ESF II project of the University of West Bohemia in Pilsen

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Rankine-Clausius cycle (RC) and Organic Rankine Cycle (ORC)

Exercises 3 (KEE/TTE)

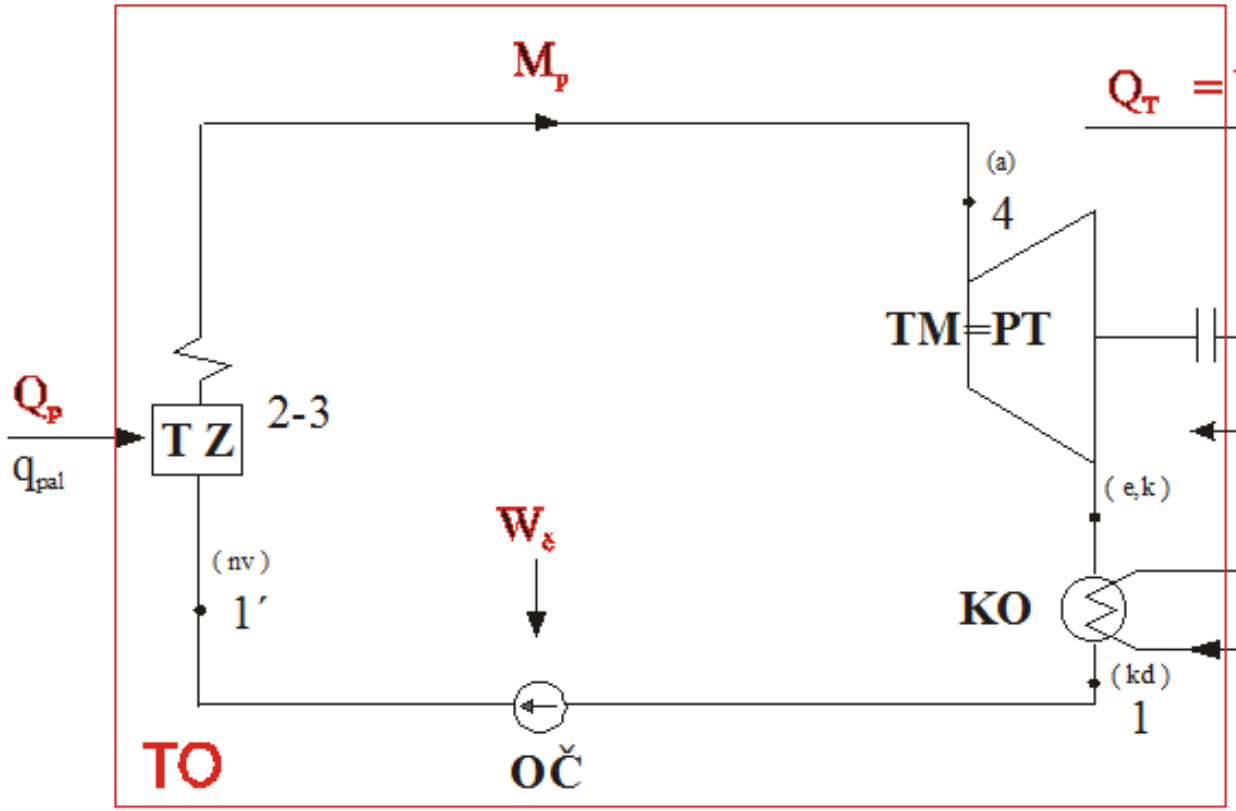
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Rankine-Clausius cycle (RC)

- **Gas cycles -** the substance in the thermal cycle is in a single-phase state (environment)
- **Steam cycles – two-phase environment** – change of state of working medium in steam generators

From a theoretical point of view, we can use any working substance in the RC cycle, but it is necessary that it has advantageous thermodynamic properties.

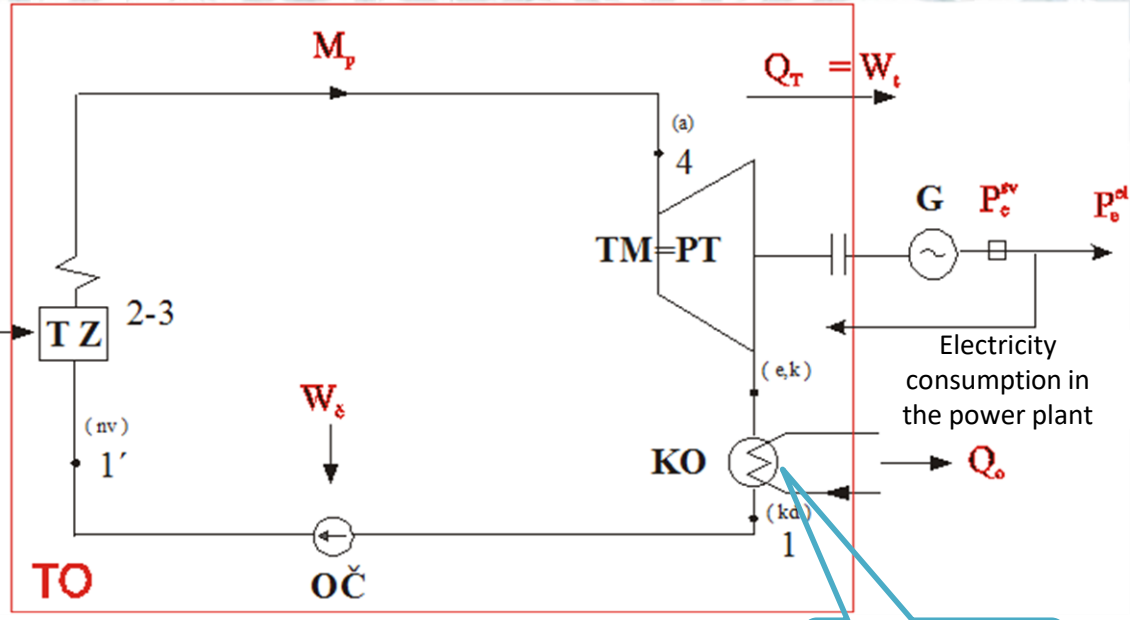


Gain of mechanical work - expansion of steam in a heat engine TM (turbine).

Electricity consumption in the power plant

RC cycle

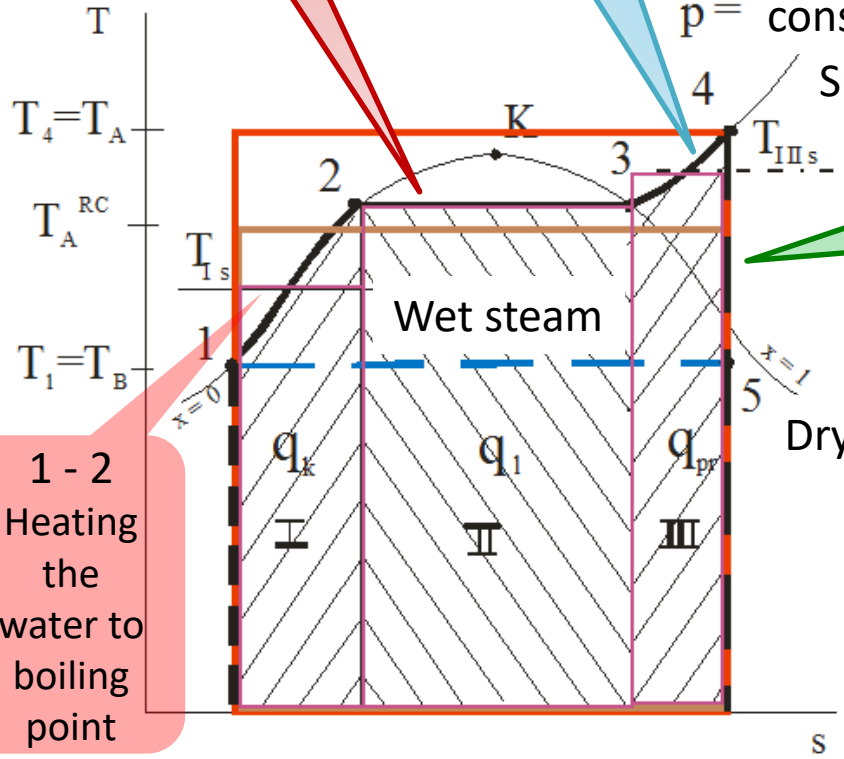
The production of steam at a constant pressure = isobaric process



2 - 3
Evaporation

3 - 4
Superheating

Condenser



p = constant

Superheated steam

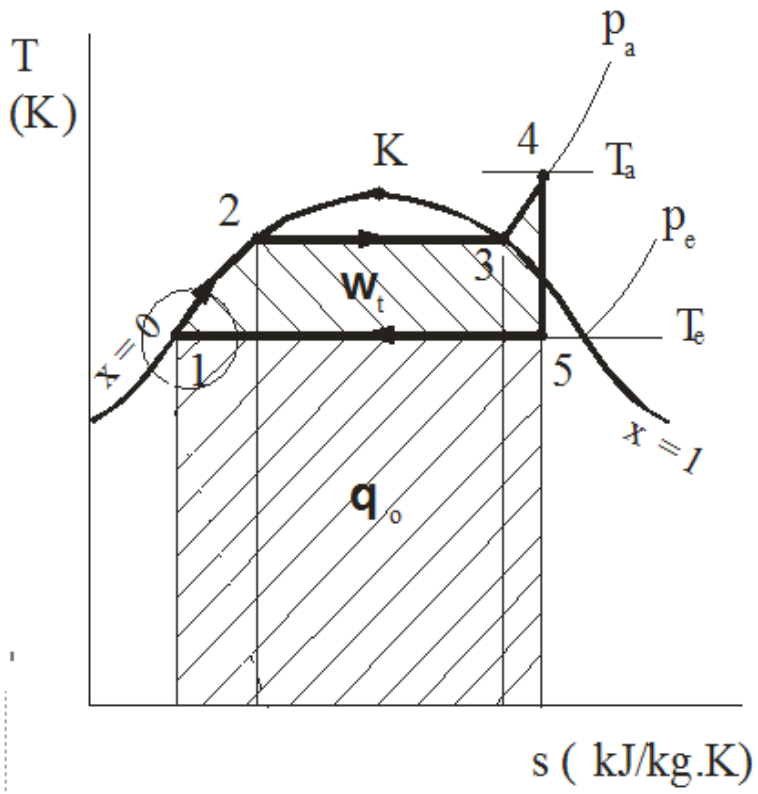
Wet steam

4 - 5
Steam expansion in the turbine

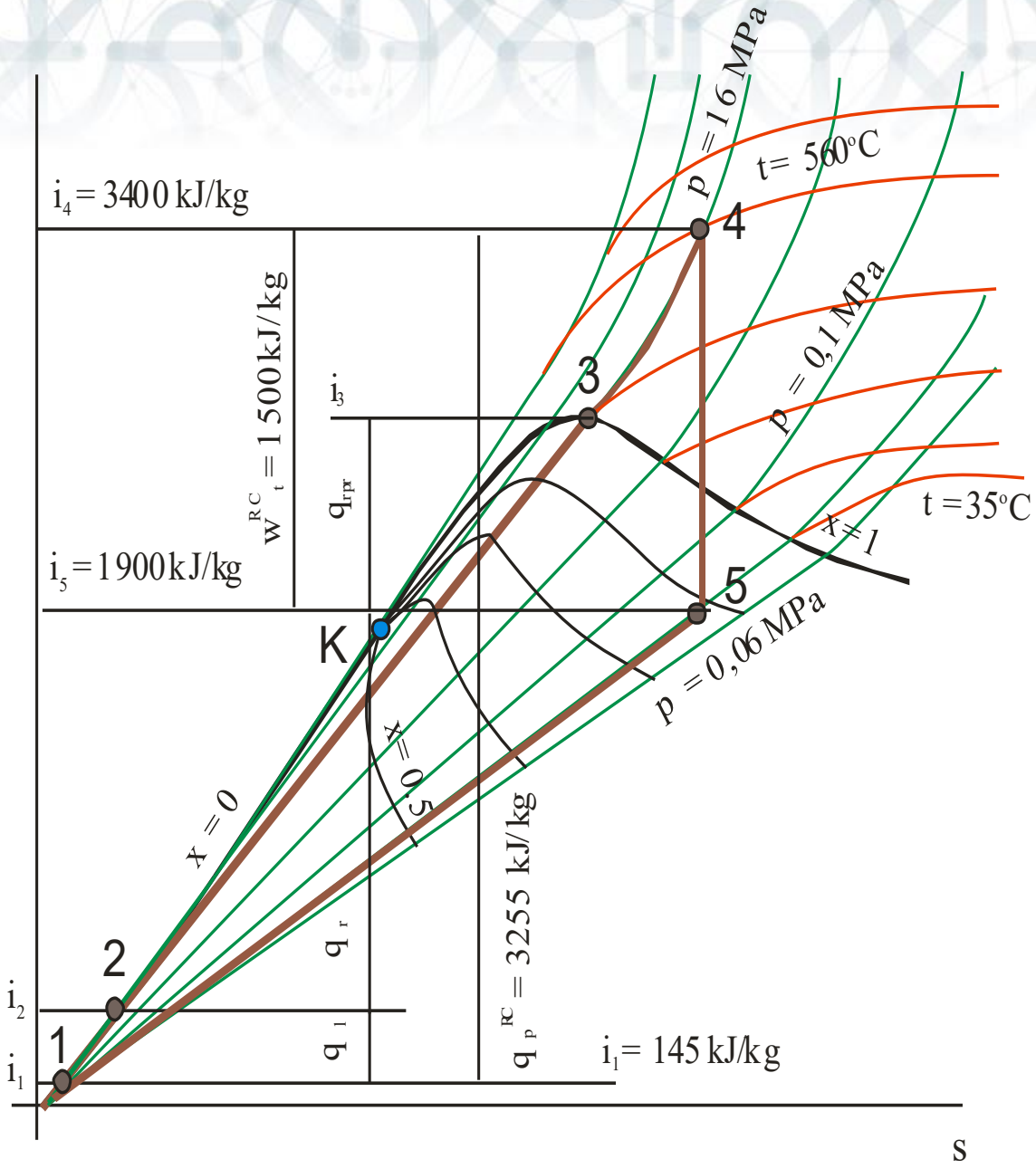
Dry steam

1 - 2
Heating the water to boiling point

RC cycle



- Latent (liquid) heat
- Evaporation heat
- Superheating heat



The amount of heat needed to produce steam

- **Steam generator** – steam production by **supply of thermal energy Q_p** (kJ/h)
  - the state of the working medium between point 1 - 4

$$dq = di = cdT$$

Isobaric change

(in wet steam - isothermal change)

$$Q = m \cdot c \cdot dt$$

$$(kJ) = (kg) \cdot \frac{(kJ)}{(kg.K)} \cdot (K)$$

$$Q = M \cdot di$$

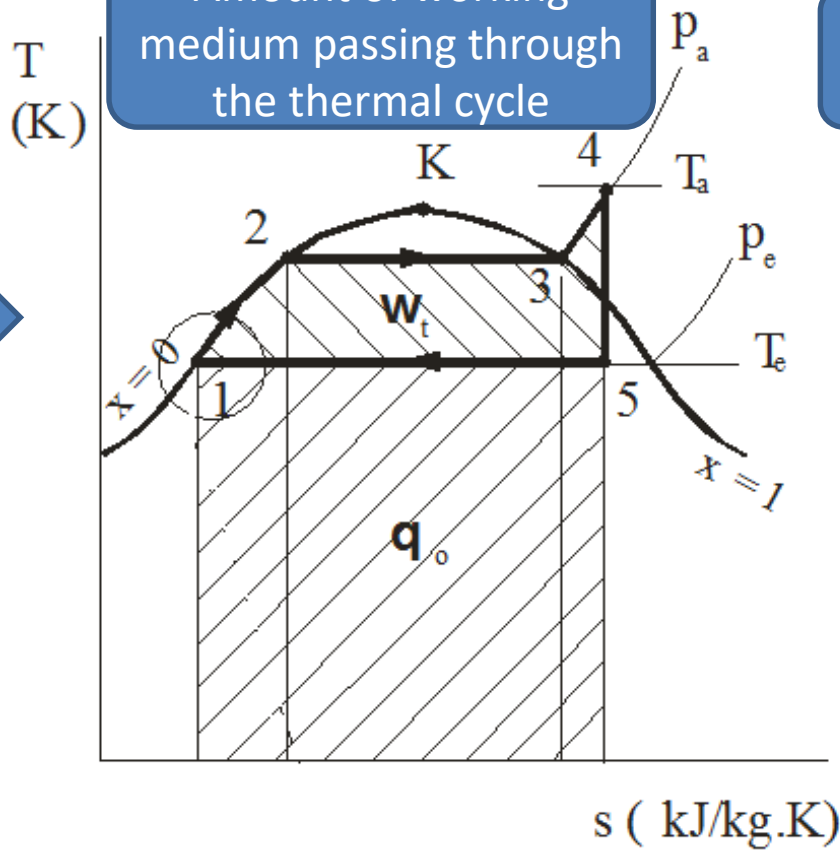
$$\frac{(kJ)}{(h)} = \frac{(kg)}{(h)} \cdot \frac{(kJ)}{(kg)}$$

