82	2566,4	0,5187	8,3323
37	0,006282	0,0010068	22,73	155,00	2568,2	0,5322	8,3129
38	0,006632	0,0010071	21,60	159,18	2570,0	0,5457	8,2936
39	0,007000	0,0010075	20,53	163,36	2571,8	0,5591	8,2746
40	0,007384	0,0010079	19,52	167,54	2573,5	0,5724	8,2557
41	0,007787	0,0010083	18,56	171,72	2575,3	0,5858	8,2369
42	0,008209	0,0010087	17,67	175,90	2577,1	0,5990	8,2183
43	0,008650	0,0010091	16,82	180,08	2578,9	0,6123	8,1999
44	0,009112	0,0010095	16,01	184,26	2580,7	0,6255	8,1816
45	0,009594	0,0010099	15,25	188,44	2582,5	0,6386	8,1634
46	0,010099	0,0010103	14,54	192,62	2584,2	0,6517	8,1454
47	0,010626	0,0010108	13,86	196,80	2586,0	0,6648	8,1276
48	0,011176	0,0010112	13,21	200,98	2587,8	0,6778	8,1099
49	0,011751	0,0010117	12,60	205,16	2589,5	0,6908	8,0923

Example 1 - Solution

- **Calculation of mean temperatures of individual phases of the cycle**

1. Mean water heating temperature

$$T_{1-2} =$$

2. Water evaporation temperature

$$T_2 = T_3 =$$

3. Mean steam superheating temperature

$$T_{3-4} =$$

4. The temperature of the wet steam, after expansion in the turbine - point 5

$$T_1 = T_5 =$$

16

Example 1 - Solution

- **Calculation of the efficiencies of individual parts of the thermal cycle**

1. Water heating

$$\eta_{tI} =$$

2. Water evaporation

$$\eta_{tII} =$$

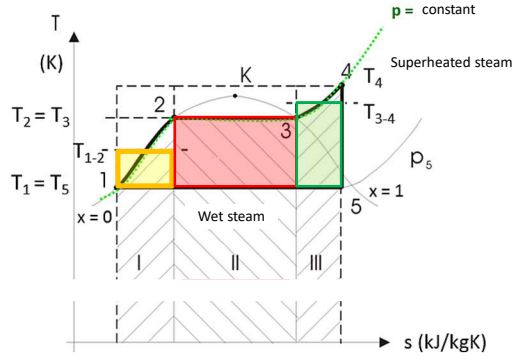
3. Steam overheating (steam superheat)

$$\eta_{tIII} =$$

17

Example 1 - Solution

- **Calculation of the efficiencies of individual parts of the thermal cycle**



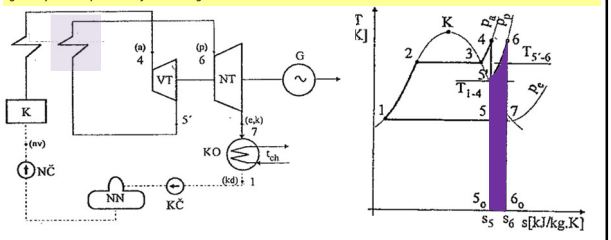
RC cycle with reheat

- **Highest partial efficiency of RC cycle = superheating steam**

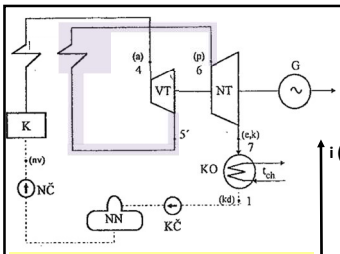
→ Increasing the thermal efficiency of the RC cycle = increasing the parameters of the admission steam

- (it is limited by the mechanical properties of the materials of the last stages of superheaters - superheated steam max approx. 565 ° C) → repeating the superheating part of the circulation = **Reheating steam**

After partial expansion in the high-pressure part of the turbine, the steam is introduced into the steam reheater, where it is heated to a temperature t_{p}, which is usually the same as the temperature of the admission steam. Furthermore, the reheated steam expands in the low-pressure (or medium-pressure and low-pressure) part of the turbine to the pressure given by the temperature of the cooling water in the condenser.



