ESF II project of the University of West Bohemia in Pilsen

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Combined heat and power generation – CHP (Cogeneration)

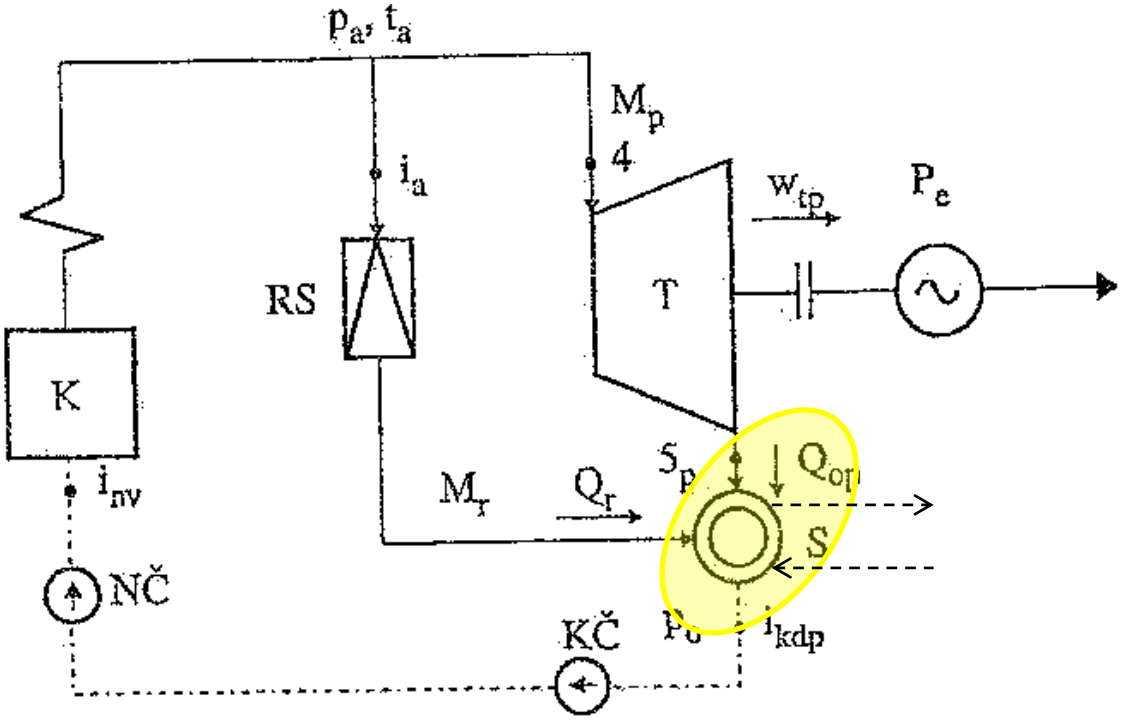
Exercises 7 (KEE/TTE)

EUROPEAN UNION
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MINISTRY OF EDUCATION, YOUTH AND SPORTS

Thermal cycle with backpressure turbine

- **Increasing efficiency** by using heat removed from the thermal cycle for technological purposes or heating → **elimination of thermal cycle losses**
- **THIS IS NOT CARNOTIZATION,** i.e. the gain of mechanical energy does not increase

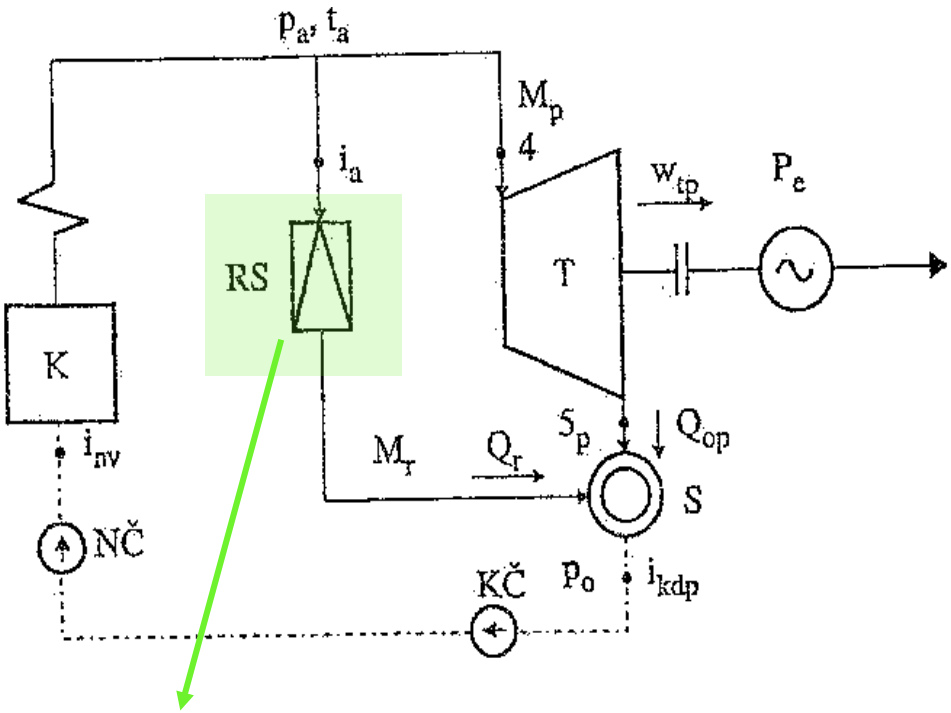


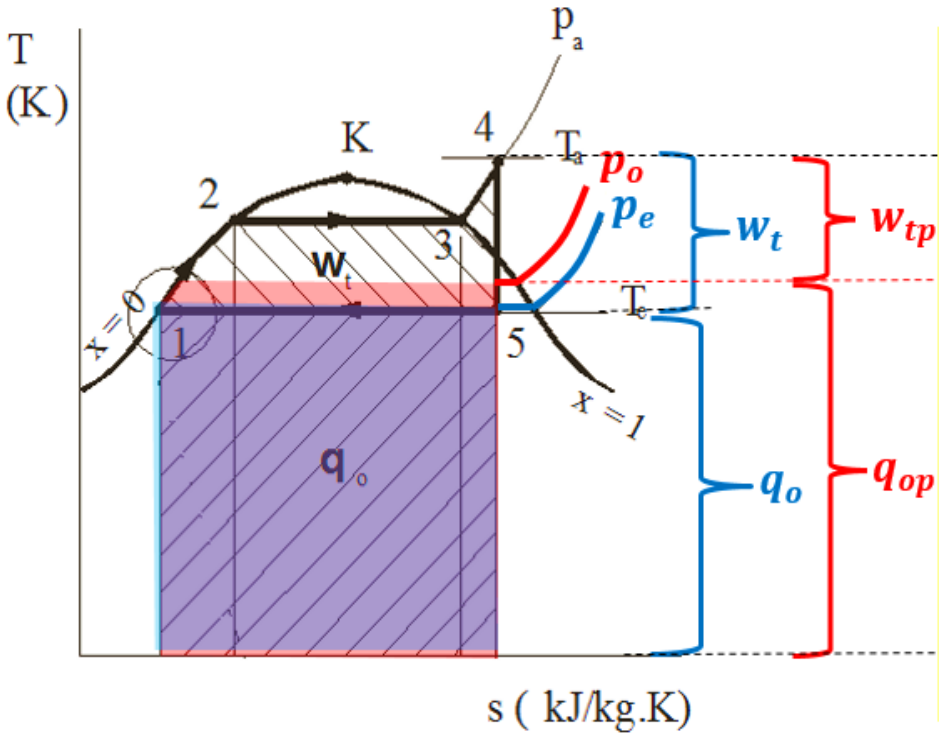
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MINISTRY OF EDUCATION, YOUTH AND SPORTS

Thermal cycle with backpressure turbine

- Superheated steam from the steam generator → expansion in the back-pressure turbine to a constant pressure p_o → emission steam led to consumers S → the steam transfers its condensing heat → the generated condensate can be used to supply the steam generator again.





- **Reduction station**

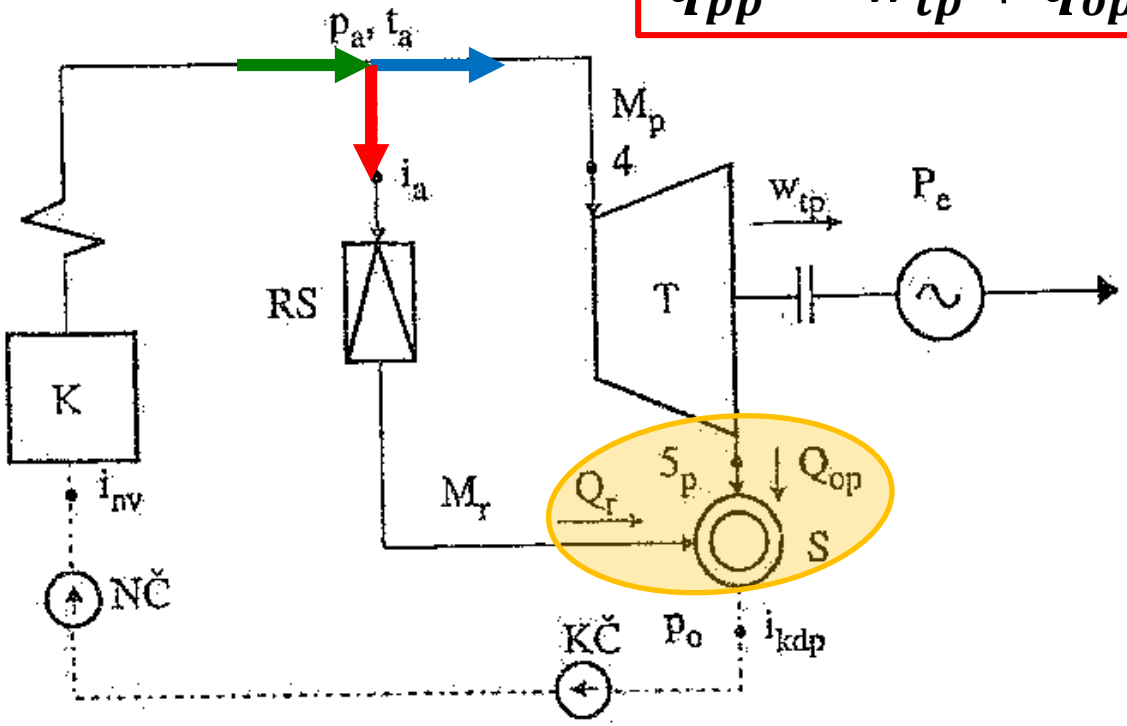
– transition from combined heat and power generation only to thermal energy production