Admission steam enthalpy

$$Q_p = M_p \cdot (i_4 - i_1) = M_p \cdot (i_a - i_{nv})$$

Amount of working medium passing through the thermal cycle

Feedwater enthalpy



Calculation of an ideal RC cycle

- In case of neglect of losses – **adiabatic expansion of the steam in a turbine** (4 – 5)
- The obtained mechanical energy w_{to} is converted into electrical energy in the generator **G**
- **Condenser**
  - wet steam after expansion in the turbine, its **heat of vaporization (removed head) Q_o** (5 - 1) is removed, which is removed from the circuit (isothermally):

$$Q_o = M_p \cdot (i_5 - i_1) = M_p \cdot (i_e - i_{kd})$$

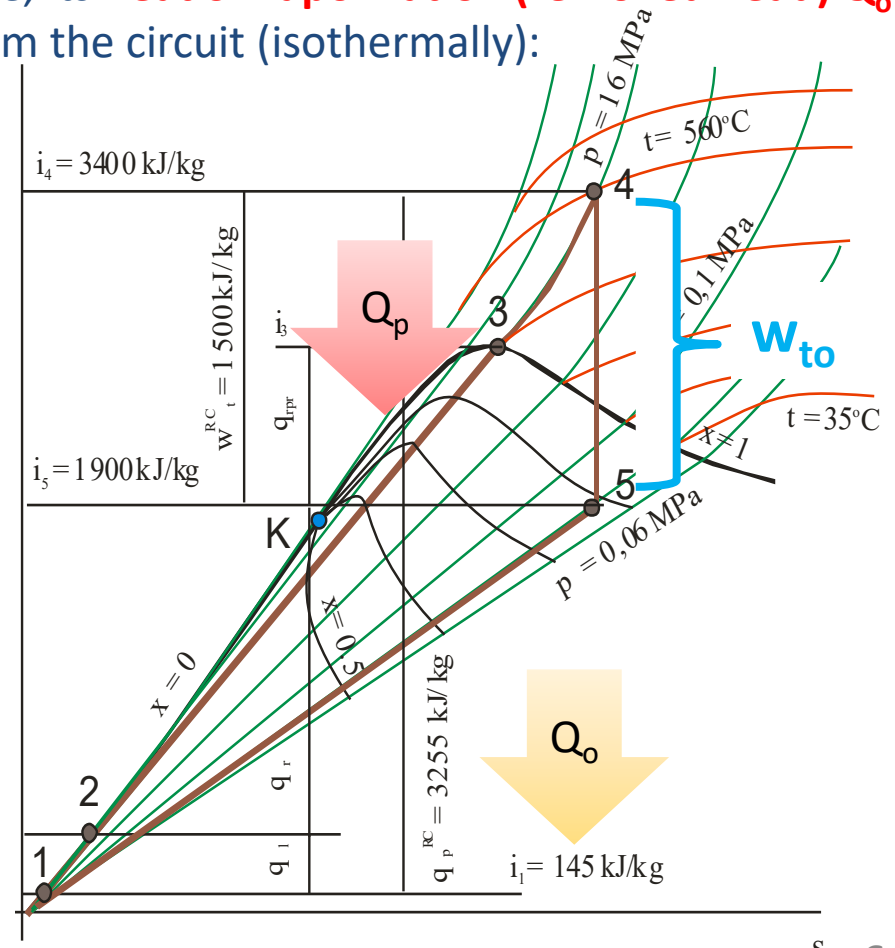
Emission steam enthalpy

X

Condensate enthalpy

Supplied heat - Q_p

$$Q_p = M_p \cdot (i_4 - i_1) = M_p \cdot (i_a - i_{nv})$$



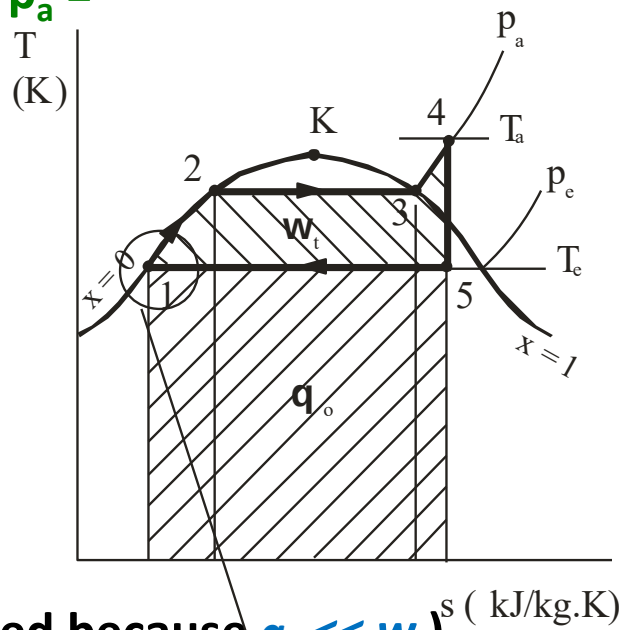
Calculation of an ideal RC cycle

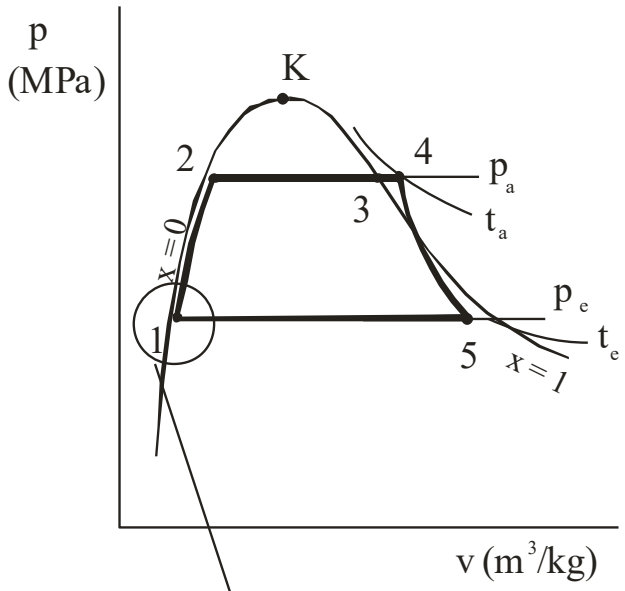
Circulation pump (feed water pump)

= pressurizes the feed water p_a =

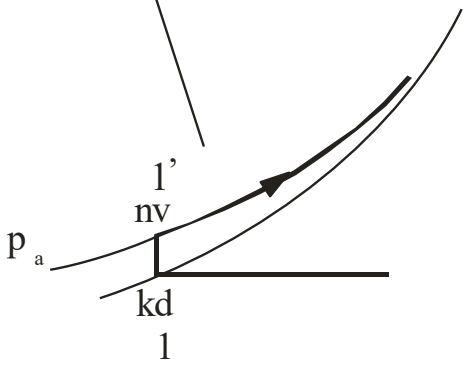
= energy gain q_c

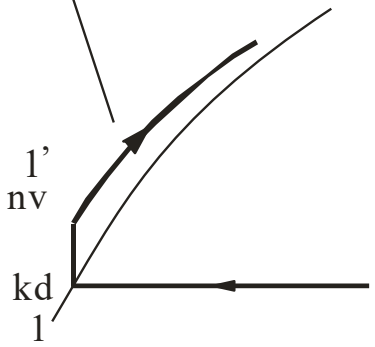
$$q_c = i_1' - i_1$$





(It is usually not considered because $q_c << w_t$)





$$i_{nv} = i_{kd}$$

Calculation of an ideal RC cycle

- Removed heat Q_o – ideally isothermally
- Supplied heat Q_p – ideally isobarically

The compression of the feed water is negligible compared to the steam expansion in the turbine.

Thermal efficiency is high if there are large differences in steam parameters at the input and output of the turbine.

- **Ideal thermal efficiency while neglecting losses for unitary flow:**

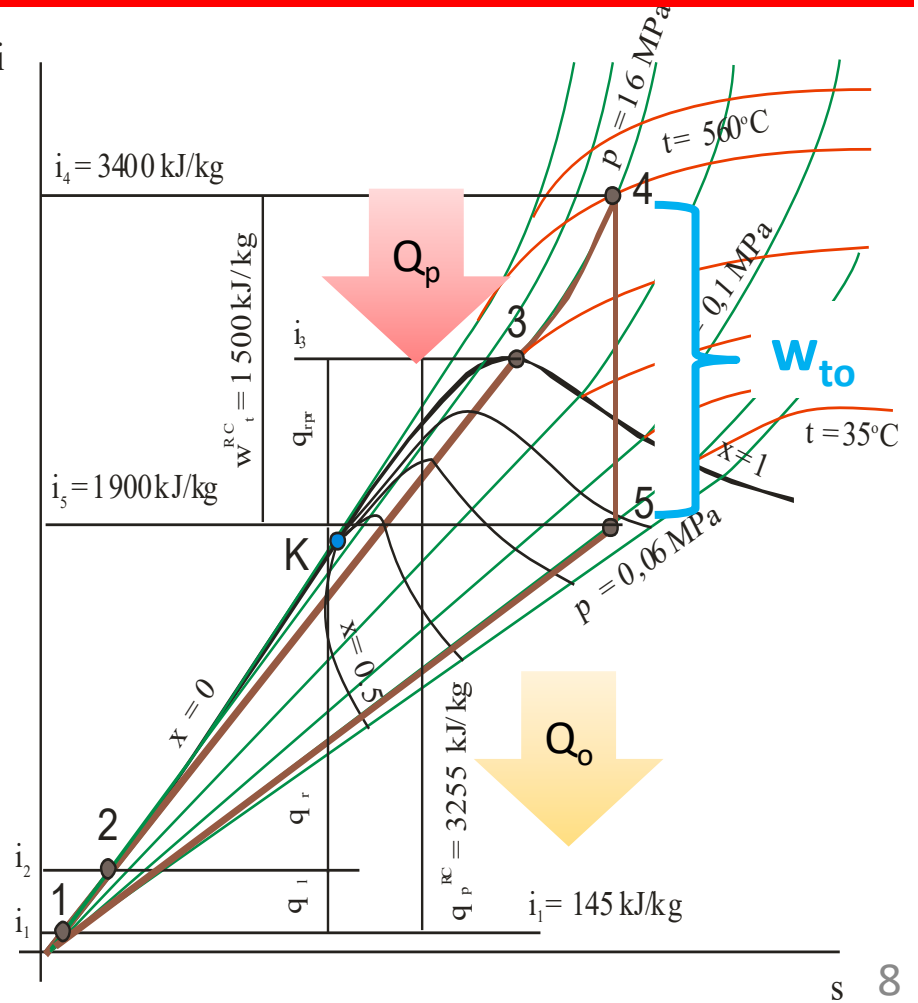
$$\eta_{to} = \frac{q_p - q_o}{q_p} = \frac{w_{to}}{q_p}$$

$$\eta_{to} = \frac{(i_4 - i_1) - (i_5 - i_1)}{i_4 - i_1} = \frac{i_4 - i_5}{i_4 - i_1}$$

$$\eta_{to} = \frac{i_a - i_e}{i_a - i_{nv}} \qquad i_{nv} = i_{kd} \qquad \eta_{to} = \frac{i_a - i_e}{i_a - i_{kd}}$$

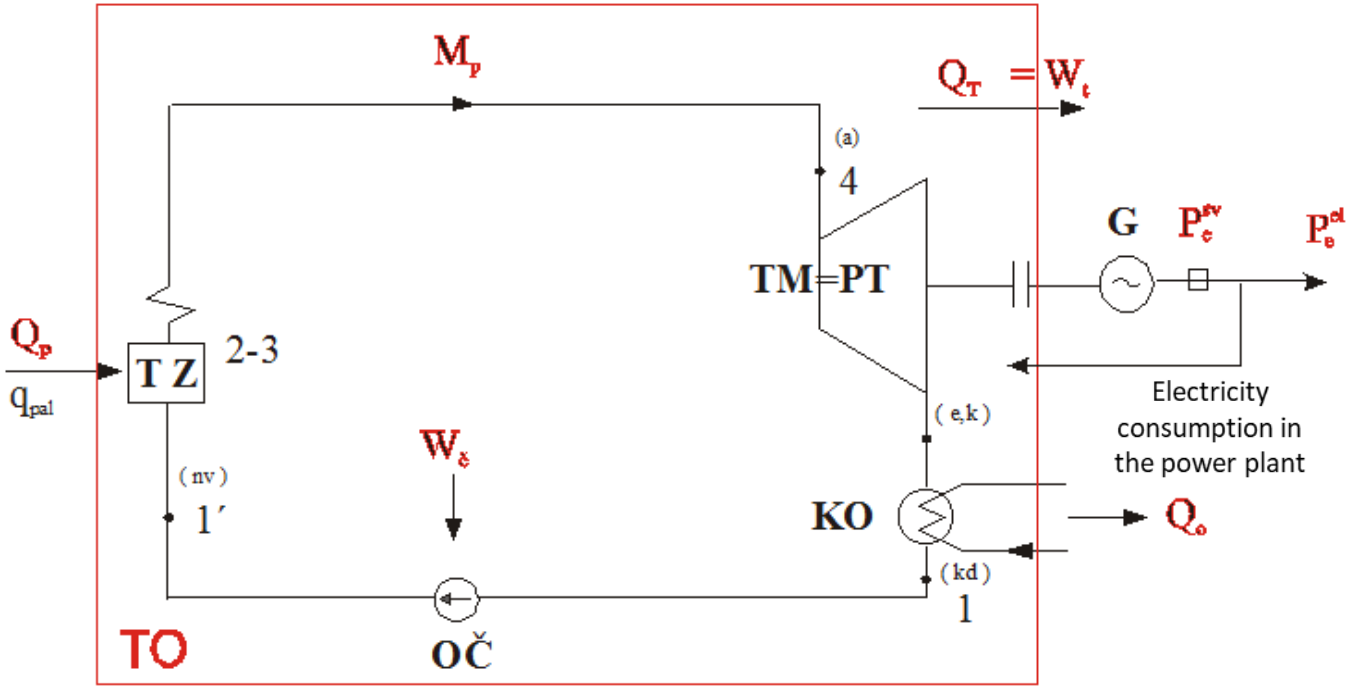
- **Ideal adiabatic (isoentropic) expansion in the turbine:**

$$h_{ad} = i_a - i_e$$



Example 1

- Calculate the **ideal thermal efficiency** of an RC cycle having the thermal scheme according to Fig. The power of the power plant unit is P_e = 55 MW. The parameters at the turbine input are: p_a=10 MPa, t_a= 500 °C. The temperature at the turbine output is t_e= 30 °C. This is an ideal lossless RC cycle.
- Furthermore, replace this thermal cycle with an equivalent Carnot cycle with the same efficiency.