RC cycle with reheat - ideal thermal cycle



The total heat supplied is composed of two parts and the profit of the technical work is also composed of two parts.

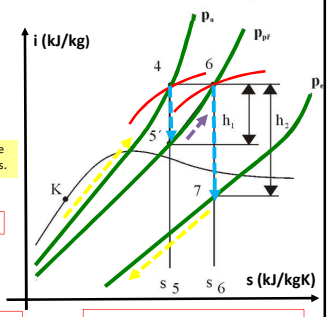
- **Specific heat supplied and removed**

$$q_p = q_{p1} + q_{p2} = (i_4 - i_1) + (i_6 - i_{5'})$$

$$q_o = i_7 - i_1 = i_e^{NT} - i_{nv}$$

- **Profit of technical work *dq = di = dw***

$$w_{to} = h_{ad1} + h_{ad2} = (i_4 - i_{5'}) + (i_6 - i_7) \Rightarrow w_{to} = (i_a - i_e^{VT}) + (i_p - i_e^{NT})$$



RC cycle with reheat - ideal thermal cycle

- **Ideal thermal efficiency of the RC cycle with reheating**

$$\eta_t^{iz} = \eta_{to} = \frac{h_{ad1} + h_{2ad}}{q_{p1} + q_{p2}}$$

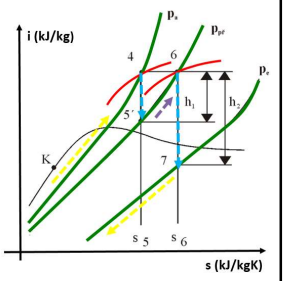
The **increase in thermal efficiency** of the thermal cycle **due to reheating** is usually **2 to 4 %.**

$$\eta_{to} = \frac{(i_4 - i_{5'}) + (i_6 - i_7)}{(i_4 - i_1) + (i_6 - i_{5'})}$$

$$\eta_{to} = \frac{(i_a - i_e^{VT}) + (i_p - i_e^{NT})}{(i_a - i_{nv}) + (i_p - i_e^{VT})}$$

- **Thermal efficiency of the ideal thermal cycle of the power plant at the generator terminals**

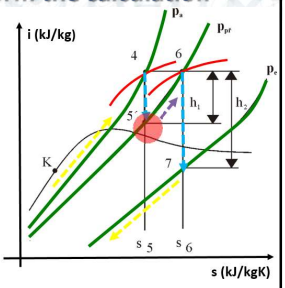
$$\eta_t^{el} = \frac{3600 \cdot P_e}{Q_p} = \eta_{to} \cdot \eta_g \cdot \eta_m \cdot \eta_k \cdot \eta_p$$



21

Values needed to perform the calculation

- We can determine the state quantities during the circulation of the working substance on the basis of knowledge of the parameters in individual places of the thermal cycle. The only parameters that we do not know are in point 5´, i.e. the states of the working substance after the first expansion in the high-pressure part of the turbine.
- Since the **output temperature even after the addition of reheating will still be the same** (given the temperature in the condenser), it can be assumed that we cannot obtain a higher temperature at the output of the reheater than the temperature of the superheated steam. The value of pressure (or enthalpy) at point 6 (reheated steam) can be determined on the basis of **adiabatic expansion in the low-pressure part** of the turbine, if **we require a minimum dryness of steam x = 0.9.**



$$T_{3-4} = T_{5'-6}$$

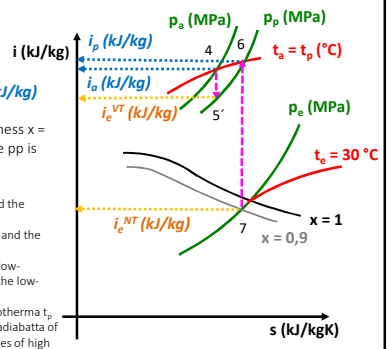
Values needed to perform the calculation

- **Emission steam parameters after ideal expansion in the high-pressure and low-pressure part of the turbine**

Given:
$t_a = t_p$ (°C)
p_a (MPa)
t_e (°C)

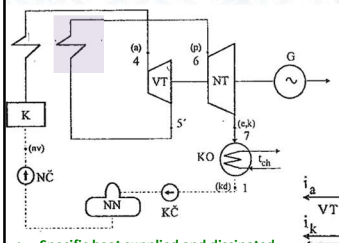
Enthalpy of emission steam i_e^{VT} (kJ/kg)