Thermal cycle with backpressure turbine

Supplied heat q_{pp} is divided into:

- **HEAT CONVERTED AT WORK w_{tp}**
- **BACK PRESSURE HEAT FOR TECHNOLOGICAL OR HEATING PURPOSES q_{op}**

$$q_{pp} = w_{tp} + q_{op}$$



- **Heating plant coefficient**

  = the ratio of the heat output supplied to the consumer by the steam from the turbine to the total heat supplied, i.e. including the heat supplied through the reduction station

$$\alpha = \frac{q_{op}}{q_r + q_{op}}$$

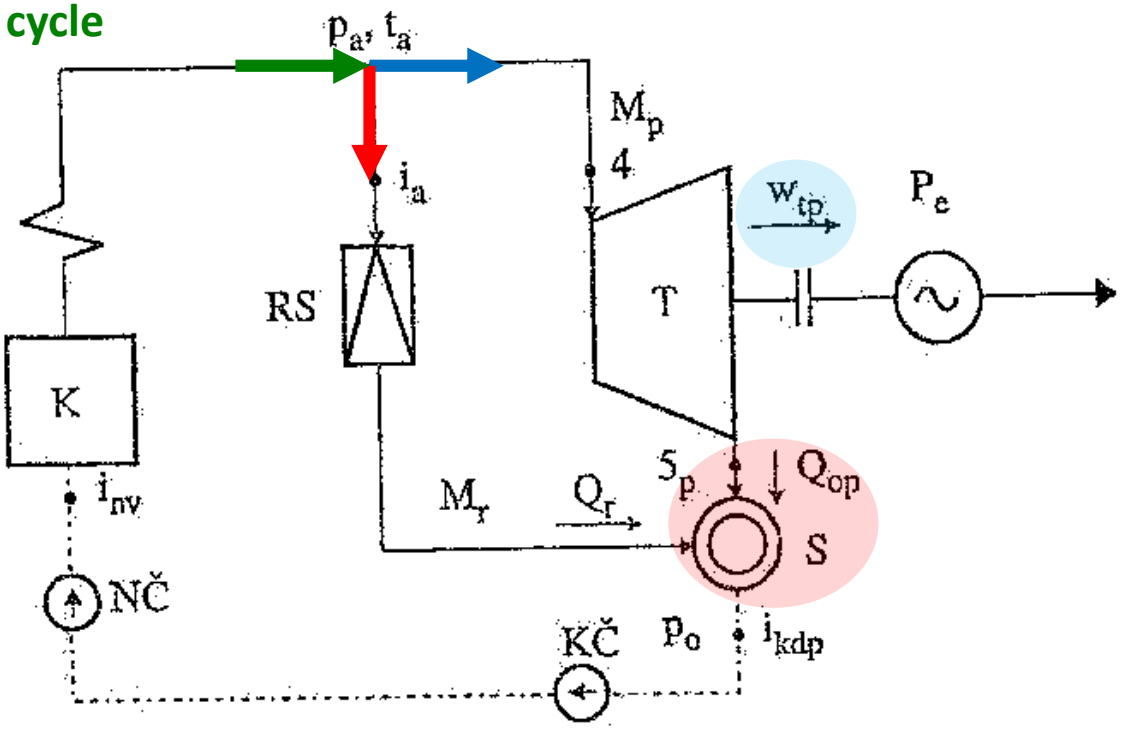
Thermal cycle with backpressure turbine

- **Thermal efficiency of the thermal cycle**

$$\eta_{tp} = \frac{w_{tp}}{q_{pp}}$$

- **Efficiency of heating heat utilization**

$$\eta_{tt} = \frac{q_{op}}{q_{pp}}$$



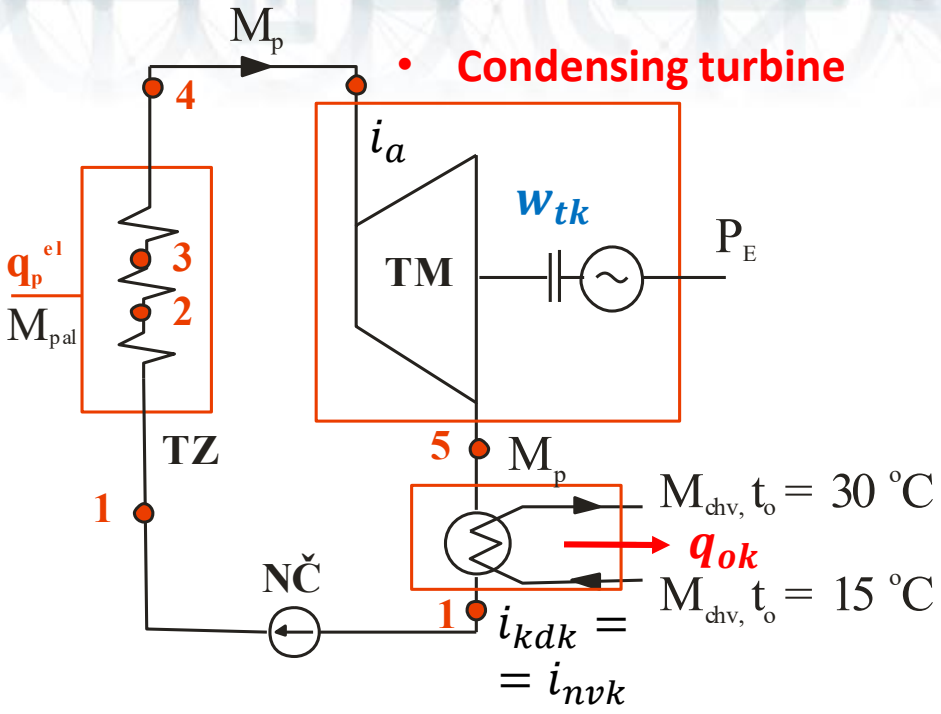
- **Total efficiency of the power plant with a backpressure cycle without losses**

$$\eta_t^{el} = \frac{w_{tp} + q_{op}}{q_{pp}} = 1$$

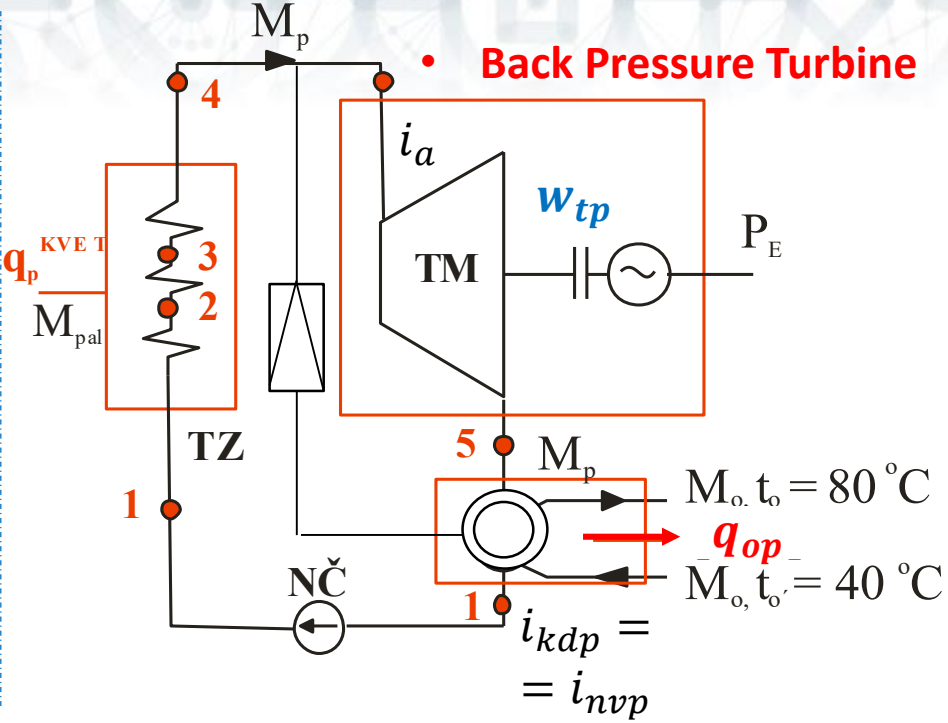
In fact, we must consider the losses in heat transfer to the consumer, the efficiency of the boiler, the efficiency of the pipes, etc.