Example 1 - Solution

- **Steam parameters after ideal expansion**

Specified parameters:

t_a = 500 °C

p_a = 10 MPa

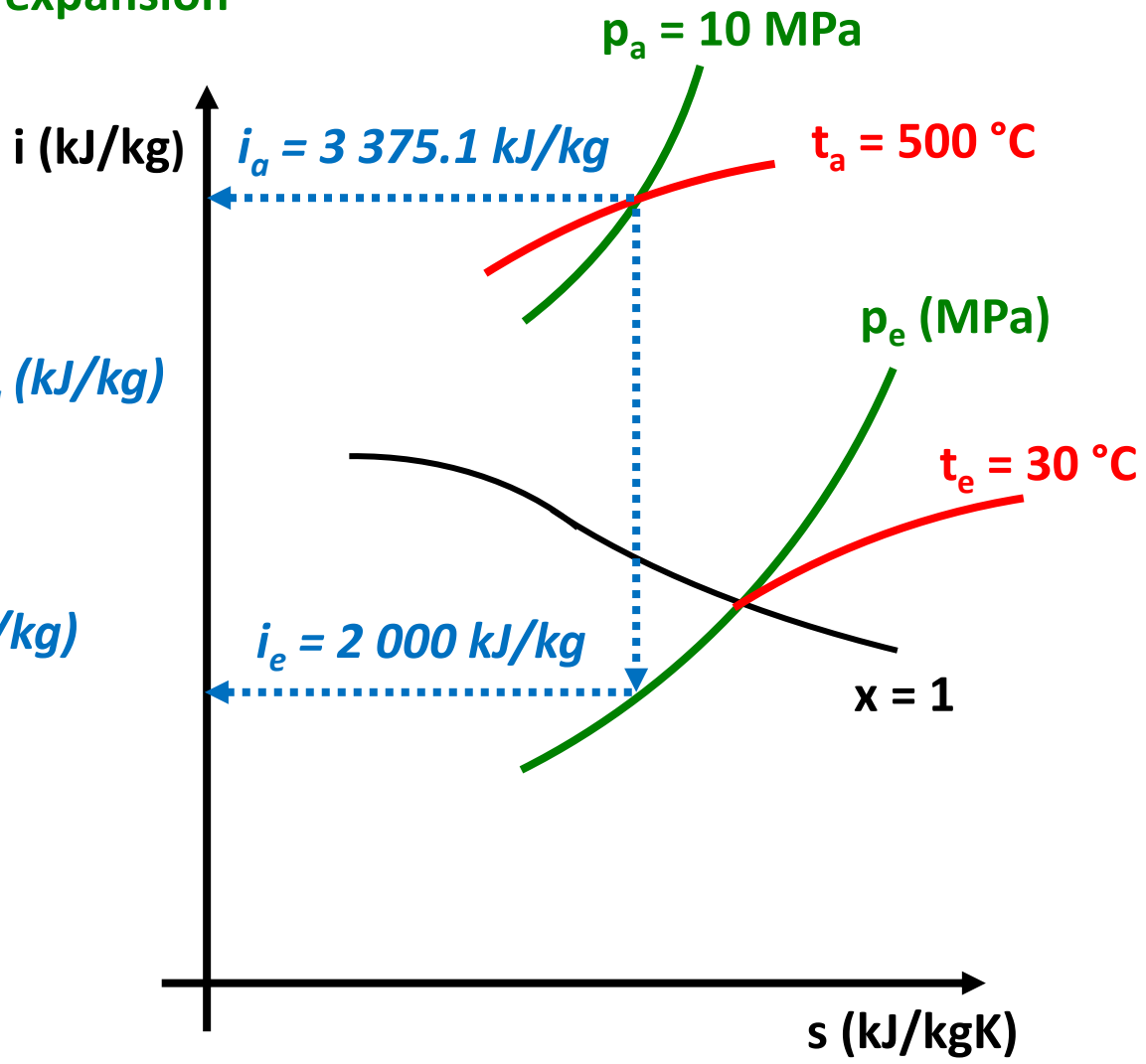
t_e = 30 °C

Enthalpy of admission steam i_a (kJ/kg)

i_a = 3 375.1 kJ/kg

Emission steam enthalpy i_e (kJ/kg)

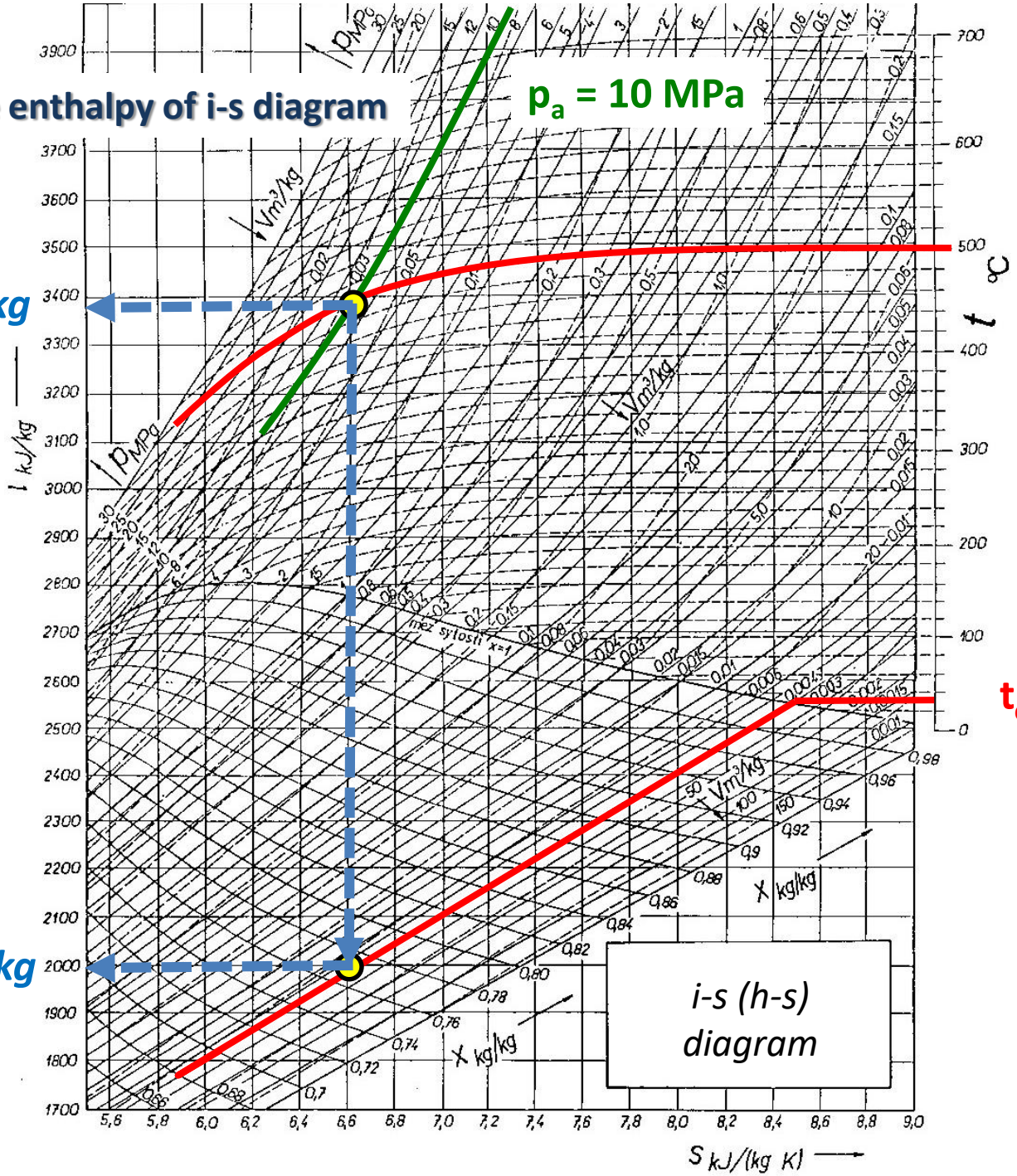
i_e = 2 000 kJ/kg



p_e = 0.004247 (MPa)

– reading from the intersection of the emission steam temperature and the right limit curve

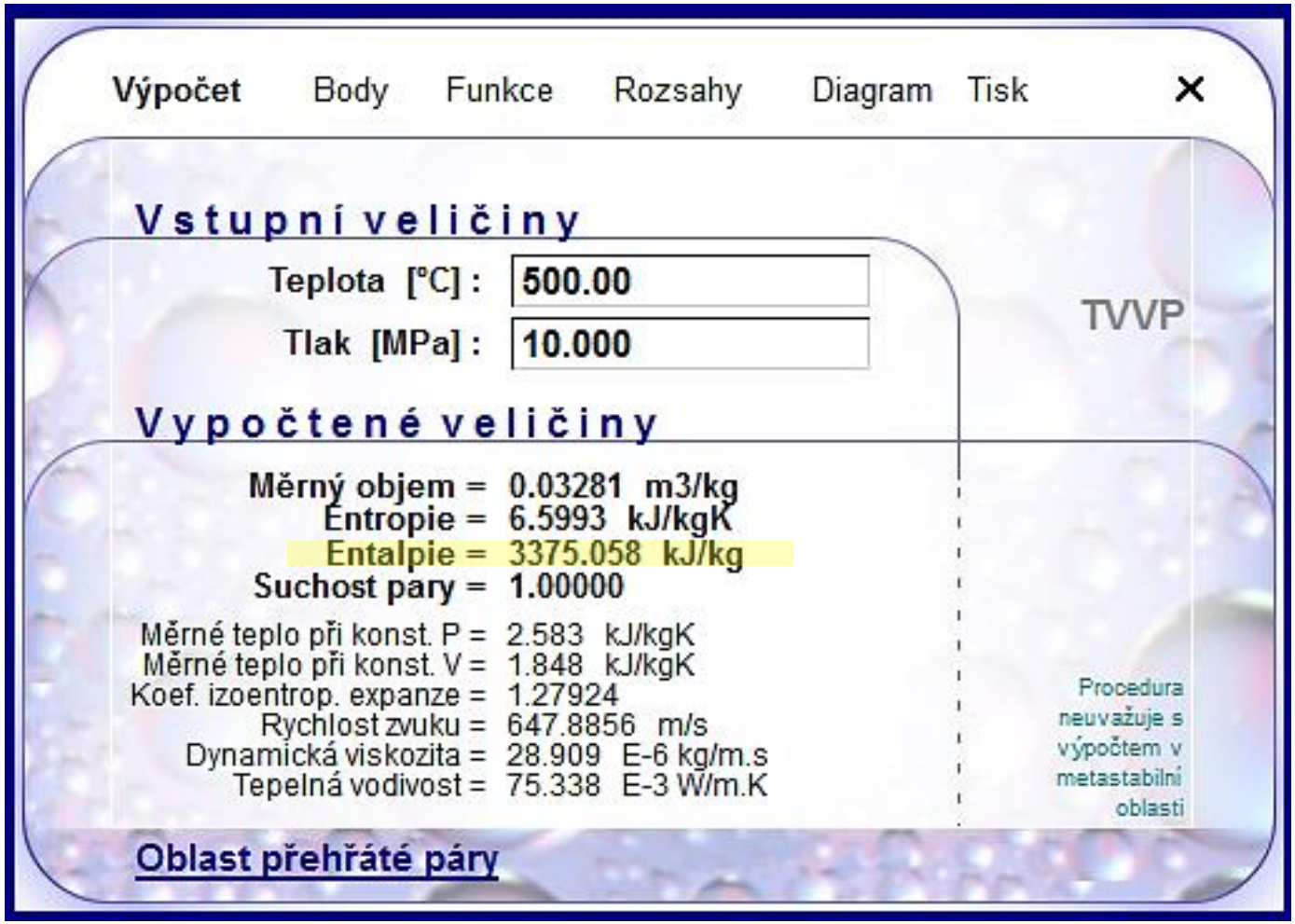
Determining the enthalpy of i-s diagram



Example 1 - Solution

- **Enthalpy of admission steam**

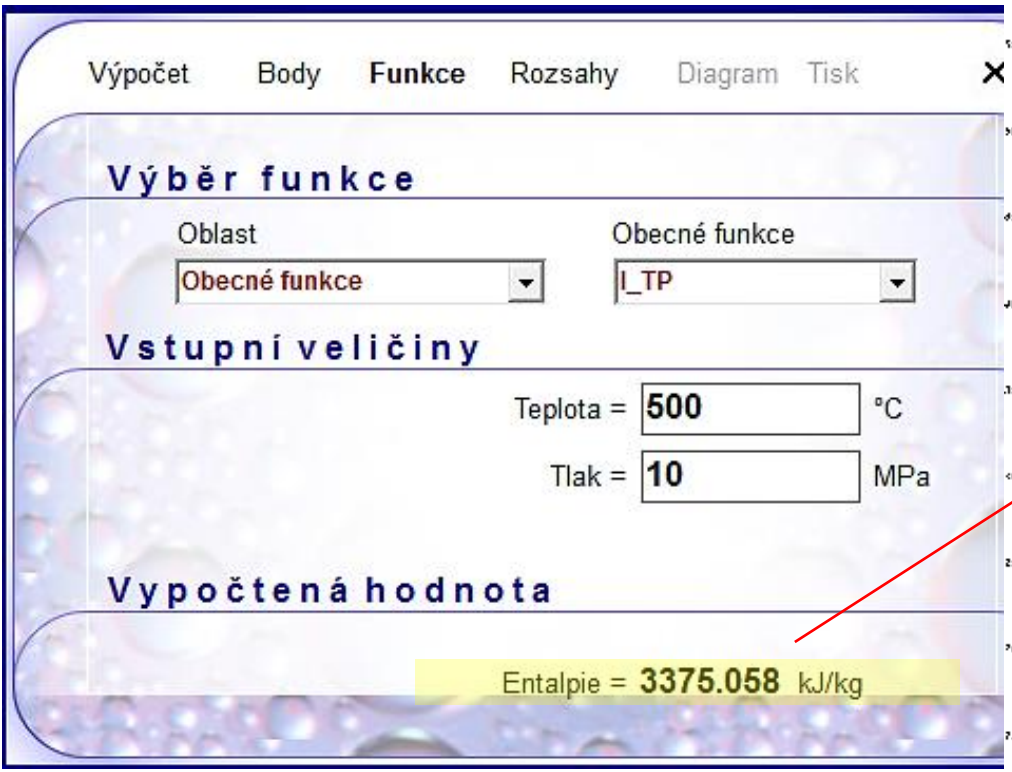
Determination of enthalpy values from Steam Tables and software