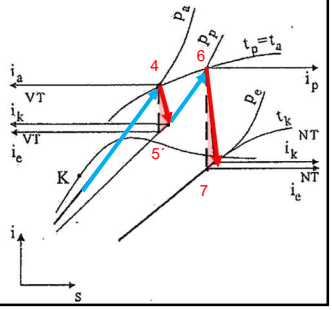
- From the i-s diagram:
- Assume → minimum steam dryness x = 0.9 (unless dryness x or pressure pp is specified)



1. I_a – the intersection of the isobara p_a and the isotherm t_a
2. I_e^{NT} – the intersection of the isotherm t_e and the curve x = 0.9
3. P_p – the intersection of t_a and adiabatic low-pressure part (expansion curves of the low-pressure part)
4. I_p – the intersection of isobara p_p and isotherma t_p
5. I_e^{VT} – the intersection of isobara p_p and adiabatta of high pressure part (expansion curves of high pressure part)

RC cycle with reheat - real thermal cycle





- **Specific heat supplied and dissipated (removed)**

$$q_p = (i_a - i_{nv}) + (i_p - i_k^{VT})$$

$$q_o = i_k^{NT} - i_{nv}$$

- **Profit of technical work *dq = di = dw***

$$w_t = h_1 + h_2$$

$$w_t = (i_a - i_k^{VT}) + (i_p - i_k^{NT})$$

RC cycle with reheat - real thermal cycle

- Real enthalpy values at the outputs of the high and low pressure part of the turbine
  - Thermodynamic efficiency of a high-pressure part of the turbine

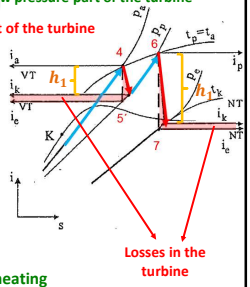
$$\eta_{td}^{VT} = \frac{h_s}{h_{ad}} = \frac{i_a - i_k^{VT}}{i_a - i_e^{VT}}$$

$$\Rightarrow \quad i_k^{VT} = i_a - \eta_{td}^{VT} \cdot (i_a - i_e^{VT})$$

  - Thermodynamic efficiency of a low-pressure part of the turbine

$$\eta_{td}^{NT} = \frac{h_s}{h_{ad}} = \frac{i_p - i_k^{NT}}{i_p - i_e^{NT}}$$

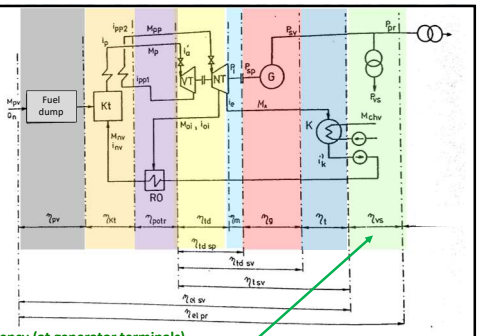
$$\Rightarrow \quad i_k^{NT} = i_p - \eta_{td}^{NT} \cdot (i_p - i_e^{NT})$$



- Real thermal efficiency of the RC cycle with reheating

$$\eta_t = \frac{h_1 + h_2}{q_{p1} + q_{p2}} = \frac{(i_a - i_k^{VT}) + (i_p - i_k^{NT})}{(i_a - i_{nv}) + (i_p - i_k^{VT})}$$

Thermal cycle efficiency analysis



- Gross block efficiency (at generator terminals)

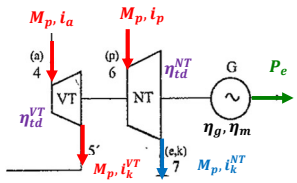
$$\eta_{sv}^{el} = \eta_{to} \cdot \eta_{td} \cdot \eta_g \cdot \eta_m \cdot \eta_k \cdot \eta_p$$

- Net efficiency of the power plant unit

$$\eta_{pr}^{el} = \eta_{to} \cdot \eta_{td} \cdot \eta_g \cdot \eta_m \cdot \eta_k \cdot \eta_p \cdot \eta_{vs}$$