The difference between a condensing turbine and a backpressure turbine

- **Condensing turbine**



- **Back Pressure Turbine**



Real thermal efficiency of the thermal cycle

$$\eta_{tk} = \frac{w_{tk}}{q_{pk}} = \frac{i_4 - i_5}{i_4 - i_1} = \frac{i_a - i_{kk}}{i_a - i_{nvk}}$$

$$\eta_{tp} = \frac{w_{tp}}{q_{pp}} = \frac{i_4 - i_5}{i_4 - i_1} = \frac{i_a - i_{kp}}{i_a - i_{nvp}}$$

Heat removed from the thermal cycle

$$q_{ok} = i_5 - i_1 = i_{kk} - i_{kdk}$$

$$q_{už} = q_{op} = i_5 - i_1 = i_{kp} - i_{kdp}$$

Total efficiency of the power plant without losses

$$\eta_{tk}^{el} = \frac{w_{tk}}{q_{pk}} = \frac{i_a - i_{ek}}{i_a - i_{kdk}} < 1$$

$$\eta_{tp}^{el} = \frac{w_{tp} + q_{op}}{q_{pp}} = \frac{(i_a - i_{ep}) + (i_{ep} - i_{kdp})}{i_a - i_{kdp}} = 1$$

The difference between a condensing turbine and a backpressure turbine

- **Condensing turbine**

- **Back Pressure Turbine**

Power plant efficiency - gross

Heat supply efficiency

$$\eta_{tk}^{el} = \eta_{tok} \cdot \eta_{td} \cdot \eta_m \cdot \eta_g \cdot \eta_k \cdot \eta_p$$

$$\eta_{tp}^{el} = \eta_t^{KVET} \cdot \eta_{td} \cdot \eta_m \cdot \eta_g \cdot \eta_k \cdot \eta_p \cdot \eta_{dt}$$

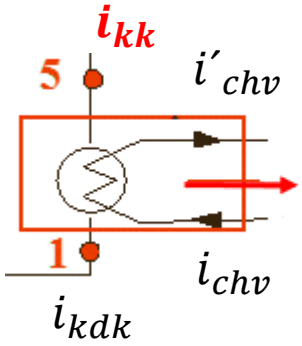
$$= \eta_{tp}^{el} = 1$$

Amount of cooling or service water

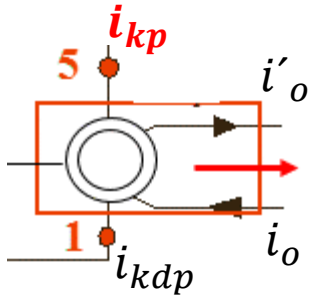
$$M_{pk} = \frac{3\,600 \cdot P_e}{(i_a - i_{ek})\eta_{td} \cdot \eta_m \cdot \eta_g} = \frac{3\,600 \cdot P_e}{(i_a - i_{kk})\eta_m \cdot \eta_g}$$

$$M_{pp} = \frac{3\,600 \cdot P_e}{(i_a - i_{ep})\eta_{td} \cdot \eta_m \cdot \eta_g} = \frac{3\,600 \cdot P_e}{(i_a - i_{kp})\eta_m \cdot \eta_g}$$

Amount of cooling or service water



$$M_{chv} = \frac{M_{pk}(i_{kk} - i_{kdk})}{(i'_{chv} - i_{chv})}$$



$$M_o = \frac{M_{pp}(i_{kp} - i_{kdp})}{(i'_o - i_o)}$$

Amount of fuel consumed

$$M_{palk} = \frac{Q_{pk}}{q_{pal}} = \frac{M_{pk} \cdot (i_a - i_{nvk})}{q_{pal} \cdot \eta_k \cdot \eta_p}$$

$$M_{palp} = \frac{Q_{pp}}{q_{pal}} = \frac{M_{pp} \cdot (i_a - i_{nvp})}{q_{pal} \cdot \eta_k \cdot \eta_p}$$

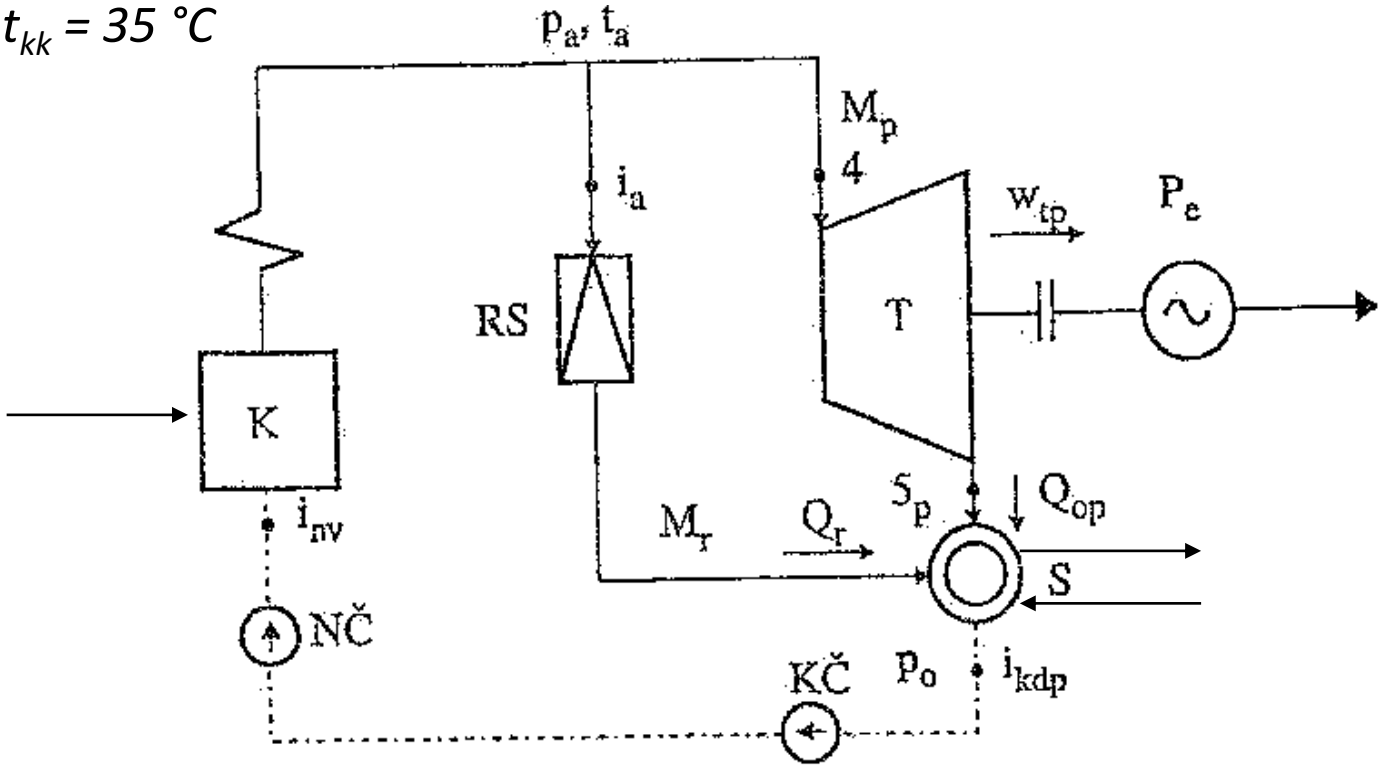
Example

- Replace the condensing turbine with a generator with an electrical output of **P_e = 6 MW** by a back-pressure turbine if we supply heat for district heating purposes with the heat removed from the thermal cycle. The required heat value is **80 °C**. The return water temperature is **40 °C**.
- Calculate how the thermal efficiency of the RC cycle will change and what the overall efficiency of CHP (combined heat and power) will be.

Specified parameters:

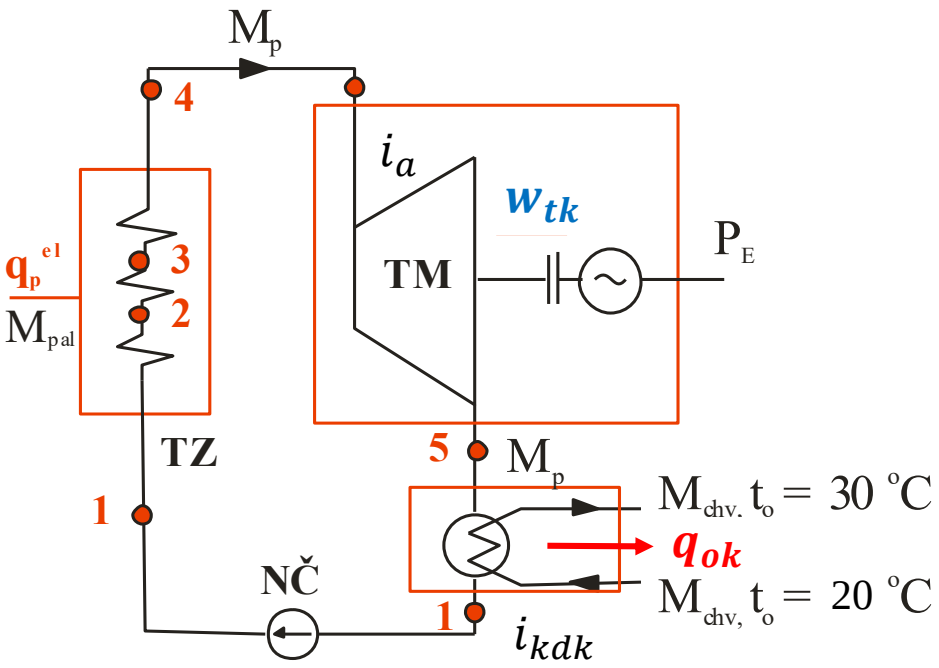
$p_4 = p_a = 3.5$ MPa, $p_5 = p_{ek} = 6$ kPa, $q_{pal} = 12\,220$ kJ/kg,
$t_4 = t_a = 435$ °C, $t_1 = t_{kk} = 35$ °C

- $\eta_k = 0.85$
- $\eta_p = 0.99$
- $\eta_m = 0.96$
- $\eta_g = 0.97$
- $\eta_{td} = 0.8$