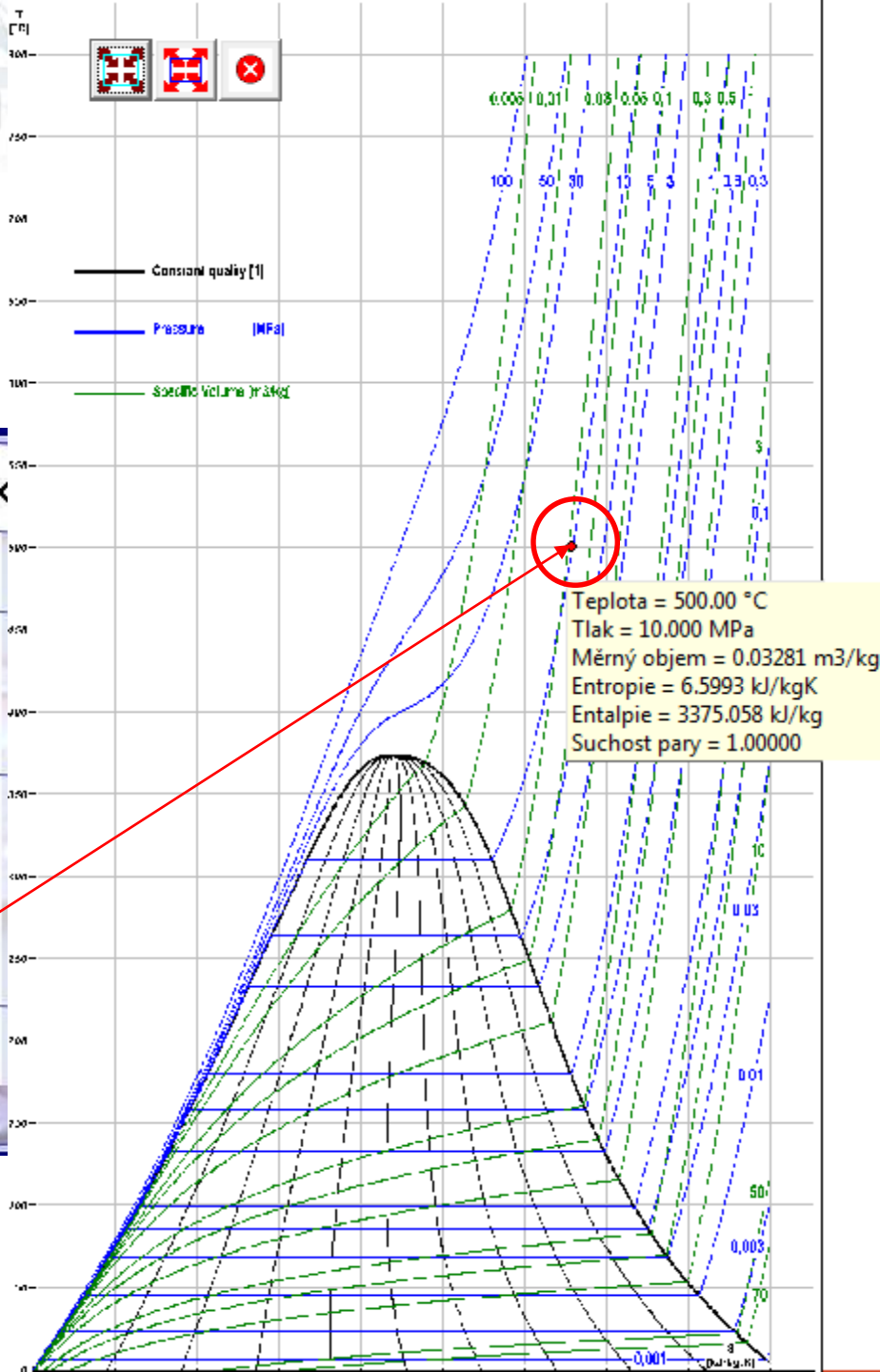


Example 1 - Solution

- **Enthalpy of admission steam**

Determination of enthalpy values from Steam Tables and software

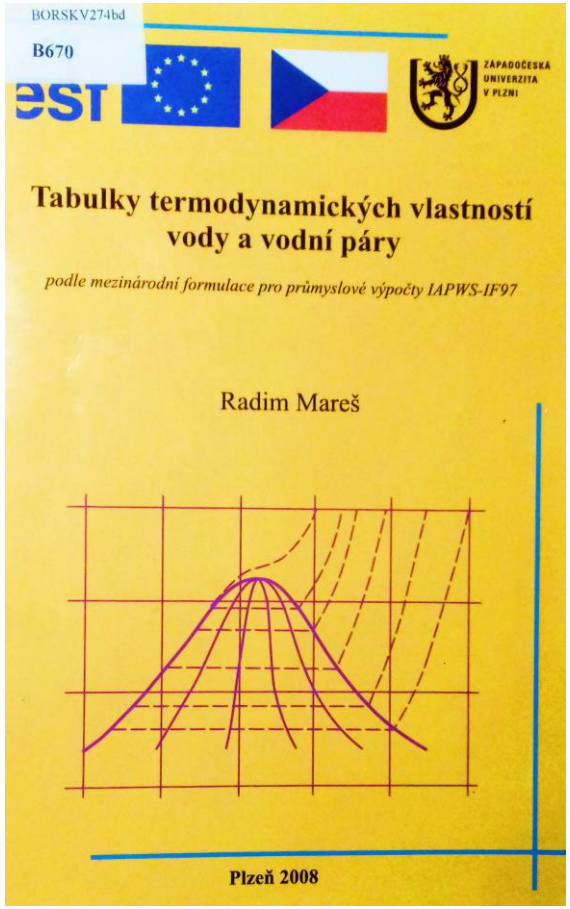




Example 1

Determination of enthalpy values from Steam Tables

- **Enthalpy of admission steam**



t	9,6MPa v	9,6MPa h	9,6MPa s	9,8MPa v	9,8MPa h	9,8MPa s	10,0MPa v	10,0MPa h	10,0MPa s	10,5MPa v	10,5MPa h	10,5MPa s
0	0,0009954	9,7	0,0003	0,0009953	9,9	0,0003	0,0009952	10,1	0,0003	0,0009950	10,6	0,0004
10	0,0009958	51,3	0,1501	0,0009957	51,5	0,1501	0,0009956	51,7	0,1501	0,0009954	52,2	0,1500
20	0,0009975	92,9	0,2945	0,0009974	93,1	0,2944	0,0009973	93,3	0,2944	0,0009971	93,8	0,2943
30	0,0010002	134,5	0,4338	0,0010001	134,6	0,4338	0,0010000	134,8	0,4337	0,0009998	135,3	0,4336
40	0,0010037	176,0	0,5687	0,0010036	176,2	0,5686	0,0010035	176,4	0,5685	0,0010033	176,8	0,5684
⋮												
300	0,0013998	1343,6	3,2501	0,0013989	1343,3	3,2493	0,0013980	1343,1	3,2484	0,0013959	1342,5	3,2462
310	0,01926	2745,9	5,6636	0,01856	2732,4	5,6341	0,0014471	1401,8	3,3498	0,0014443	1400,9	3,3471
320	0,02058	2804,1	5,7627	0,01992	2793,6	5,7381	0,01927	2782,7	5,7131	0,01773	2753,5	5,6484
330	0,02173	2853,6	5,8454	0,02108	2844,7	5,8236	0,02045	2835,7	5,8017	0,01895	2811,9	5,7460
340	0,02276	2897,5	5,9176	0,02211	2889,9	5,8978	0,02149	2882,1	5,8780	0,02002	2861,8	5,8281
350	0,02371	2937,6	5,9825	0,02307	2930,8	5,9641	0,02244	2924,0	5,9458	0,02098	2906,3	5,9000
360	0,02460	2974,8	6,0418	0,02395	2968,8	6,0245	0,02333	2962,6	6,0073	0,02186	2946,9	5,9646
370	0,02545	3009,9	6,0967	0,02479	3004,4	6,0803	0,02416	2998,8	6,0641	0,02268	2984,6	6,0238
380	0,02625	3043,2	6,1482	0,02559	3038,2	6,1325	0,02495	3033,1	6,1170	0,02346	3020,2	6,0786
390	0,02702	3075,2	6,1967	0,02635	3070,6	6,1817	0,02571	3065,9	6,1668	0,02421	3054,0	6,1300
400	0,02776	3106,0	6,2429	0,02709	3101,7	6,2283	0,02644	3097,4	6,2139	0,02492	3086,4	6,1785
410	0,02848	3135,9	6,2869	0,02780	3131,9	6,2728	0,02714	3127,8	6,2589	0,02561	3117,6	6,2246
420	0,02918	3165,0	6,3292	0,02849	3161,2	6,3155	0,02783	3157,5	6,3019	0,02628	3147,9	6,2686
430	0,02987	3193,4	6,3699	0,02917	3189,9	6,3565	0,02850	3186,3	6,3432	0,02693	3177,3	6,3108
440	0,03053	3221,2	6,4092	0,02983	3217,9	6,3961	0,02915	3214,6	6,3831	0,02756	3206,1	6,3514
450	0,03119	3248,6	6,4473	0,03047	3245,4	6,4344	0,02978	3242,3	6,4217	0,02818	3234,3	6,3907
460	0,03183	3275,5	6,4843	0,03111	3272,5	6,4716	0,03041	3269,5	6,4591	0,02878	3262,0	6,4287
470	0,03246	3302,1	6,5203	0,03173	3299,2	6,5078	0,03102	3296,4	6,4955	0,02938	3289,2	6,4656
480	0,03309	3328,3	6,5553	0,03234	3325,6	6,5431	0,03163	3322,9	6,5310	0,02996	3316,1	6,5015
490	0,03370	3354,3	6,5896	0,03295	3351,7	6,5775	0,03223	3349,1	6,5655	0,03054	3342,6	6,5365
500	0,03431	3380,0	6,6230	0,03354	3377,5	6,6111	0,03281	3375,1	6,5993	0,03110	3368,9	6,5706
510	0,03491	3405,5	6,6558	0,03413	3403,1	6,6440	0,03339	3400,8	6,6324	0,03166	3394,9	6,6041
520	0,03550	3430,8	6,6880	0,03472	3428,6	6,6763	0,03397	3426,3	6,6648	0,03222	3420,6	6,6368
530	0,03608	3456,0	6,7195	0,03529	3453,8	6,7079	0,03454	3451,7	6,6965	0,03276	3446,2	6,6688
540	0,03667	3481,0	6,7505	0,03587	3479,0	6,7390	0,03510	3476,9	6,7277	0,03331	3471,6	6,7003
550	0,03724	3505,9	6,7809	0,03643	3503,9	6,7696	0,03566	3501,9	6,7584	0,03384	3496,9	6,7312
560	0,03781	3530,7	6,8109	0,03699	3528,8	6,7996	0,03621	3526,9	6,7885	0,03437	3522,1	6,7615
570	0,03838	3555,5	6,8404	0,03755	3553,6	6,8292	0,03676	3551,8	6,8182	0,03490	3547,1	6,7914
580	0,03894	3580,1	6,8694	0,03811	3578,3	6,8583	0,03730	3576,5	6,8474	0,03542	3572,0	6,8208
590	0,03950	3604,7	6,8981	0,03865	3602,9	6,8870	0,03784	3601,2	6,8761	0,03594	3596,9	6,8498
600	0,04006	3629,2	6,9263	0,03920	3627,5	6,9153	0,03838	3625,8	6,9045	0,03646	3621,7	6,8783

Example 1 - Solution

- Gain of technical work = ideal isoentropic gradient

$h_{ad} =$

- Condensate enthalpy = enthalpy of the feed water

$i_{kd} =$

- Specific heat consumption of the thermal cycle

$q_p =$

$q_p =$

- Specific heat removed from the thermal cycle

$q_o =$

Example 1 - Solution

- **Ideal thermal efficiency of the thermal cycle**

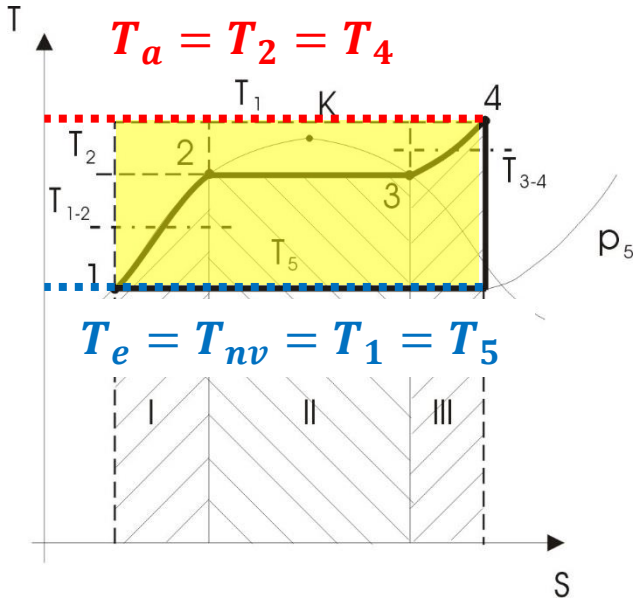
$\eta_{to} =$

$\eta_{to} =$

- **Maximum thermal efficiency of the thermal cycle (Carnot cycle)**

$\eta_t^{CO} =$

$\eta_t^{CO} =$



Calculation of the real RC cycle

- Losses in the turbine - mainly by friction and are converted into heat

$$dq = Tds$$

→ heating the steam and increasing its entropy

Expansion according to polyentropy
Lower gain of mechanical work in the turbine

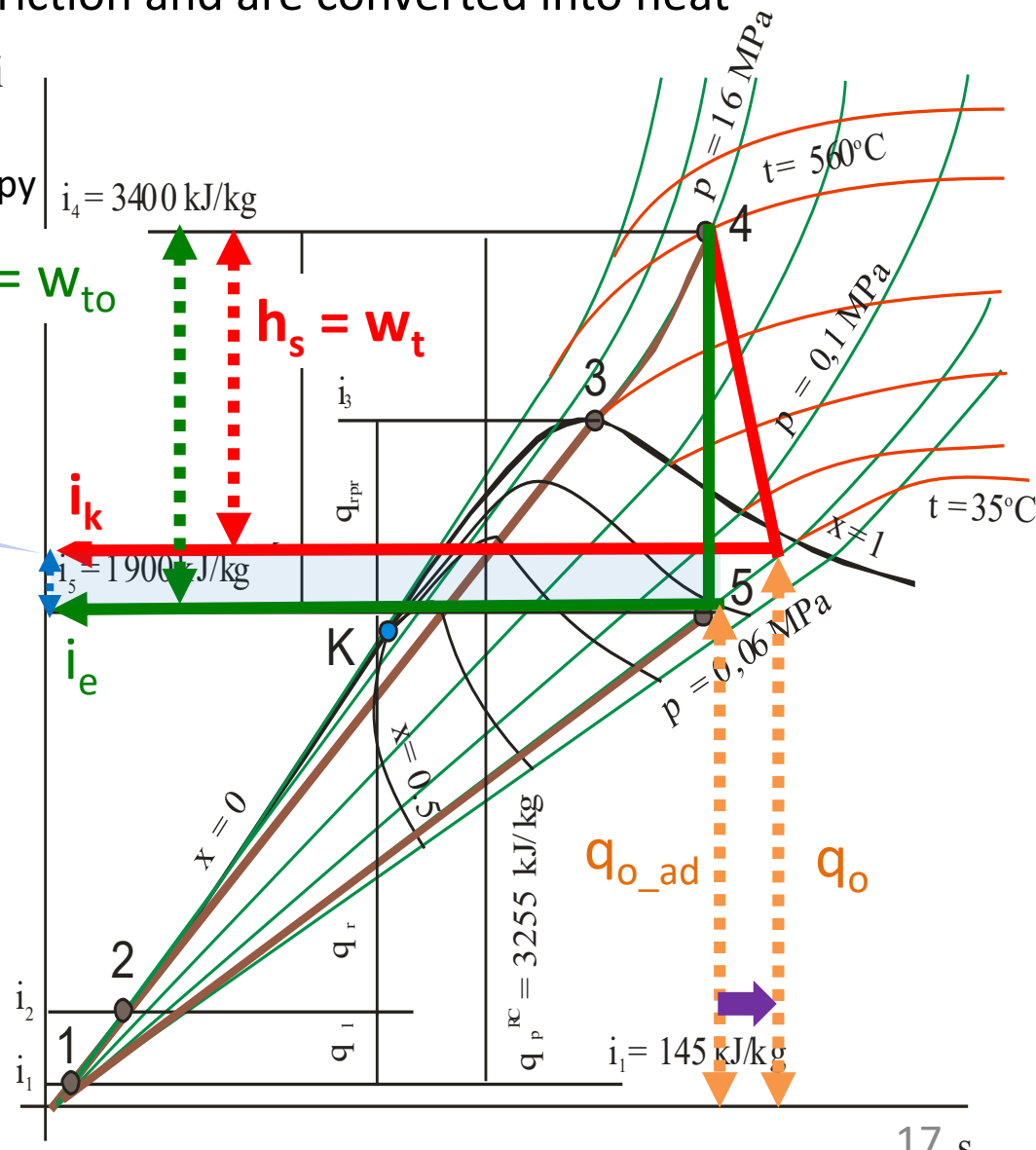
Turbine losses = $h_{ad} - h_s$

Enthalpy of real expanded steam

$$\eta_t = \frac{i_4 - i_5'}{i_4 - i_1} = \frac{i_a - i_k}{i_a - i_{nv}} = \frac{h_s}{i_a - i_{nv}}$$