RC cycle with reheat - real thermal cycle

- Mass flow of working substance = balance equation of turbine and generator



$$input \;=\; output$$

$$M_p \cdot i_a + M_p \cdot i_p = M_p \cdot i_k^{VT} + M_p \cdot i_k^{NT} + \frac{3\,600 \cdot P_e}{\eta_g \cdot \eta_m}$$

$$\left[M_p \cdot (i_a - i_k^{VT}) + M_p \cdot (i_p - i_k^{NT})\right] \cdot \eta_g \cdot \eta_m = 3\,600 \cdot P_e$$

  - Assuming that $\eta_{td}^{VT} = \eta_{td}^{VT}$

$$\left[M_p \cdot (i_a - i_e^{VT}) + M_p \cdot (i_p - i_e^{NT})\right] \cdot \eta_{td} \cdot \eta_g \cdot \eta_m = 3\,600 \cdot P_e$$

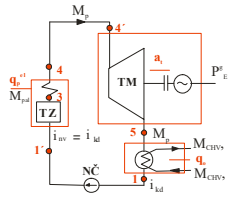
  - Assuming that $\eta_{td}^{VT} \neq \eta_{td}^{VT}$

$$\left[M_p \cdot \eta_{td}^{VT} (i_a - i_e^{VT}) + M_p \cdot \eta_{td}^{NT} (i_p - i_e^{NT})\right] \cdot \eta_g \cdot \eta_m = 3\,600 \cdot P_e$$

Calculation of the mass flow of the working substance

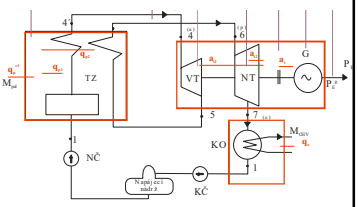
= amount of superheated steam at the turbine input

- Thermal cycle without steam reheating



$$M_p = \frac{3\,600 \cdot P_e}{(i_a - i_k)\eta_g \cdot \eta_m}$$

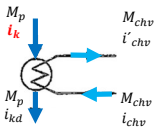
- Thermal cycle with steam reheating



$$M_p = \frac{3\,600 \cdot P_e}{[(i_a - i_k^{VT}) + (i_p - i_k^{NT})]\eta_g \cdot \eta_m}$$

Calculation of the mass flow of the cooling water

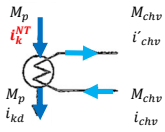
- Thermal cycle without steam reheating



$$M_p(i_k - i_{kd}) - M_{chv}(i'_{chv} - i_{chv}) = 0$$

$$M_{chv} = \frac{M_p(i_k - i_{kd})}{(i'_{chv} - i_{chv})}$$

- Thermal cycle with steam reheating



$$M_p(i_k^{NT} - i_{kd}) - M_{chv}(i'_{chv} - i_{chv}) = 0$$

$$M_{chv} = \frac{M_p(i_k^{NT} - i_{kd})}{(i'_{chv} - i_{chv})}$$

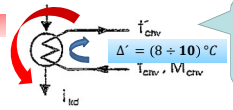
- Heating of the Cooling water M_p, i_k

$\Delta'' = (3 \div 5)\,°C$

$t_k = t_{kd}$

Gives only the heat of condensation

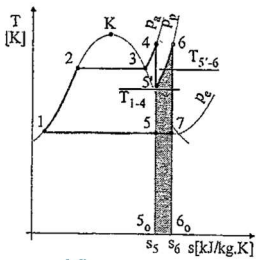
$t_{kd} = t_{chv} + \Delta' + \Delta''$



Due to the highest possible thermal gradient in the turbine (highest efficiency), we require that the temperature t_k be as low as possible.