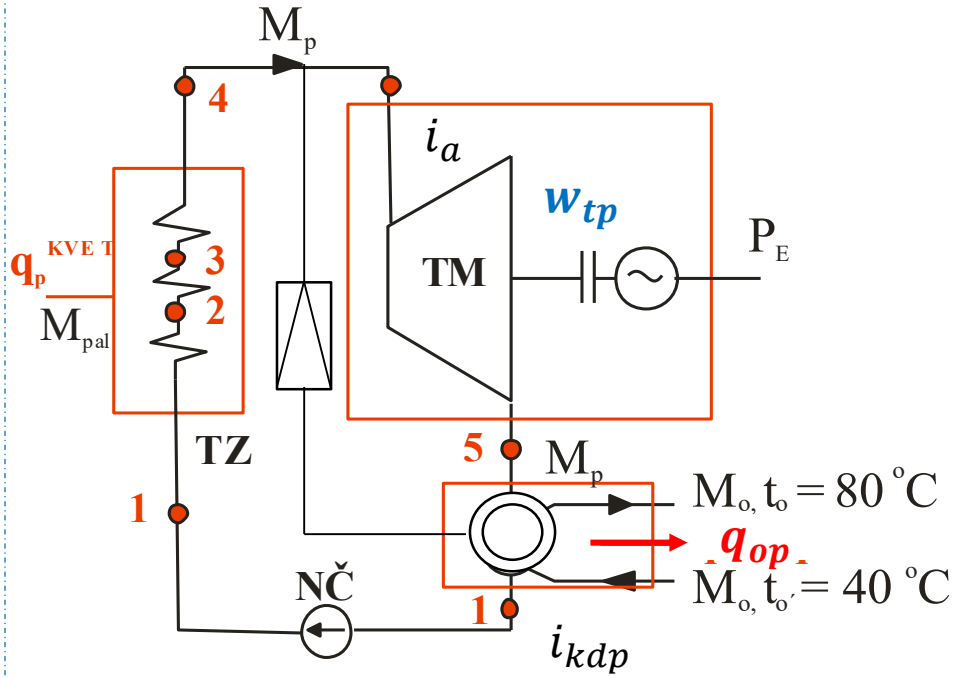
Example - Solution

- **Condensing turbine**



- p_a = 3.5 MPa, t_a = 435 °C
- p_{ek} = 6 kPa, t_{kk} = 35 °C

- **Back Pressure Turbine**



- p_a = 3.5 MPa, t_a = 435 °C
- t_{op} = 80 °C = t_{kp}

Example - Solution

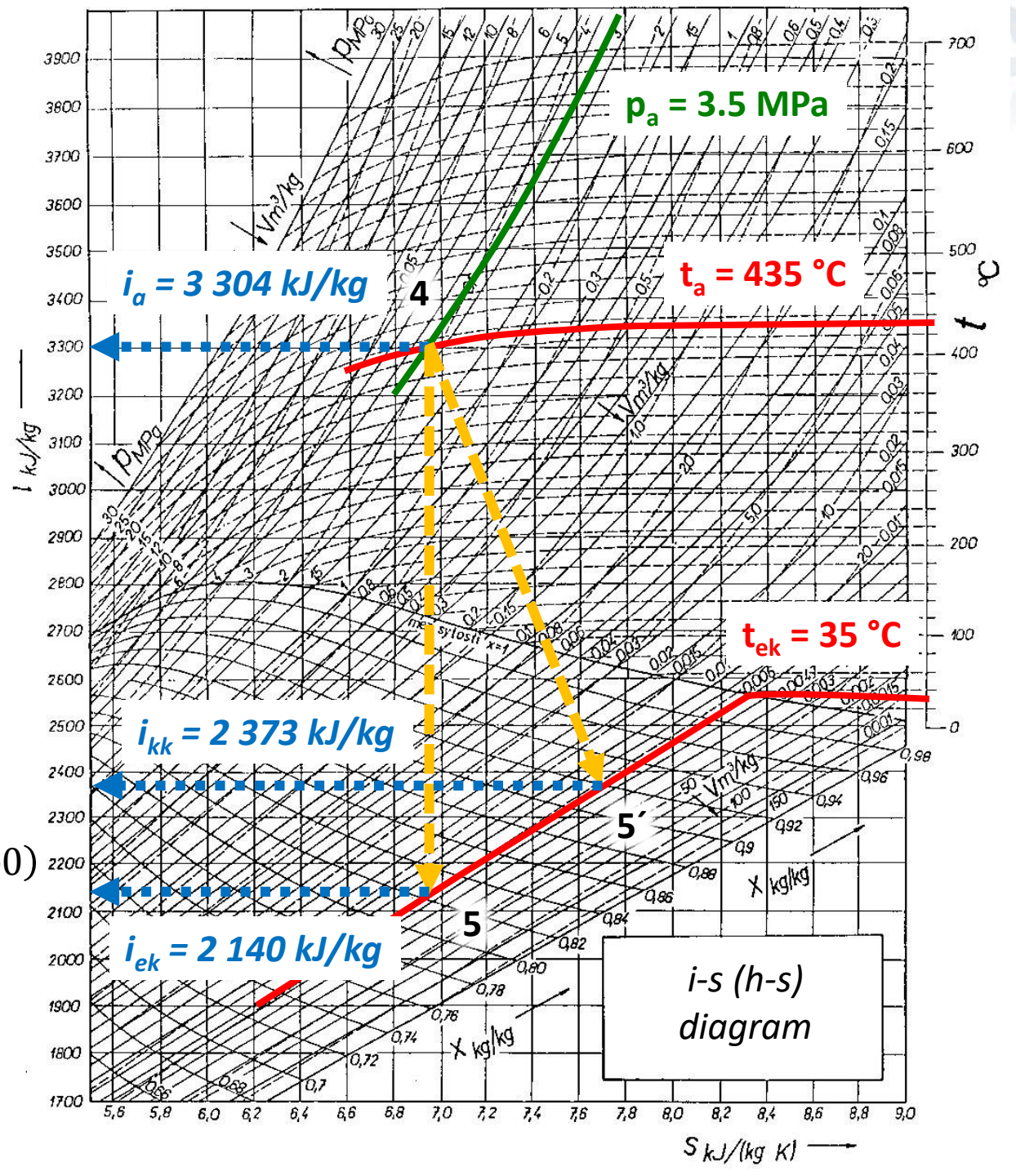
Condensing turbine

- **Determination of steam and condensate parameters**
  - ✓ p_a = 3.5 MPa, t_a = 435 °C
  - ✓ p_e = 6 kPa, t_k = 35 °C
  - ✓ $\eta_{td} = 0.8$

- **Enthalpy calculation i_{kk}**

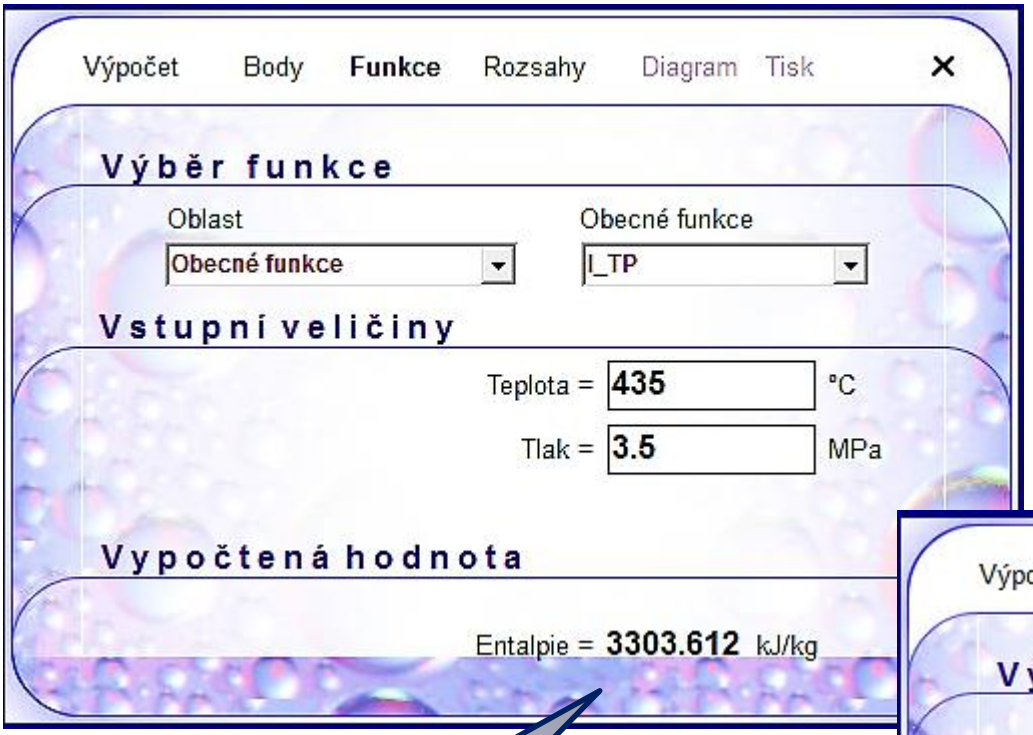
$$i_{kk} = i_a - \eta_{td} \cdot (i_a - i_{ek})$$

$$\boldsymbol{i_{kk}} = \\ = 3\,304 - 0.8 \cdot (3\,304 - 2\,140) \\ = \mathbf{2\,372.8\ kJ/kg}$$



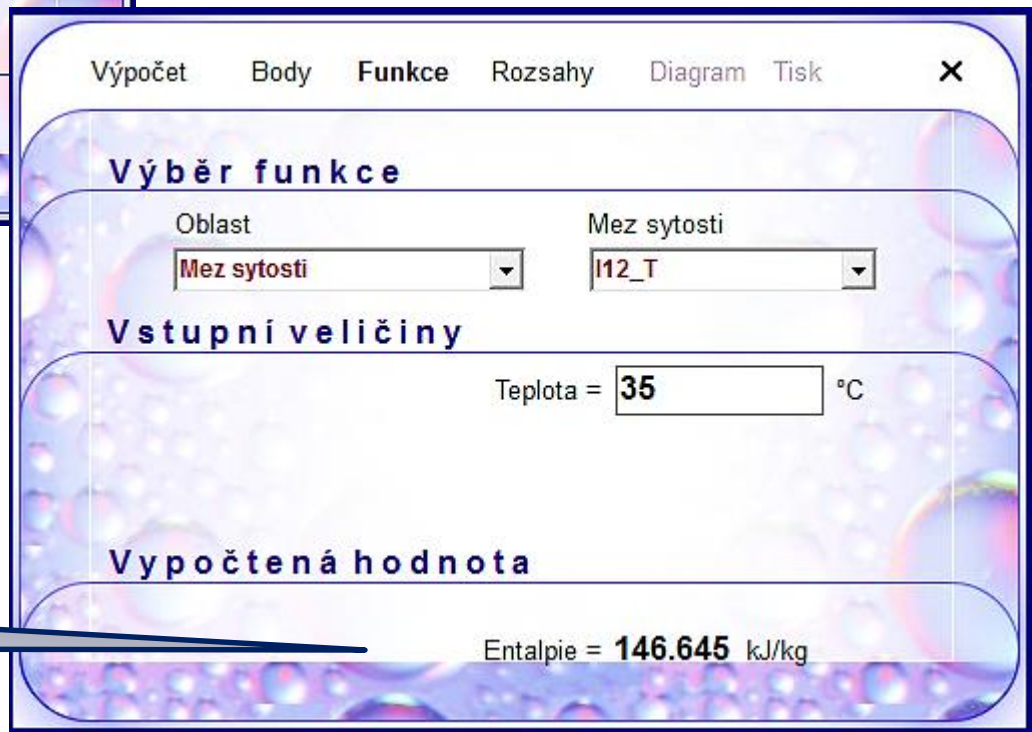
Example - Solution

- **Determination of enthalpies of admission steam and condensate using software**