$$i_{nv} = i_{kd}$$

$$\eta_t = \frac{i_a - i_k}{i_a - i_{kd}}$$



Thermal cycle efficiency analysis

- **Thermodynamic efficiency of a turbine (0.78 až 0.86)**

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

- **Real thermal efficiency of thermal cycle**

Ideal thermal efficiency of thermal cycle

$$\eta_t = \eta_{to} \cdot \eta_{td}$$

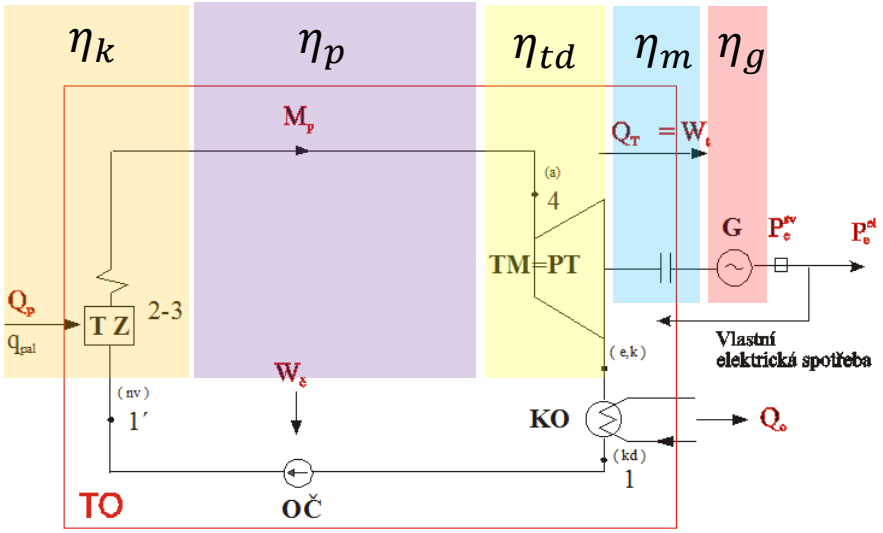
- **Mechanical efficiency of the turbine (0.98 až 0.99)**

$$\eta_m = \frac{P_{sp}}{P_i}$$

Thermal cycle efficiency analysis

- **Thermodynamic efficiency at the coupling**

$$\eta_{td}^{sp} = \eta_{td} \cdot \eta_m$$



- **Generator efficiency (0.97 až 0.985)**

$$\eta_g = \frac{P_e}{P_{sp}}$$

- **Boiler efficiency**

$$\eta_k = \frac{Q_k}{Q_p} = \frac{M_p(i_{ko} - i_{nv})}{M_{pal} \cdot q_{pal}}$$

- **Efficiency of steam pipelines (0.95 až 0.99)**

$$\eta_p = \frac{Q_T}{Q_K}$$

Thermal cycle efficiency analysis

$$1\ kWh = 3\ 600\ kJ$$

- **Thermal efficiency of the power plant at the generator terminals**

$$\eta_t^{el} = \frac{3600 \cdot P_e}{Q_p} = \frac{3\ 600}{q_p} = \frac{M_p(i_a - i_e)}{M_p(i_a - i_{nv})} = \eta_{to} \cdot \eta_{td} \cdot \eta_g \cdot \eta_m \cdot \eta_k \cdot \eta_p$$

$$M_p(\boldsymbol{i_a - i_{nv}}) \cdot \boldsymbol{\eta_{to}} \cdot \eta_{td} \cdot \eta_g \cdot \eta_m \cdot \eta_k \cdot \eta_p = 3\ 600 \cdot P_e$$

$$M_p(\boldsymbol{i_a - i_e}) \cdot \boldsymbol{\eta_{td}} \cdot \eta_g \cdot \eta_m \cdot \eta_k \cdot \eta_p = 3\ 600 \cdot P_e$$

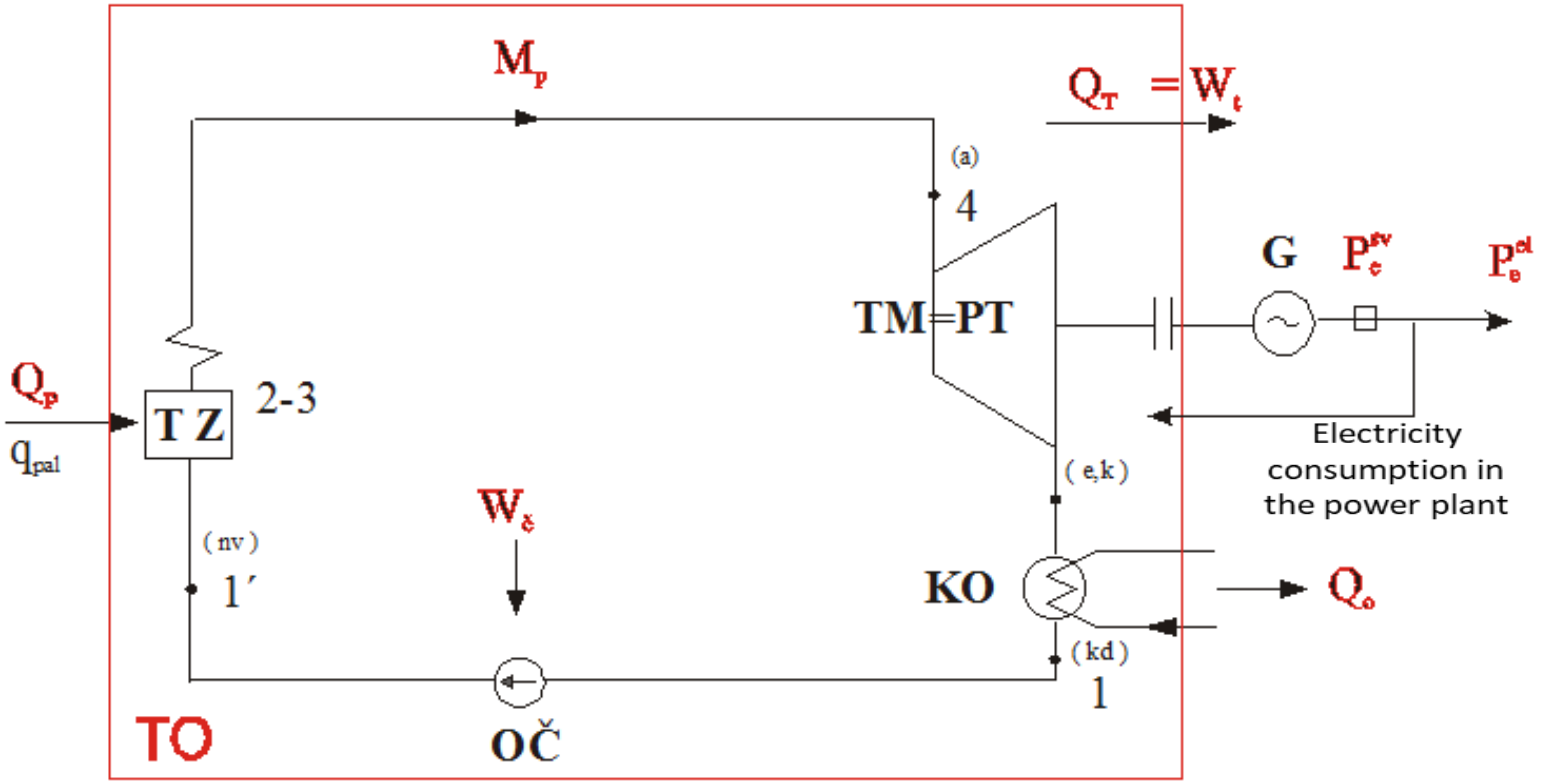
$$M_p(\boldsymbol{i_a - i_k}) \cdot \eta_g \cdot \eta_m \cdot \eta_k \cdot \eta_p = 3\ 600 \cdot P_e$$

- **Specific steam consumption**

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

Example 2

- Calculate the **real thermal efficiency** of the RC cycle. Output power of the power plant unit is P_e=55 MW. The parameters at the turbine input are: p_a=10 MPa, t_a= 500 °C. Turbine output temperature t_e= 30 °C. If you know that the mechanical efficiency is 0.99, the generator efficiency is 0.98, the boiler efficiency is 0.85, the pipe efficiency is 0.99 and the thermodynamic efficiency is 0.8. Calculate the required amount of steam.



Example 2 – Solution – From Example 1:

- **Steam parameters after ideal expansion**

Specified parameters:

t_a = 500 °C

p_a = 10 MPa

t_e = 30 °C

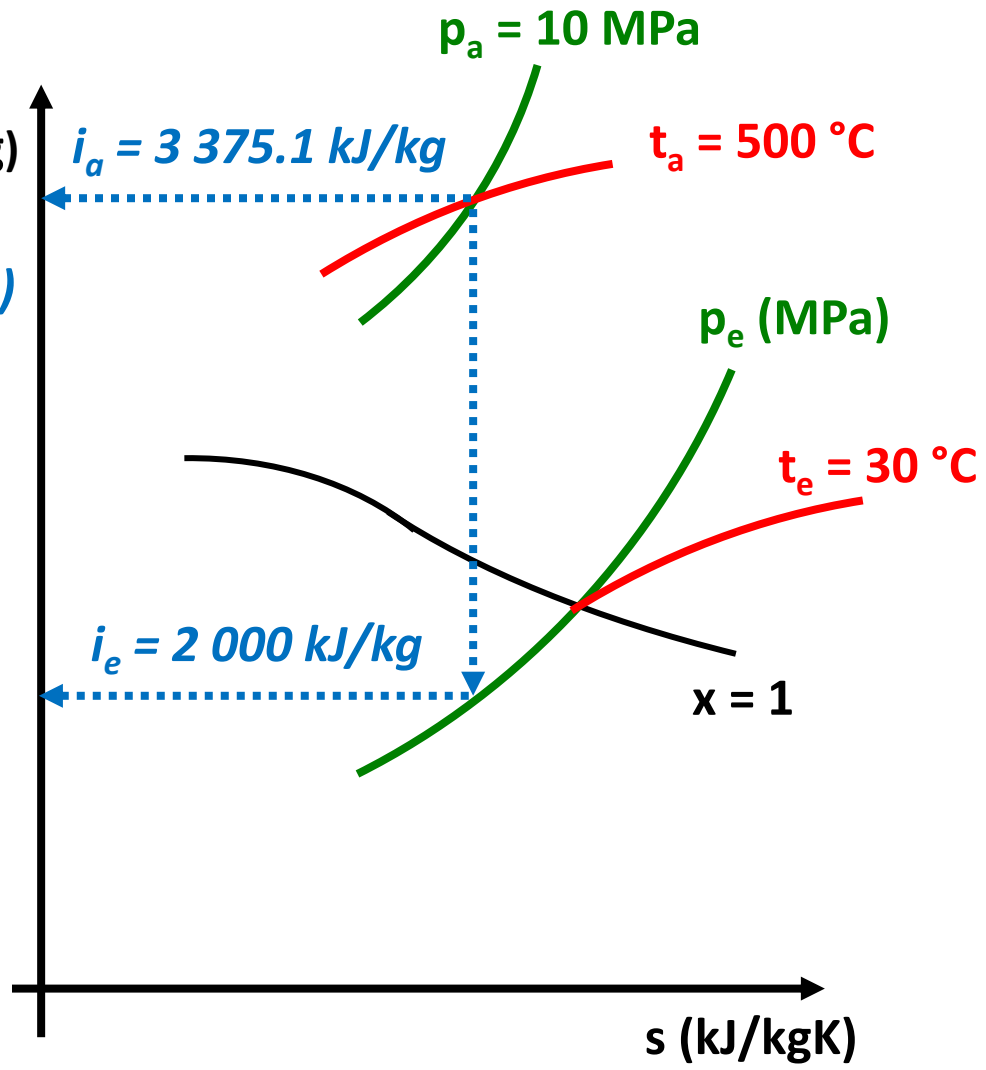
Enthalpy of admission steam i_a (kJ/kg)

i_a = 3 375.1 kJ/kg

Emission steam enthalpy i_e (kJ/kg)

i_e = 2 000 kJ/kg

p_e = 0.004247 (MPa) – reading from the intersection of the emission steam temperature and the right limit curve