Example 2

- Calculate the thermal efficiency of the RC cycle if losses in the cycle are included in the calculation and Carnotization adjustment of the steam reheating is performed. The power of the power plant unit (block) is **P_e = 55 MW**. The parameters at the turbine input are: **p_a = 10 MPa, t_a = 510 °C**, the temperature of the working substance at the output of the turbine is **t_e = 30 °C**. The cooling water temperature at the condenser input is **t_{chv}= 15 °C**. Individually circuit losses are:
  - Mechanical losses of the heat engine 2 %
  - Losses in the generator 1 %
  - Losses in the steam supply line to the turbine 2 %
  - Losses in the heat source (boiler) 15 %.
  - The actual consumption of the block is 10 %



Example 2 - Solution

Given:
p_a = 10 MPa
t_a = 510 °C
t_e = 30 °C

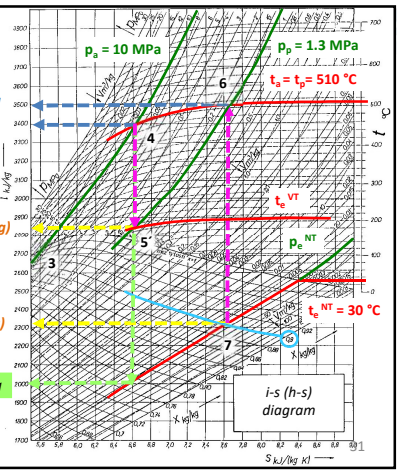
i_p = 3 498 kJ/kg
i_a = 3 400 kJ/kg

i_e^{VT} = 2 850 (kJ/kg)

Enthalpy of the emission steam - thermal cycle without reheating

i_e^{NT} = 2 313 (kJ/kg)

$i_e = 2\,000\ kJ/kg$



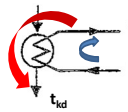
31

Example 2 - Solution

- Condensate temperature

$t_{kd} = t_{chv} + \Delta' + \Delta''$

t_e = 30 °C



$\Delta' = (8 \div 10)\,°C$

$\Delta'' = (3 \div 5)\,°C$

- Calculation of the feedwater enthalpy $t_e = t_{kd} = t_{nv}$

$i_{nv} =$

32

Example 2 - Solution

- Ideal thermal efficiency of the RC cycle with reheating

$\eta_{to} =$

- Ideal thermal efficiency of the RC cycle without reheating $i_e = 2\,000\ kJ/kg$

$\eta_{to_B} =$

- About what percentage will the thermal efficiency increase due to the reheating of the steam?

$\eta_{to} - \eta_{to_B} =$

33

Example 2 - Solution

- **Gross power plant efficiency –** we do not consider the turbine losses

- Mechanical losses of the heat engine 2 %
- Losses in the generator 1 %
- Losses in the steam supply line to the turbine 2 %
- Losses in the heat source (boiler) 15 %.
- The actual consumption of the block is 10 %

$\eta_{tsv}^{el} =$

$\boldsymbol{\eta_{tsv}^{el}} =$

- **Net power plant efficiency –** we do not consider the turbine losses

$\eta_{tp}^{el} =$

$\boldsymbol{\eta_{tpr}^{el}} =$

34

Example 2 - Solution

- **Steam consumption relative to the terminals of the generator**

$M_p =$

$\boldsymbol{M_p} =$

- **Heat consumption for the turbine and generator**

$Q_T =$

$\boldsymbol{Q_T} =$

35

Example 2 - Solution

- **Heat consumption for the whole power plant**

$\boldsymbol{Q_p} =$

- **Specific heat consumption for the turbine and generator**

$q_T =$

- **Specific heat consumption for the required output power**

$\eta_{ts}^{el} = \frac{3600 \cdot P_e}{Q_p} = \frac{3\,600}{q_p}$ ➡

36

Example 2 - Solution

- **Amount of the fuel consumed** $q_{pal} = 12\,200\ kJ/kg$

$$M_{pal} =$$

- **Amount of the cooling water**

$$M_{chv} =$$

37

Used and recommended literature

- Dvorsky, Emil; Hejtmankova, Pavla; Kocmich, Martin. Elektrarny : zaklady vyroby elektricke energie : priklady. 1. vyd. Pilsen : UWB, 1994. ISBN 80-7082-133-7.
- Dvorsky, Emil; Hejtmankova, Pavla. Elektrarny : zvysovani ucinnosti premen energie v tepelnych elektrarnach : priklady. 1. vyd. Pilsen : UWB, 1994. ISBN 80-7082-523-5.
- ..... and other literature listed in the course syllabus on the website Portal of the UWB in Pilsen

Next exercise

Regenerative Rankine-Clausius cycle
(Recuperative heating of feed water)

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