Enthalpy of admission steam

Condensing turbine



Condensate enthalpy

Example - Solution

Back Pressure Turbine

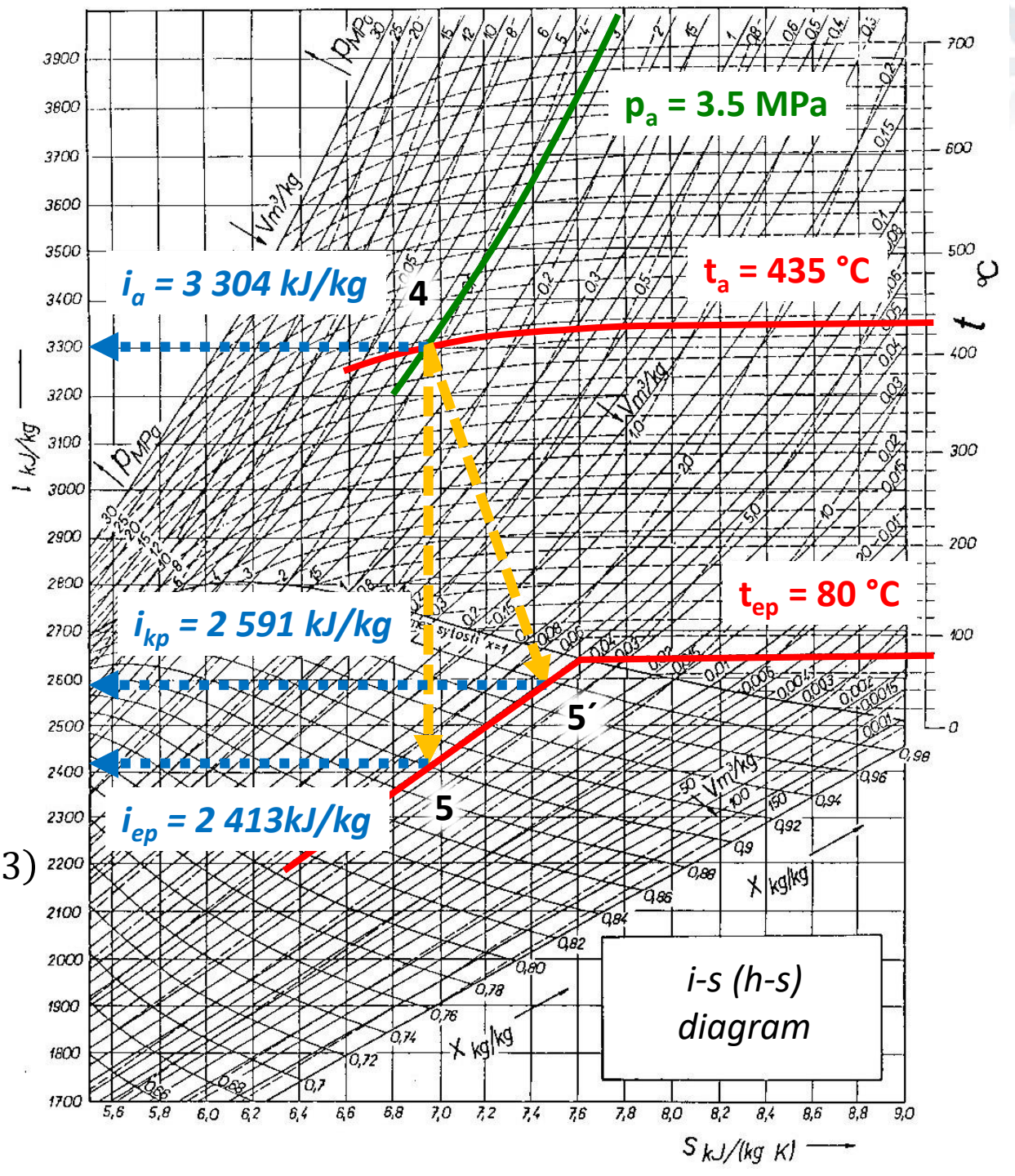
- **Determination of steam and condensate parameters**

- p_a = 3.5 MPa, t_a = 435 °C
- t_{op} = 80 °C = t_{kp}
- ✓ $\eta_{td} = 0.8$

- **Enthalpy calculation i_{kp}**

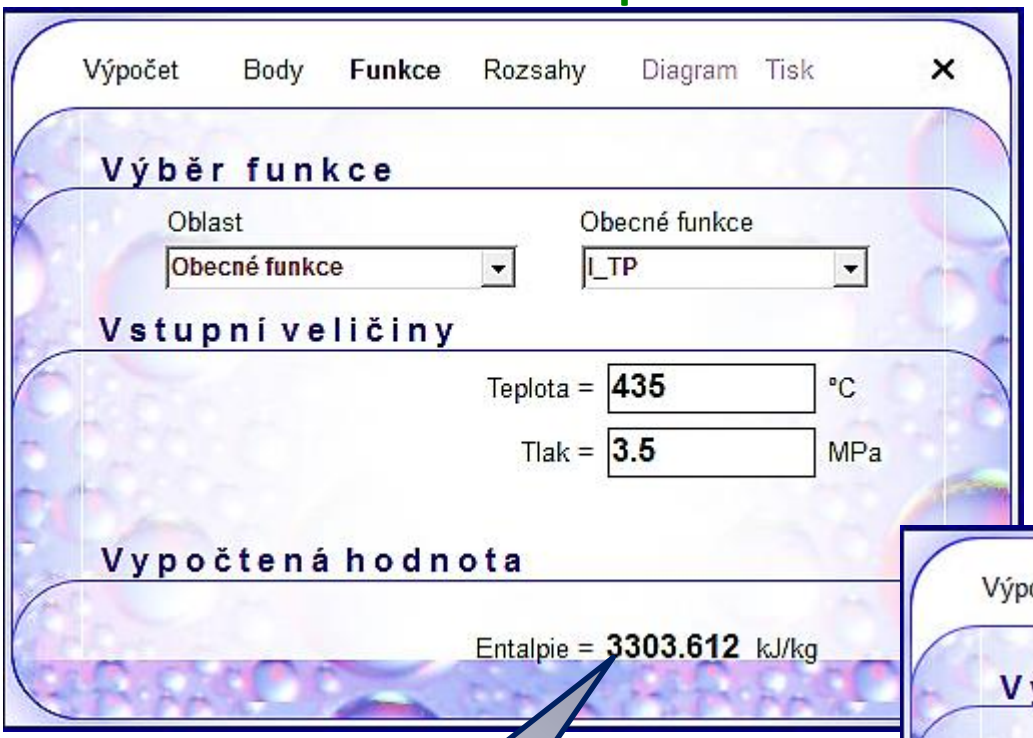
$$i_{kp} = i_a - \eta_{td} \cdot (i_a - i_{ep})$$

$$\boldsymbol{i_{kp}} = 3\,304 - 0.8 \cdot (3\,304 - 2\,413) = \mathbf{2\,591.2\ kJ/kg}$$



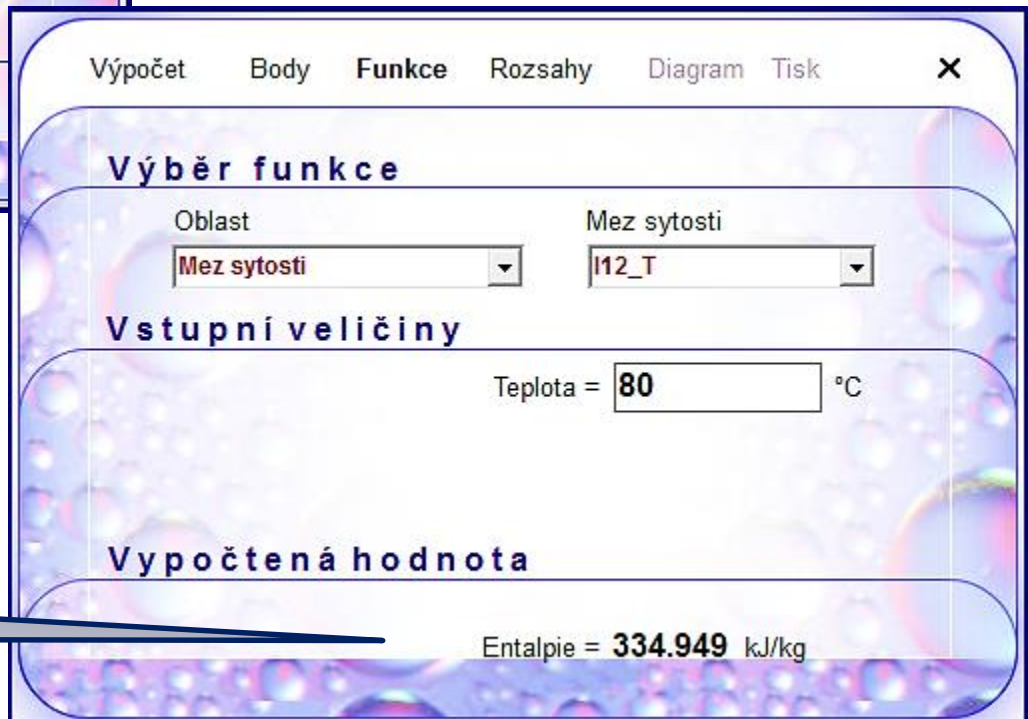
Example - Solution

- **Determination of enthalpies of admission steam and condensate using software**