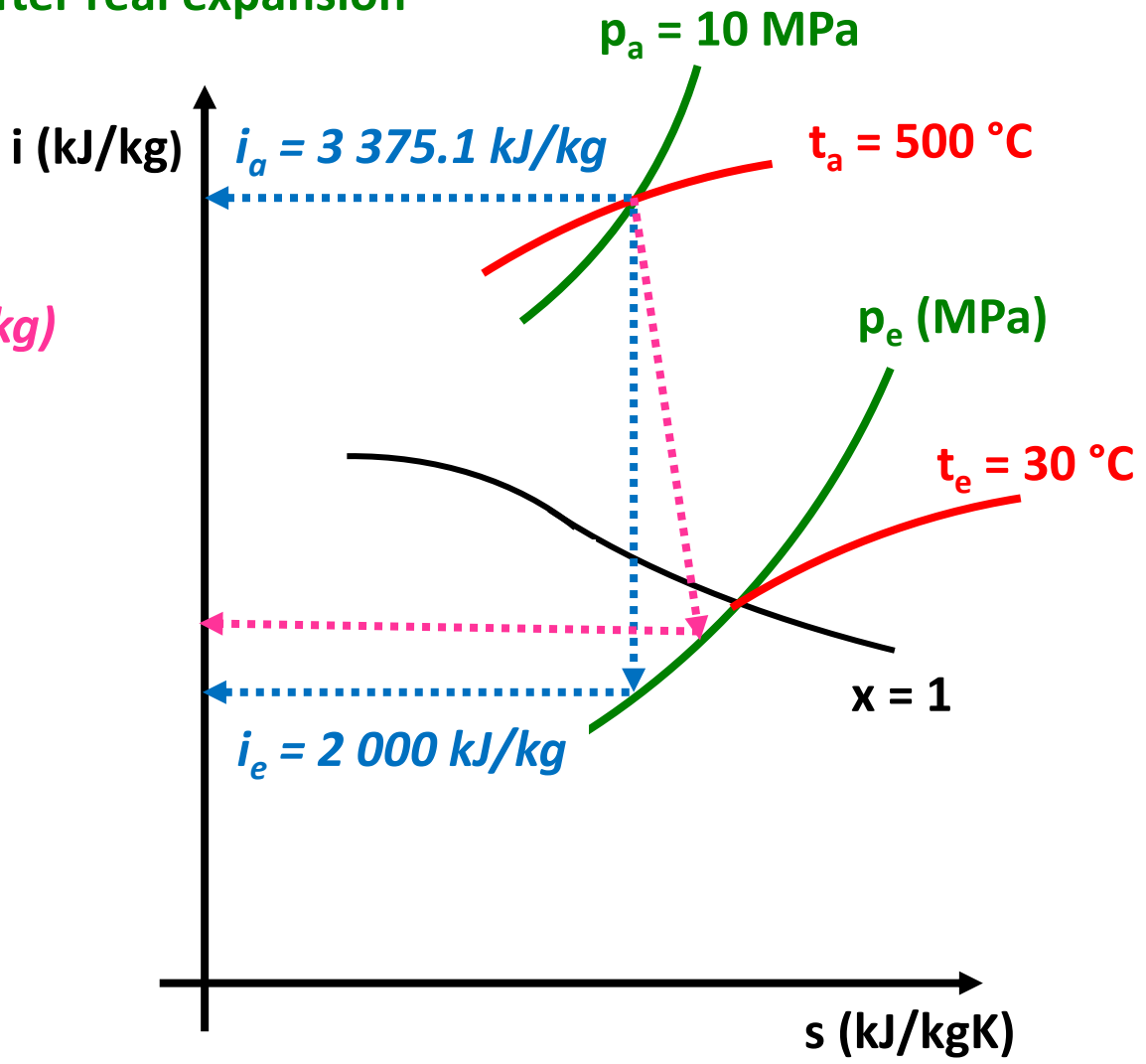


Example 2 - Solution

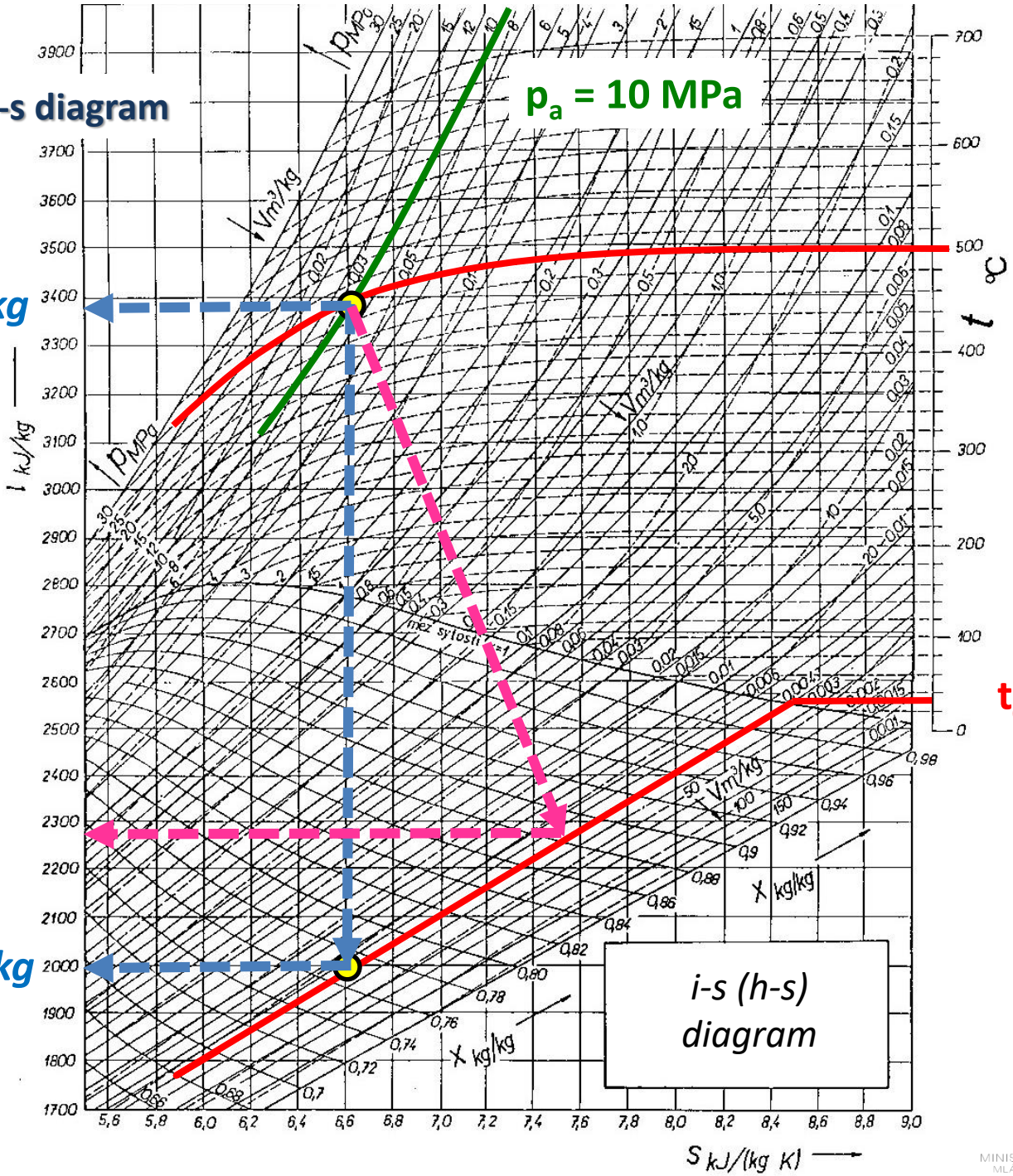
- **Emission steam parameters after real expansion**

Specified parameter: η_{td} = 0.8

Emission steam enthalpy i_k (kJ/kg)



Presentation in i-s diagram



Example 2 - Solution

- **Real thermal gradient in the turbine**

Specified parameter: η_{td} = 0.8 $\boldsymbol{h_{ad} = w_t =}$

$\eta_{td} =$ $\rightarrow \boldsymbol{h_s =}$

- **Thermal efficiency of an ideal RC cycle - see Example 1**

$\boldsymbol{\eta_{to} =}$

- **Thermal efficiency of a real RC cycle**

$\boldsymbol{\eta_t =}$

Example 2 - Solution

Specified parameters: $\eta_{td} = 0.8;\ \eta_g = 0.98;\ \eta_m = 0.99;\ \eta_k = 0.85;\ \eta_p = 0.99$

- **The thermal efficiency in the turbine set at the generator terminals**

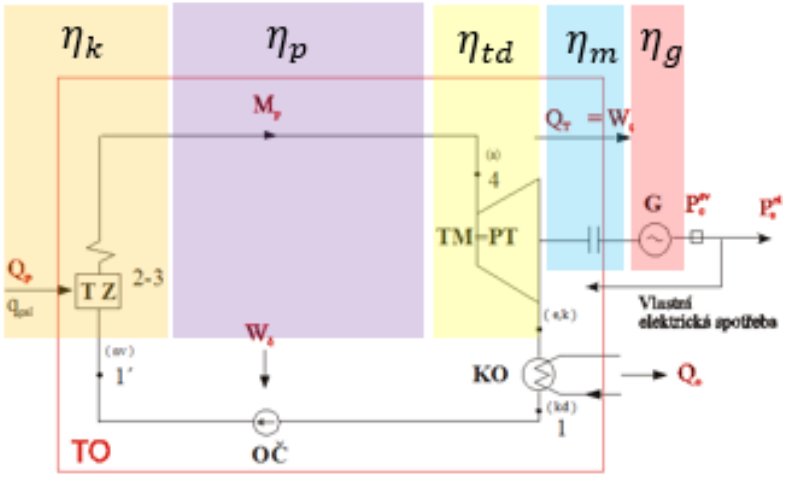
$$\eta_t^e =$$

- **Thermal efficiency of the power plant at the generator terminals**

$$\eta_t^{el} =$$

- **Comparison of results with Example 1**

η_t^{CO}	η_{to}	η_t	η_t^e	η_t^{el}



Example 2 - Solution

Specified parameters: $\eta_{td} = 0.8;\ \eta_g = 0.98;\ \eta_m = 0.99;\ \eta_k = 0.85;\ \eta_p = 0.99$

$P_e = 55\ MW$

- **Steam consumption**

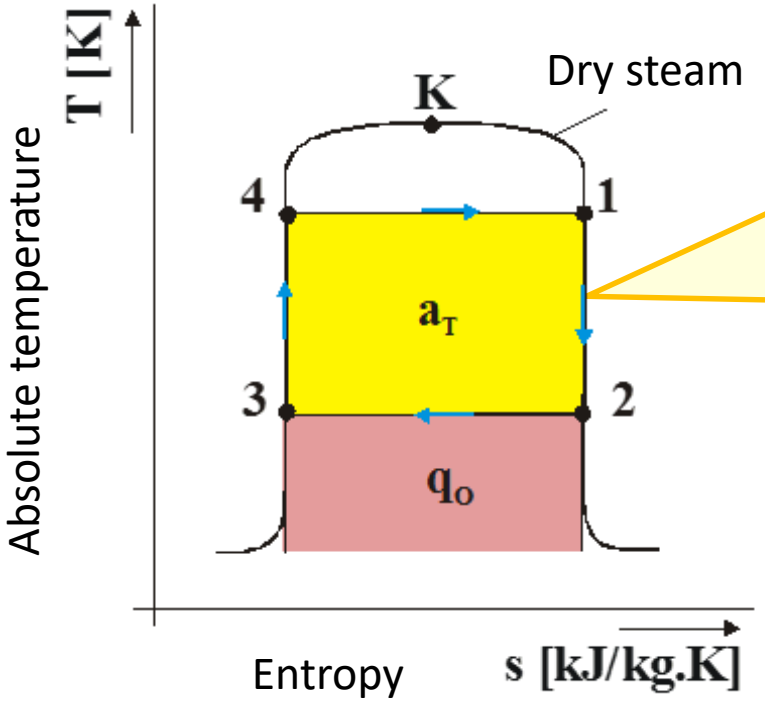
$$M_p =$$

- **Specific steam consumption**

$$m_p =$$

Choice of working substance in RC cycle

- According to the thermodynamic properties of the working substance
- Comparison of thermal cycle courses with the course of an ideal Carnot cycle
- **Most ideal** = right and left boundary curve approximately equal to isoentrope
  → profit of technical work = rectangle (1, 2, 3, 4)



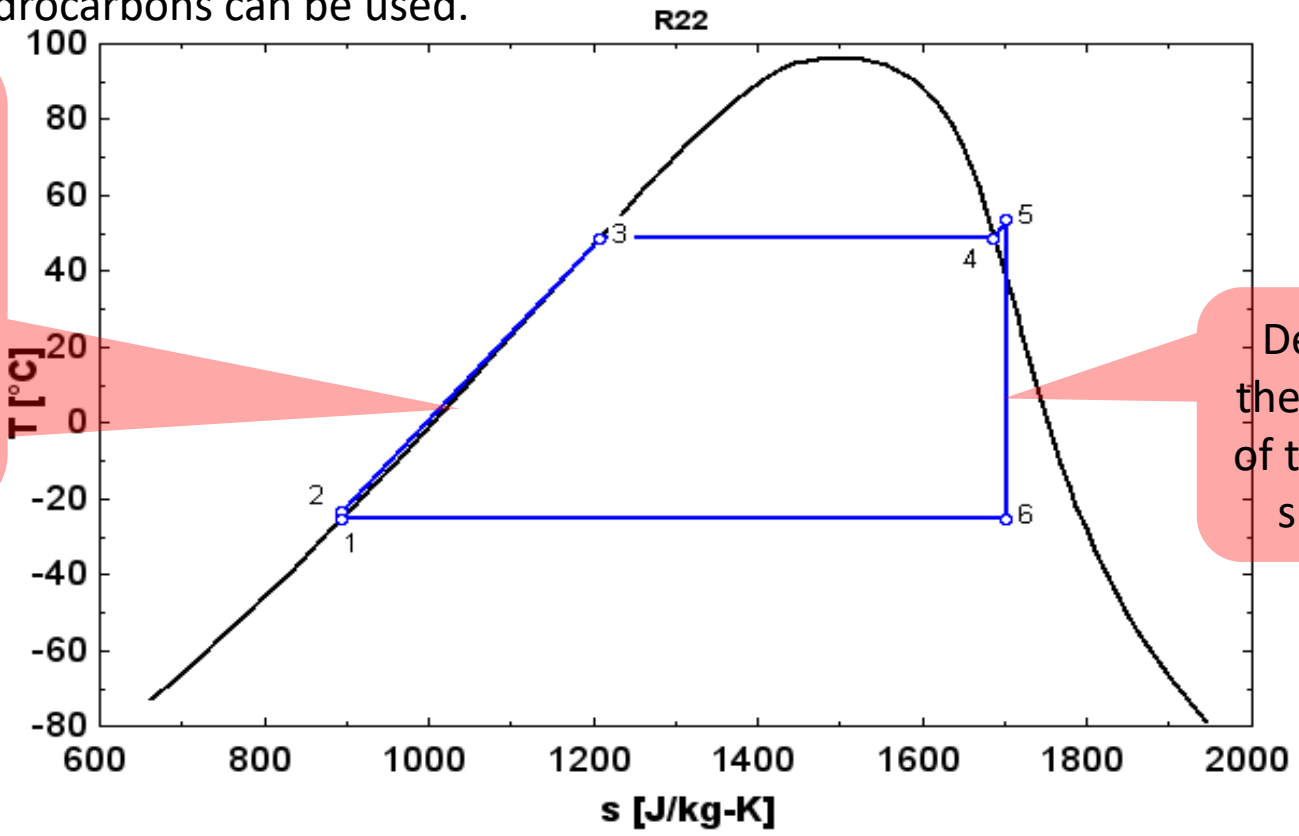
Expansion in the turbine on the boundary curve (not into the wet steam area)
→
Losses of thermal gradient are minimal (influence of higher weight of water vapor droplets)
→
Real working substances do not have this course of the thermal cycle

Real working substances

ORC = organic Rankine Clausius cycle

= **Low temperature thermal cycles,** i.e. the flow temperature is lower than with conventional RC cycles. In ORC cycles, either substances used in refrigeration cycles or mixtures of hydrocarbons can be used.