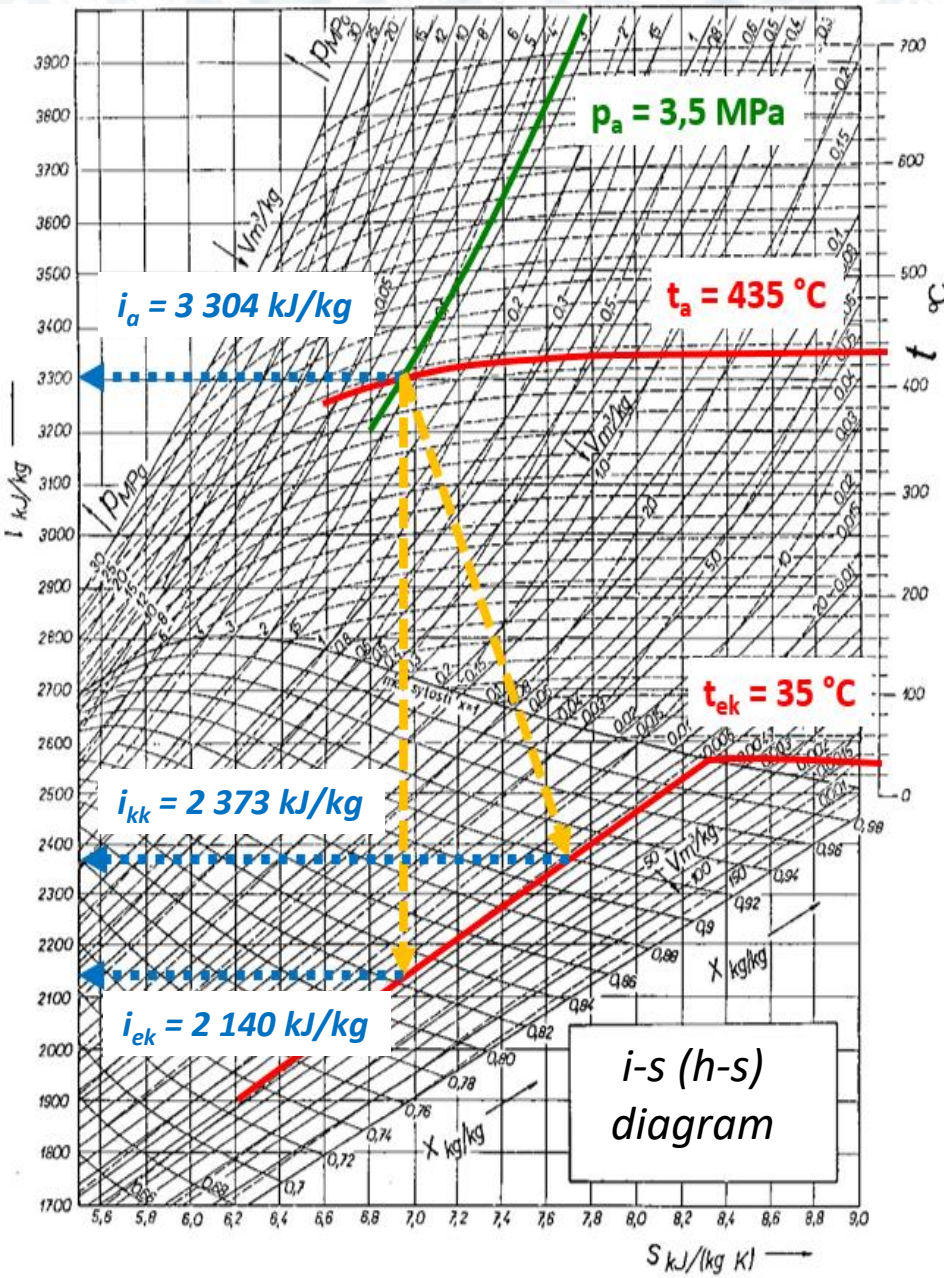
Enthalpy of admission steam

Back Pressure Turbine

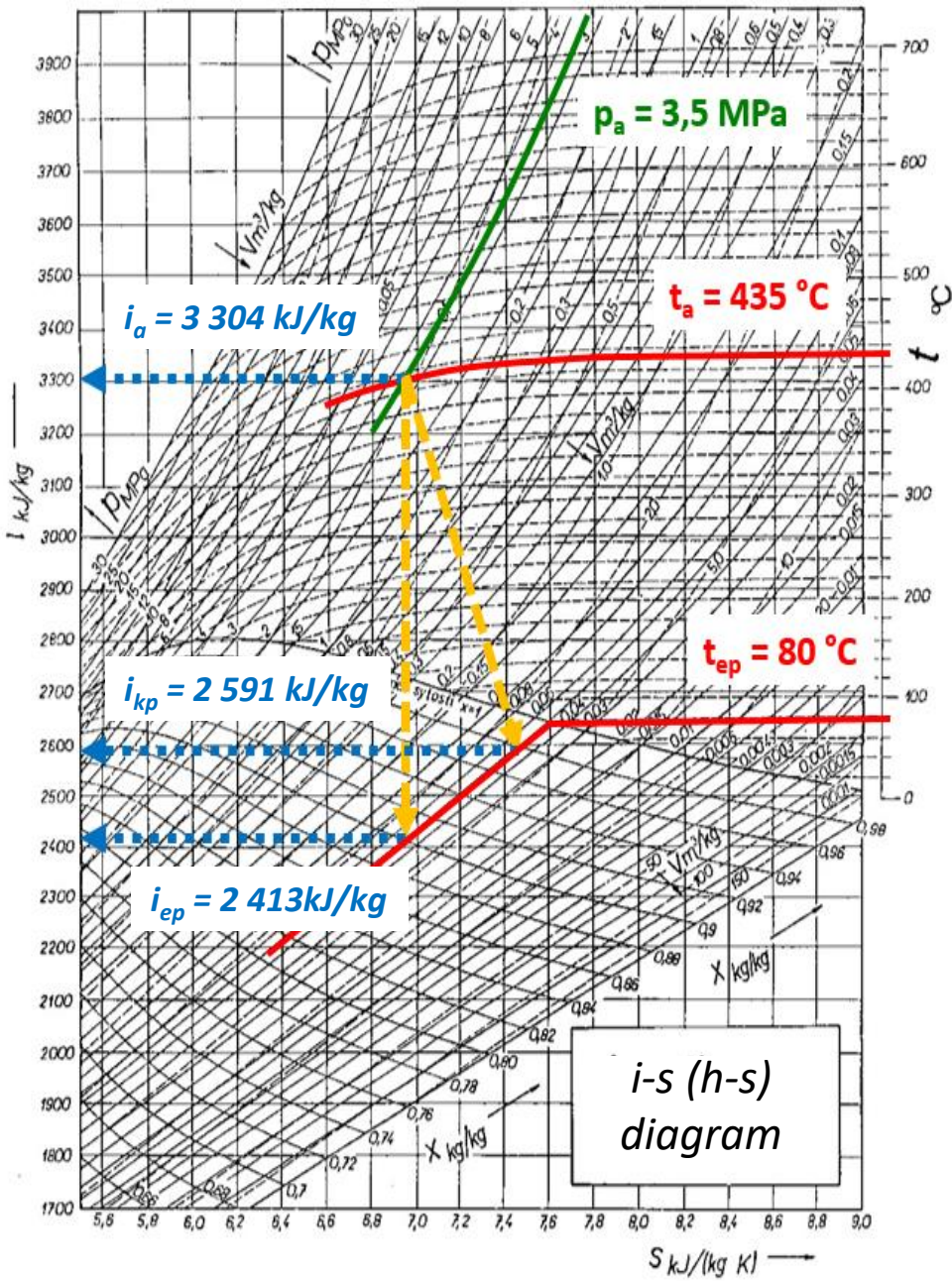


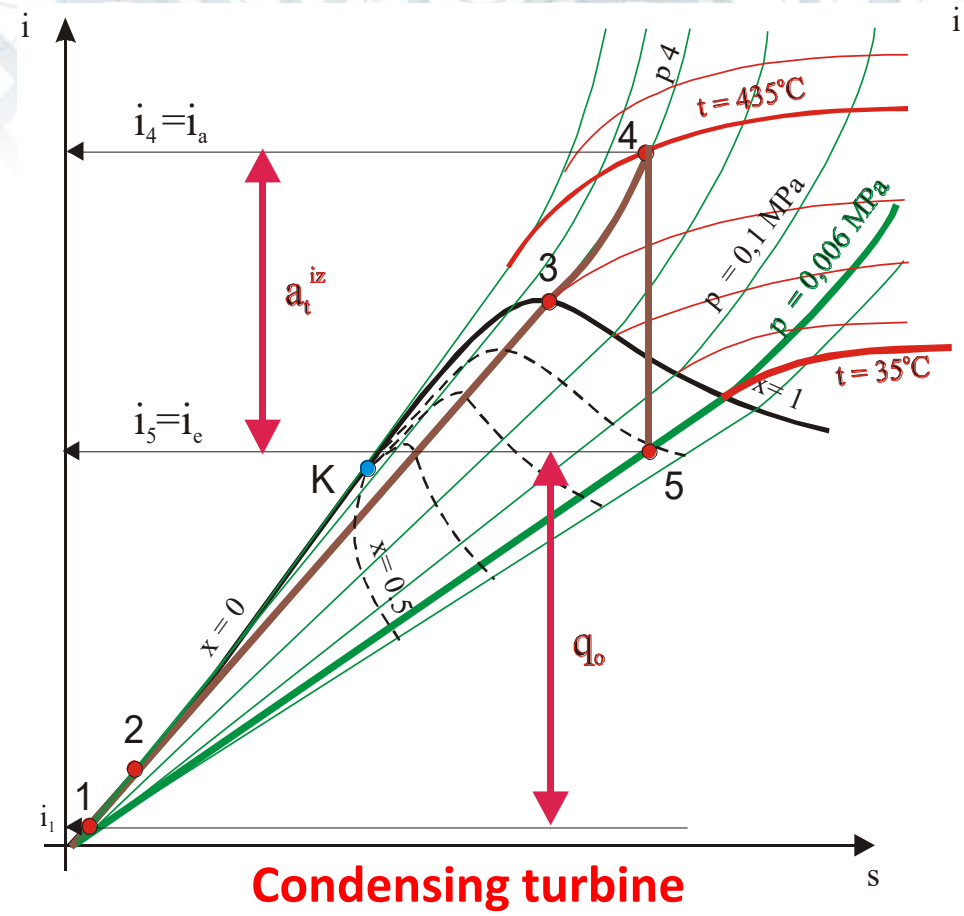
Condensate enthalpy

Condensing turbine

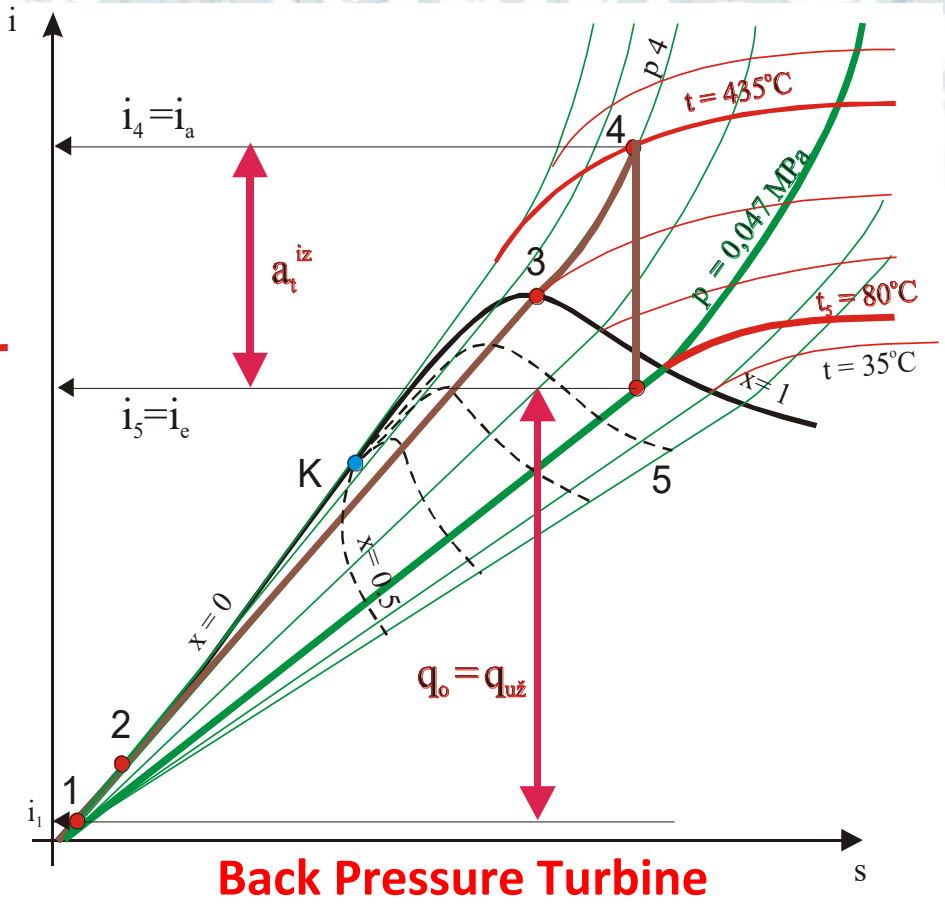


Back Pressure Turbine





Condensing turbine



Back Pressure Turbine

	Point	Temperature (°C)	Pressure (MPa)	Enthalpy (kJ/kg)
Condensing turbine	4	435	3.5	3 304
	5	35	0.006	2 140
	5´	35	0.006	2 373
	1	35	0.006	147
Back Pressure Turbine	4	435	3.5	3 304
	5	80	0.047	2 413
	5´	80	0.047	2 591
	1	80	0.047	335

Example - Solution

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

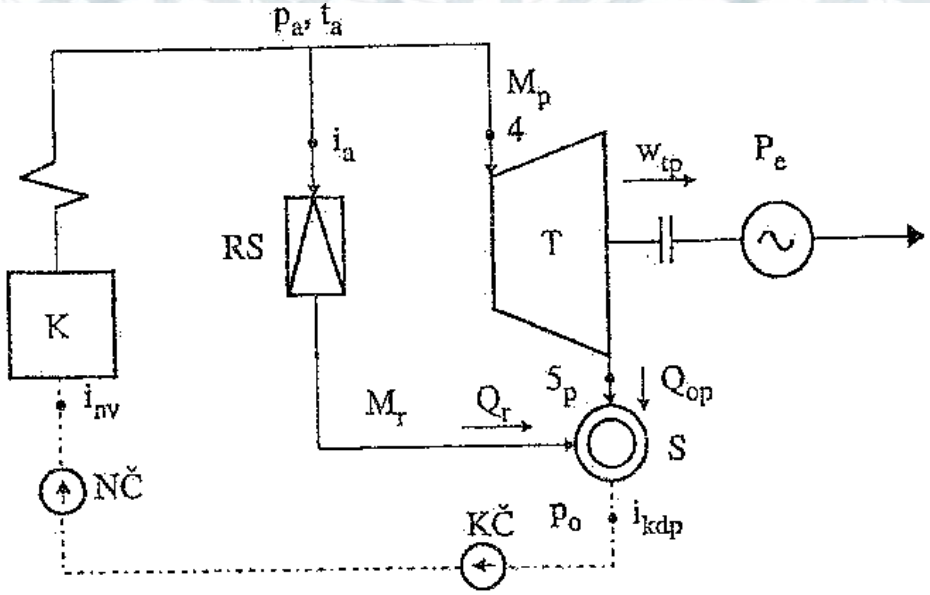
$$\eta_{tok} = \frac{w_{tk}}{q_{pk}} = \frac{i_a - i_{ek}}{i_a - i_{kdk}}$$

$\boldsymbol{\eta_{tok}} =$

- **Back Pressure Turbine**

$$\eta_{top} = \frac{w_{tp}}{q_{pp}} = \frac{i_a - i_{ep}}{i_a - i_{kdp}}$$

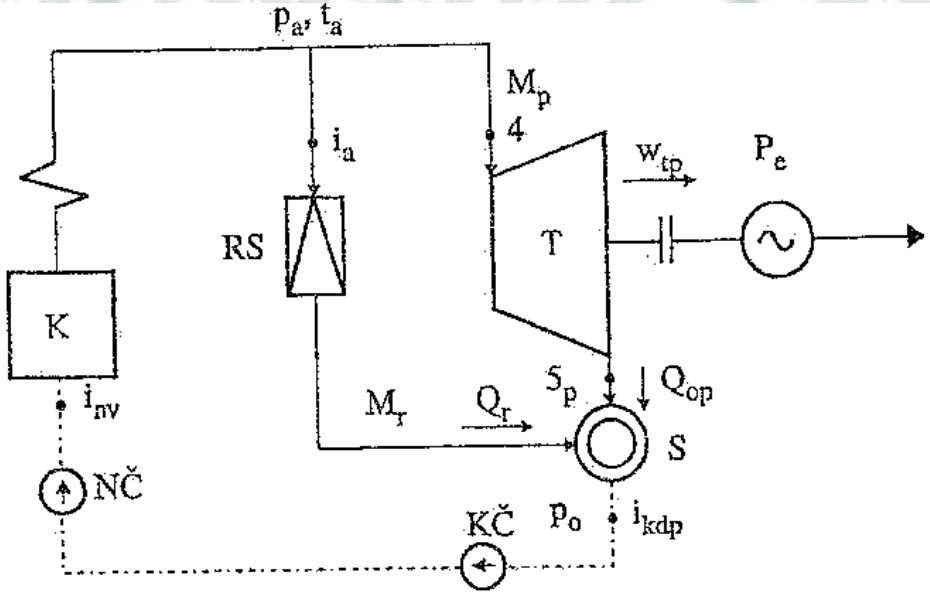
$\boldsymbol{\eta_{top}} =$



Example - Solution

- **Real thermal efficiency of the thermal cycle**
- **Condensing turbine**

$$\eta_{tk} = \frac{w_{tk}}{q_{pk}} = \frac{i_a - i_{kk}}{i_a - i_{kdk}}$$



- **Back Pressure Turbine**

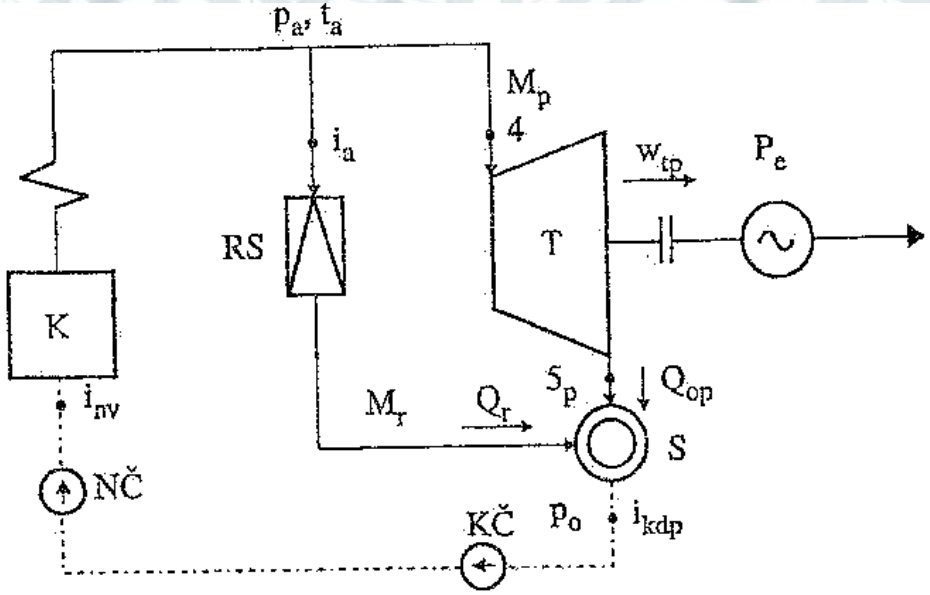
$$\eta_{tp} = \frac{w_{tp}}{q_{pp}} = \frac{i_a - i_{kp}}{i_a - i_{kdp}}$$