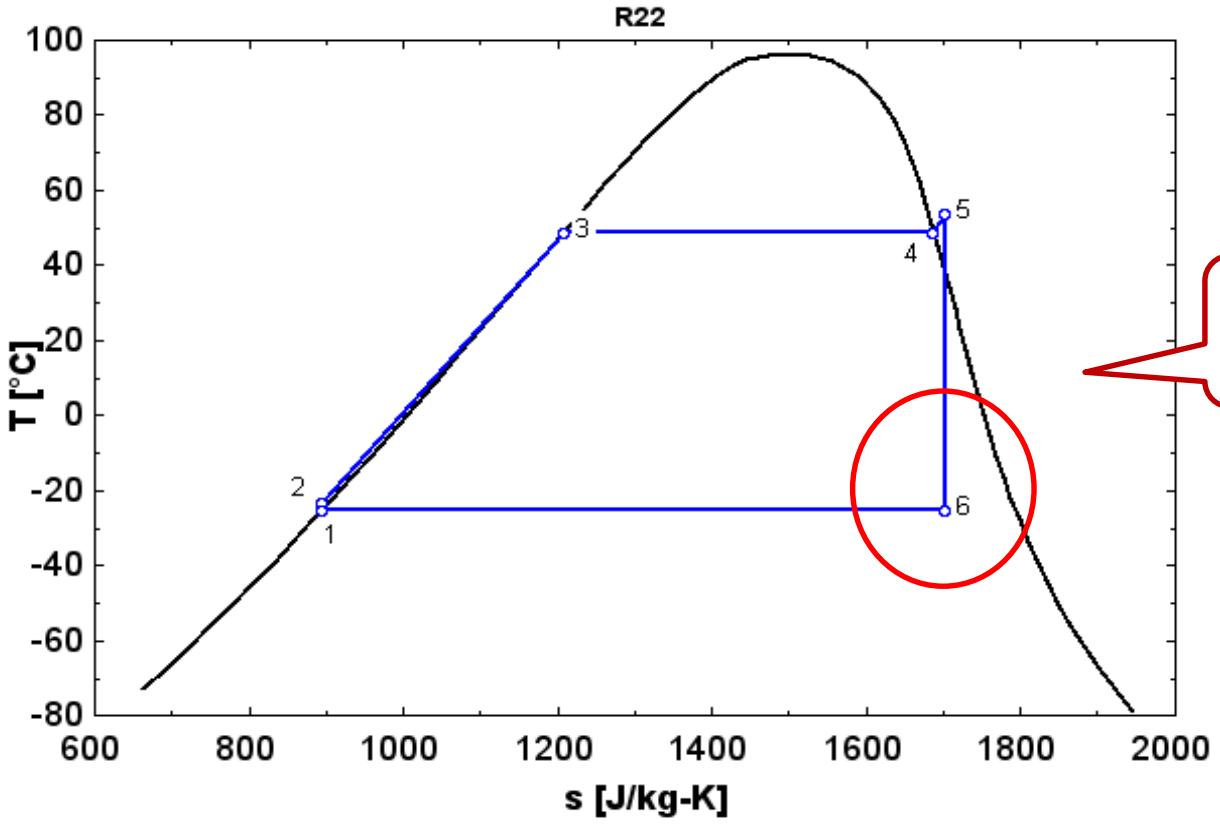
The course of the increase in entropy during the supply of liquid heat to the working substance



Determines the properties of the working substance

Wet working substances

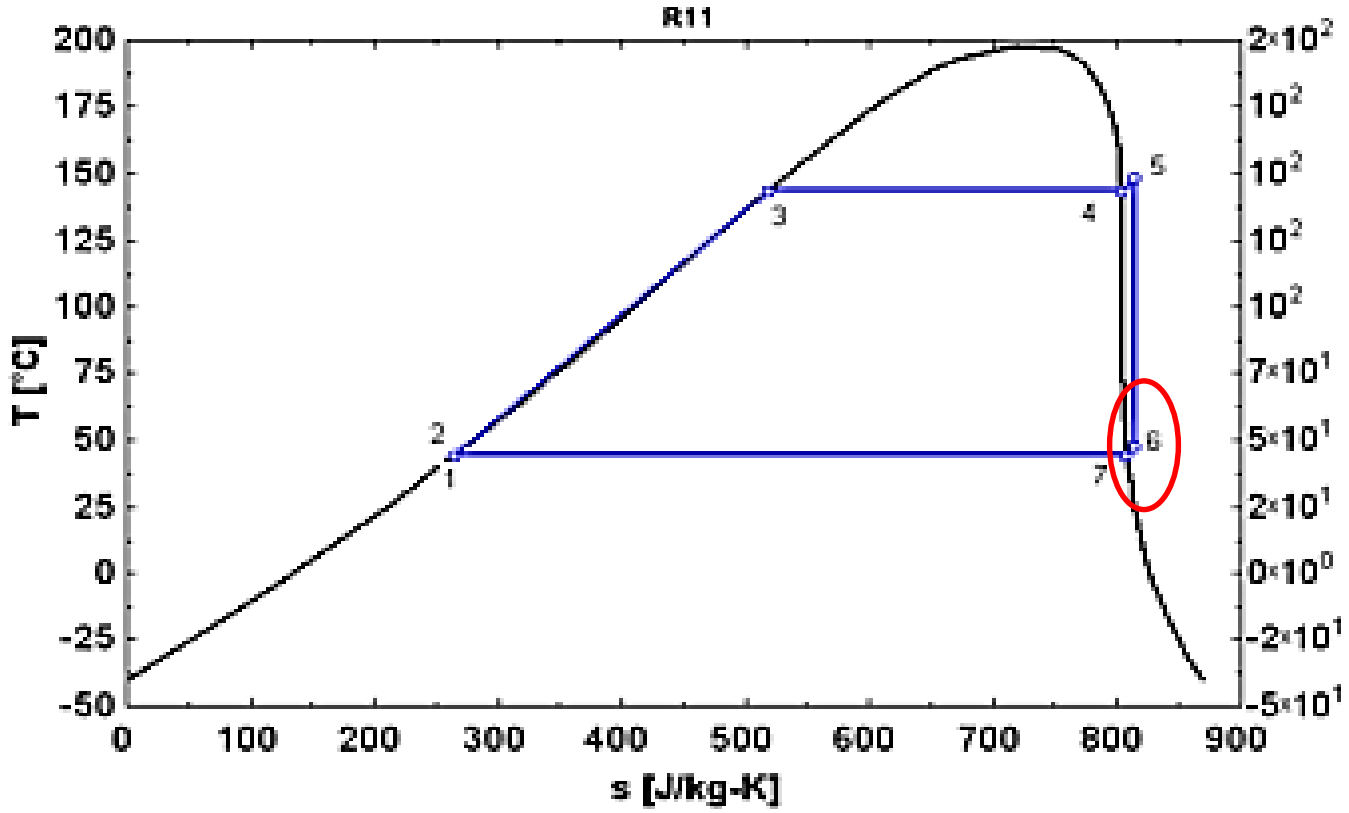
- water and some organic substances
- = the working substance enters **into the wet steam area** after adiabatic expansion in the turbine



FREON 22

Isoentropic working substances

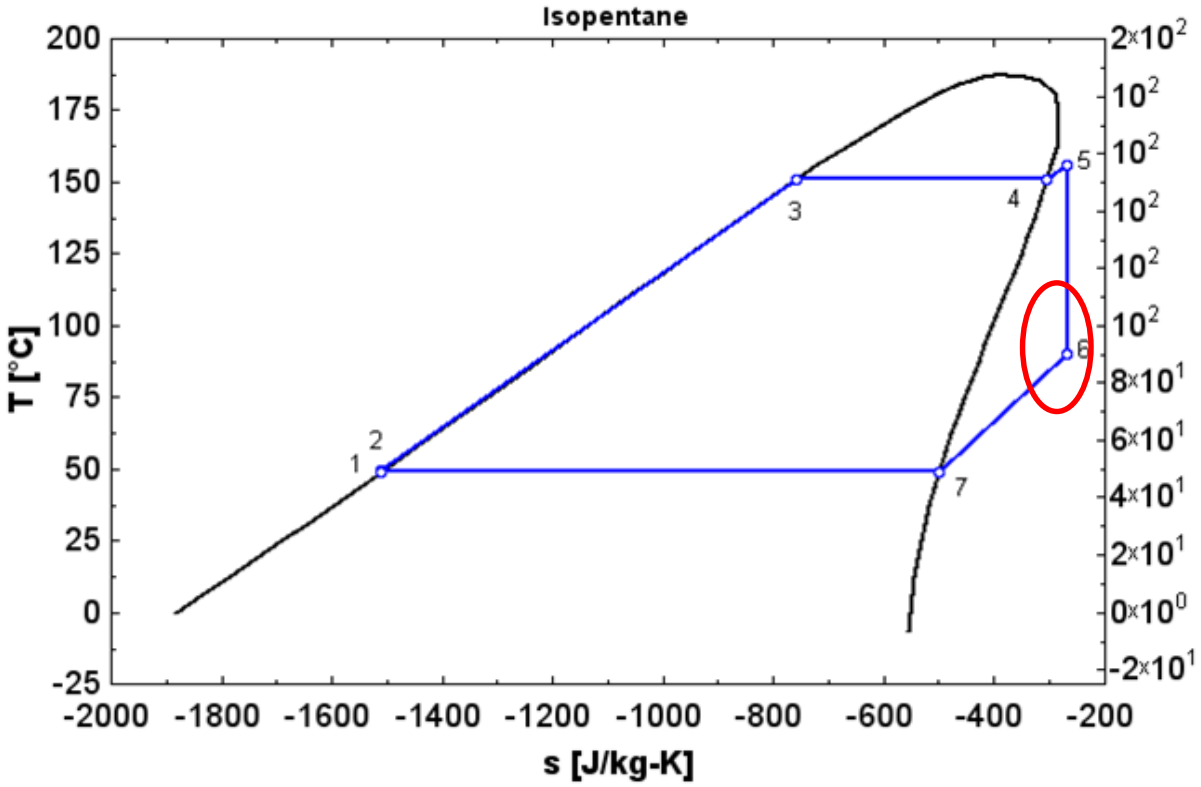
- organic substances
- = the working substance **remains in the superheated steam area** after expansion in the turbine



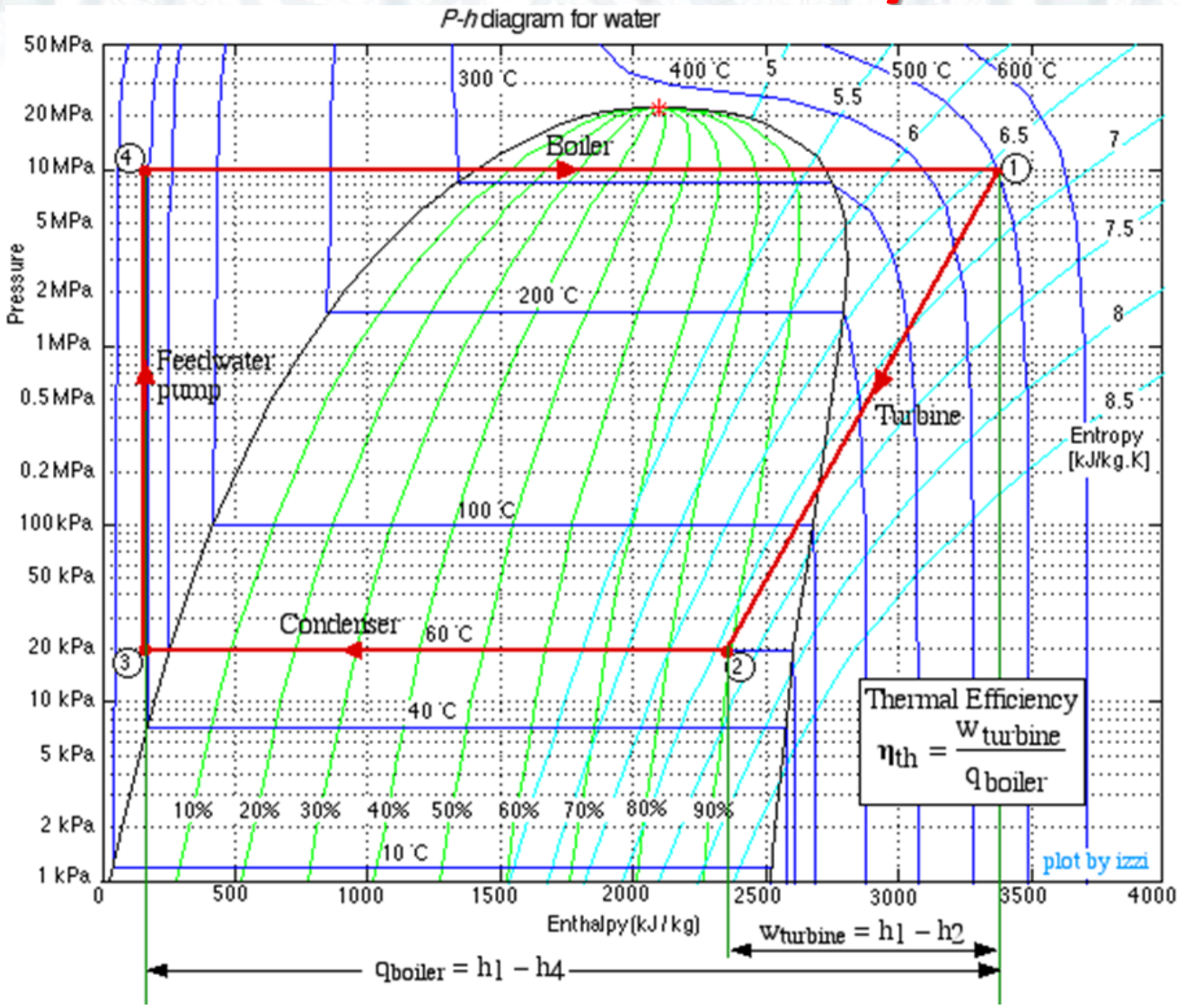
FREON 11

Dry working substances

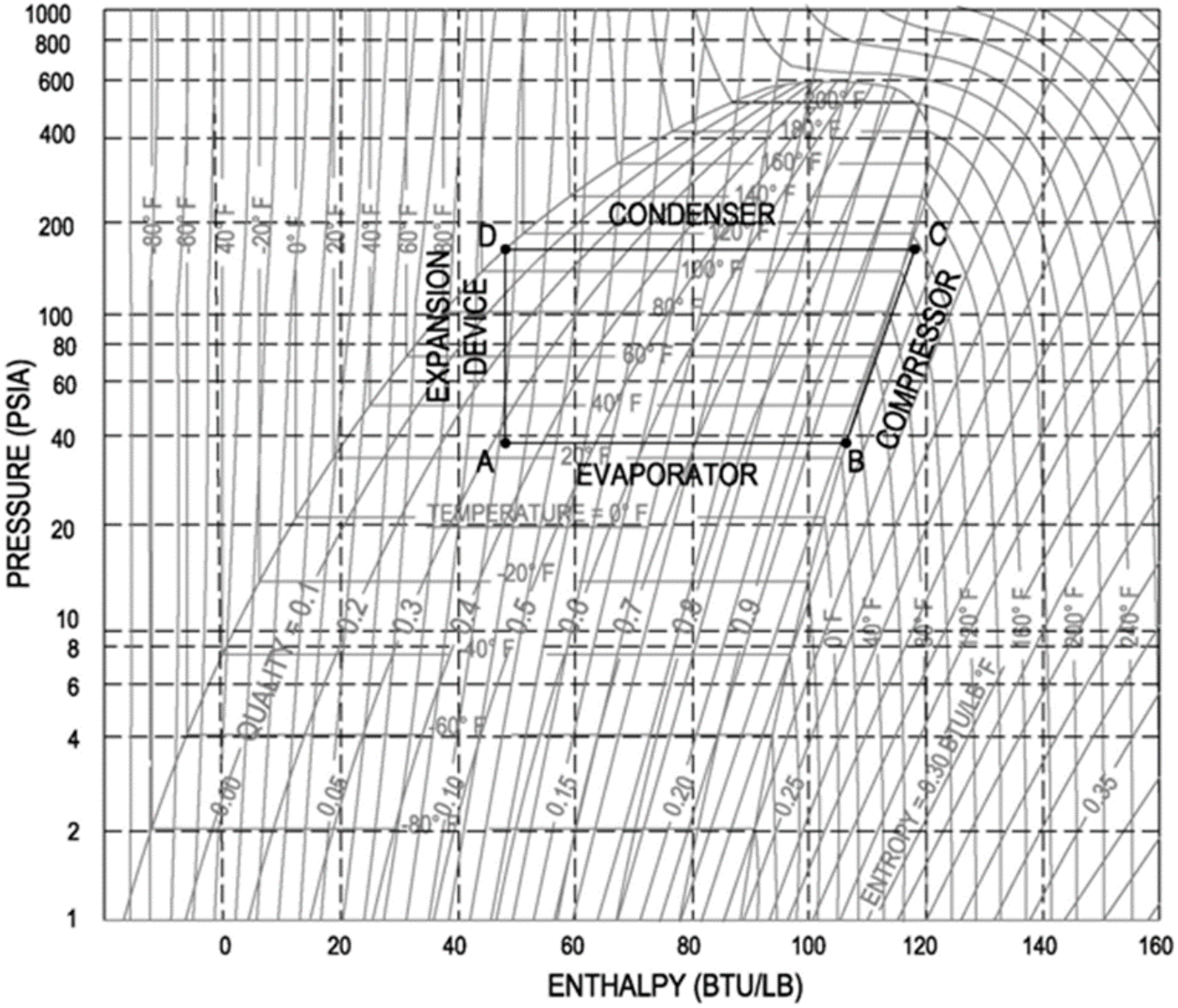
- organic substances
- = the working substance **remains in the superheated steam area** after expansion in the turbine
- the entropy of saturated vapors increases with temperature, i.e. as the condensation pressure decreases, the entropy also decreases