$$\boldsymbol{\eta_{tp}} =$$

Example - Solution

- **Efficiency of heating heat utilization**

$$\eta_{tp} = \frac{q_{op}}{q_{pp}} = \frac{i_{kp} - i_{kdp}}{i_a - i_{nvp}}$$



- **Total ideal efficiency of the power plant without losses**
  - **Condensing turbine**

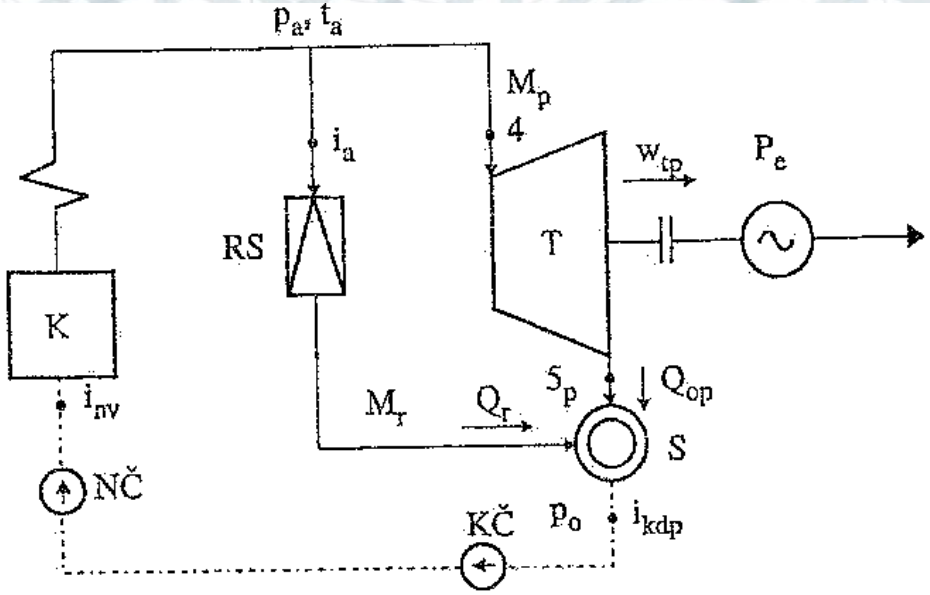
$$\eta_{tk}^{el} =$$

  - **Back Pressure Turbine**

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

Example - Solution

- **Power plant efficiency - gross**
  - ✓ $\eta_k = 0.85$
  - ✓ $\eta_p = 0.99$
  - ✓ $\eta_m = 0.96$
  - ✓ $\eta_g = 0.97$
  - ✓ $\eta_{td} = 0.8$



- **Condensing turbine**

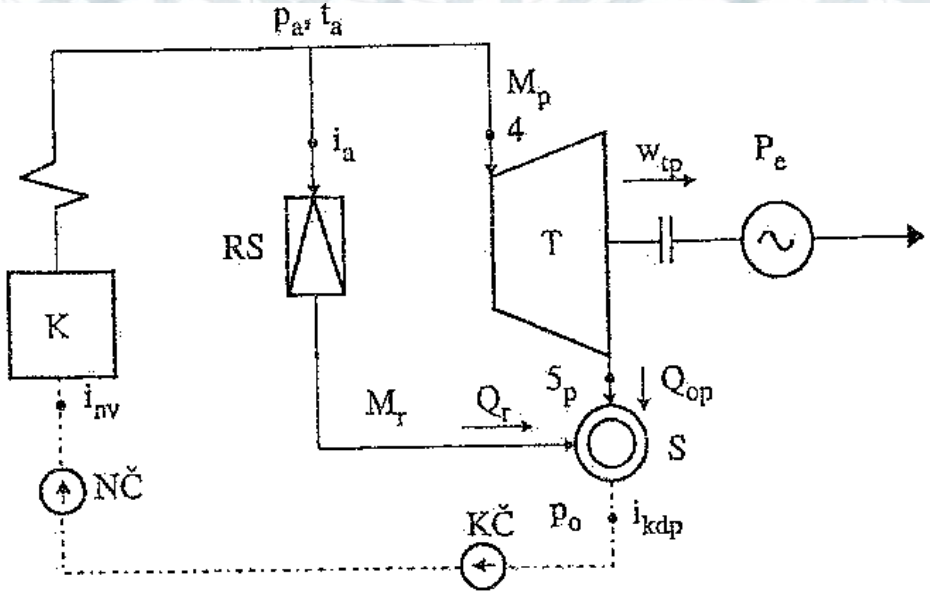
$$\eta_{tk}^{el} = \eta_{tok} \cdot \eta_{td} \cdot \eta_m \cdot \eta_g \cdot \eta_k \cdot \eta_p =$$

- **Back Pressure Turbine**

$$\eta_{tp}^{el} = \eta_t^{KVET} \cdot \eta_{td} \cdot \eta_m \cdot \eta_g \cdot \eta_k \cdot \eta_p \cdot \eta_{dt} =$$

Example - Solution

- **Mass flow of the working substance**
  - ✓ $\eta_m = 0.96$
  - ✓ $\eta_g = 0.97$
  - ✓ $P_e = 6\ MW$



- **Condensing turbine**

$$\boldsymbol{M_{pk}} =$$

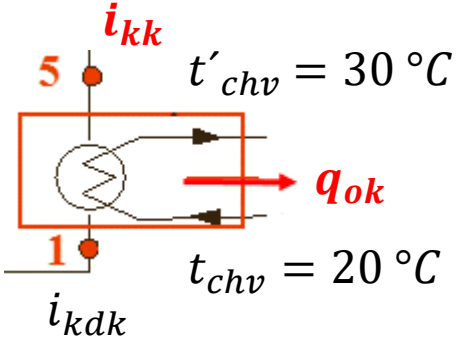
- **Back Pressure Turbine**

$$\boldsymbol{M_{pp}} =$$

Example - Solution

- **Mass flow of cooling water and service water**

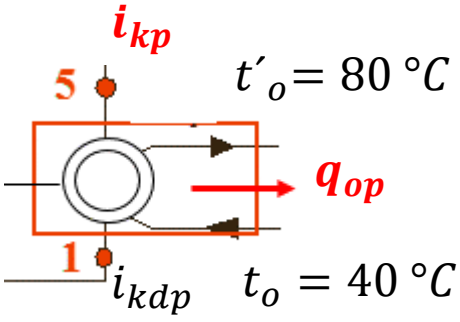
- **Condensing turbine**



$$M_{chv} =$$

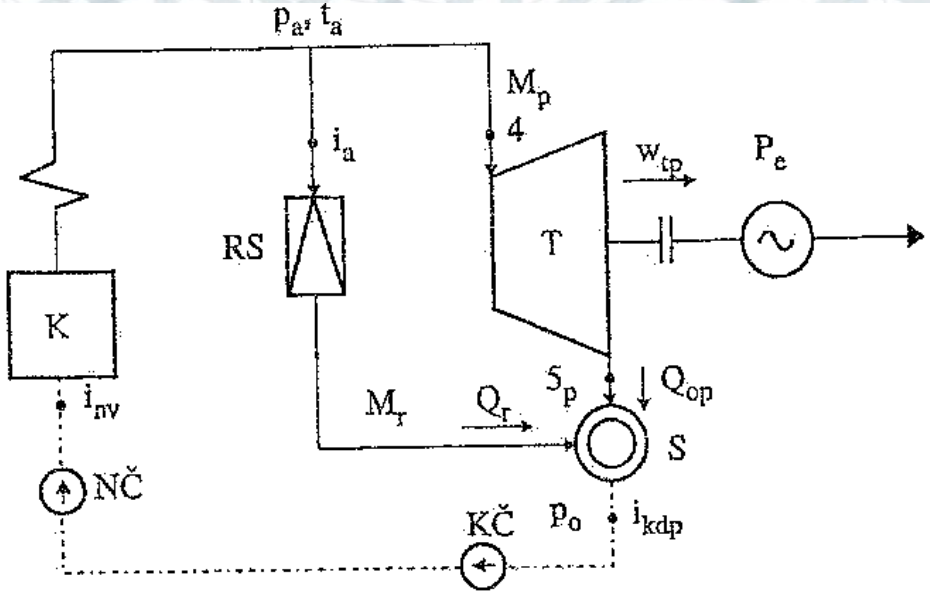
- **Back Pressure Turbine**

$$M_o =$$



Example - Solution

- **Amount of fuel** $q_{pal} = 12\ 220\ kJ/kg$
  - ✓ $\eta_k = 0.85$
  - ✓ $\eta_p = 0.99$



- **Condensing turbine**

$$M_{palk} =$$

$$M_{palk} =$$

- **Back Pressure Turbine**

$$M_{palp} =$$

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

Steam-gas cycle

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