RC – ideal thermal cycle

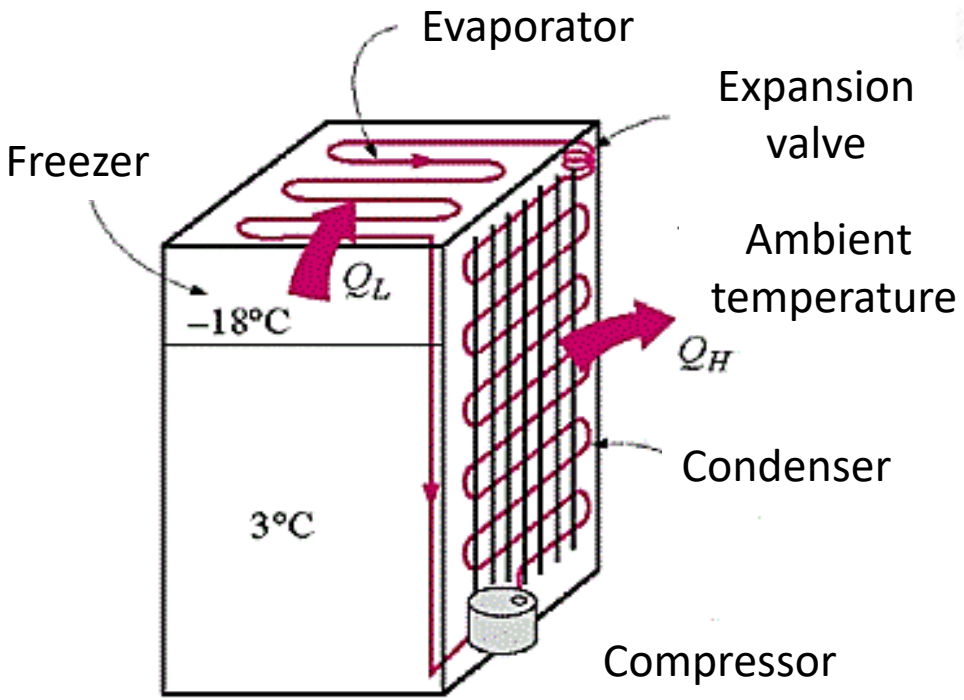


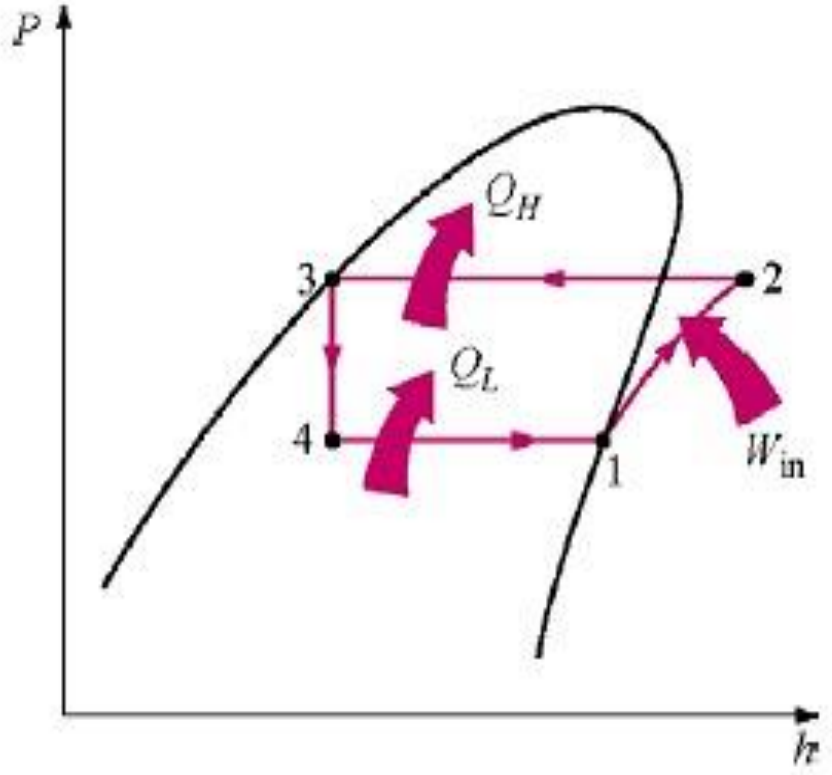
ORC – ideal cooling cycle



Example 3

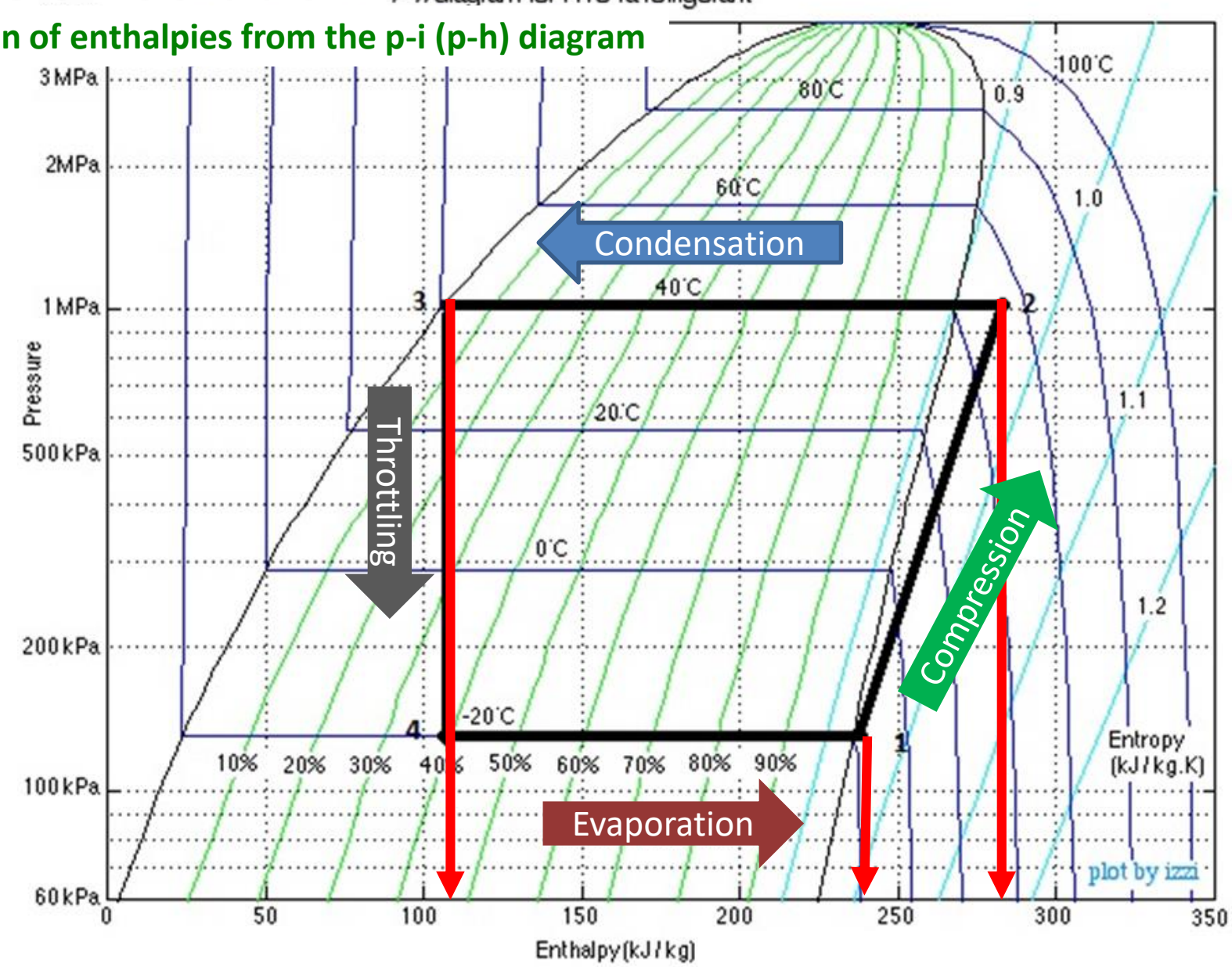
- Calculate the cooling factor (COP_R) and its maximum value ($COPR_{,CO}$) for an ideal compression cooling circuit. The working substance of the thermal cycle is the refrigerant R -134a, which has a temperature of -20 °C at the output of the evaporator. The mass flow is 3 kg / min. The ambient temperature is 25 °C.



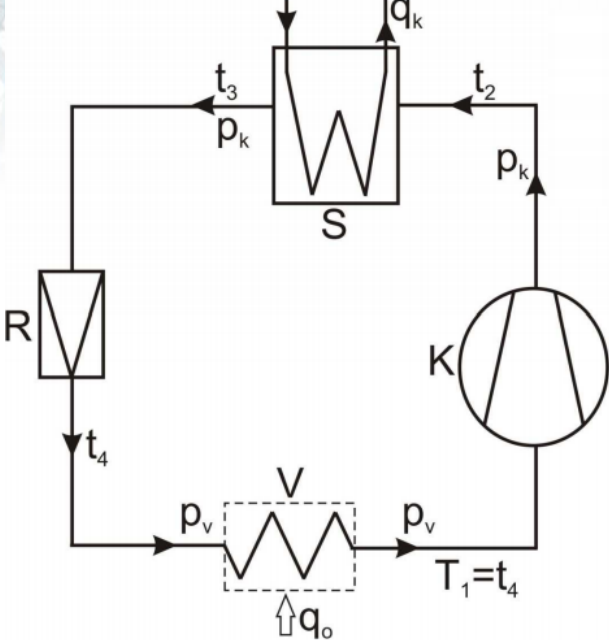


Example 3 - Solution

- Subtraction of enthalpies from the p-i (p-h) diagram



Example 3 - Solution



- **Work done by the compressor**

$$\boldsymbol{w_k} = i_2 - i_1 =$$

- **Heat dissipated (removed) by the condenser**

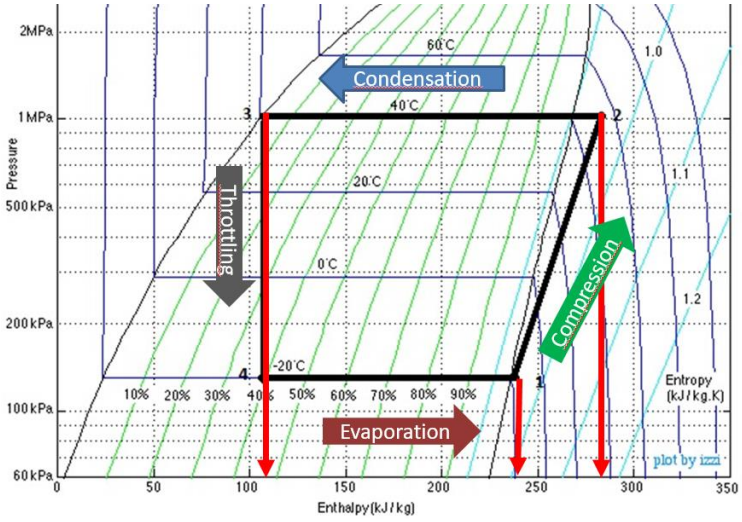
$$\boldsymbol{q_k} = i_2 - i_3 =$$

- **The enthalpy does not change during throttling (isoentropic expansion)**

$$\boldsymbol{i_3} = \boldsymbol{i_4} =$$

- **Dissipated (removed) heat for refrigerant evaporation**

$$\boldsymbol{q_o} = i_1 - i_4 =$$



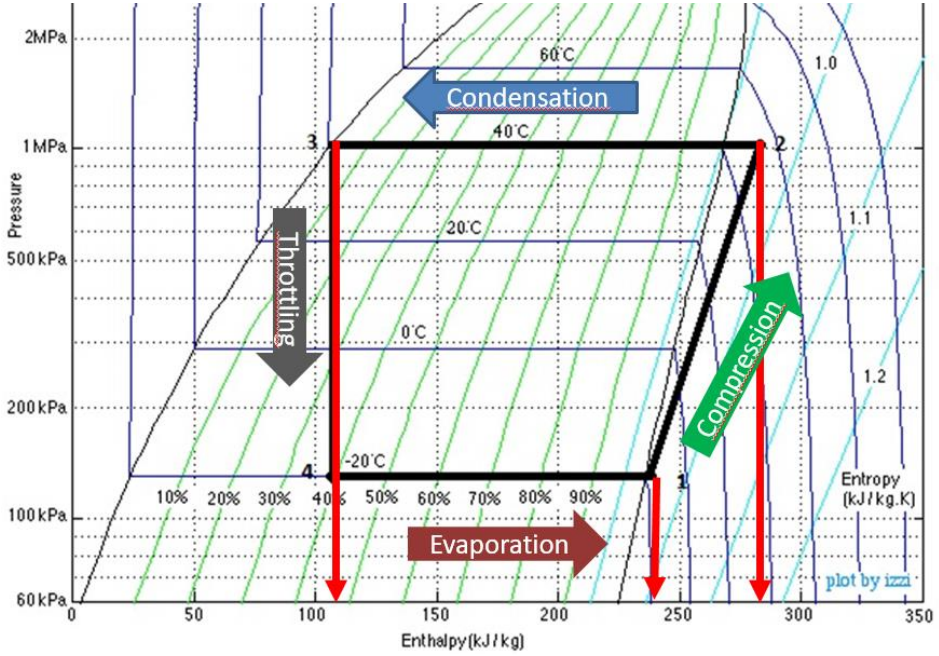
Example 3 - Solution

$i_1 = 240\ kJ/kg$ $i_2 = 285\ kJ/kg$ $i_3 = i_4 = 108\ kJ/kg$

- **Cooling factor**

$$\varepsilon_{CH} = \frac{Q_0}{W_t} =$$

= how much heat we removed to the working substance in the cooling circuit in relation to the supplied technical work.



- **Cooling performance**

$$P_{CH} = m_{CH} \cdot q_o = \frac{3}{60} \cdot (i_1 - i_4) =$$

$$\boldsymbol{P_{CH}} =$$

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, 1999. ISBN 80-7082-523-5.

- …… and other literature listed in the course syllabus on the website Portal of the UWB in Pilsen

Next exercise

Carnotization of the thermal cycle

and

RC cycle with reheat

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