ESF II project of the University of West Bohemia in Pilsen

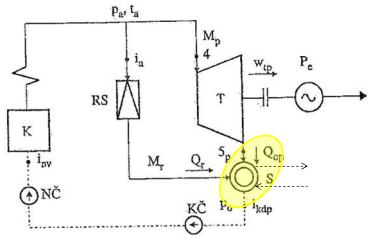
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Combined heat and power generation – CHP (Cogeneration)

Exercises 7 (KEE/TTE)

Thermal cycle with backpressure turbine

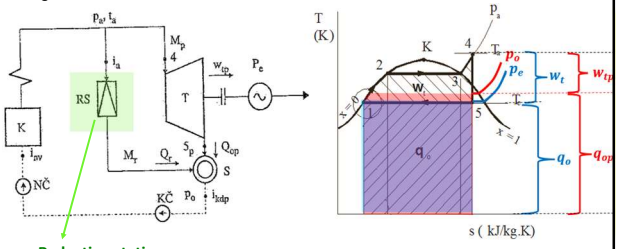
- Increasing efficiency by using heat removed from the thermal cycle for technological purposes or heating → elimination of thermal cycle losses
- THIS IS NOT CARNOTIZATION, i.e. the gain of mechanical energy does not increase



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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

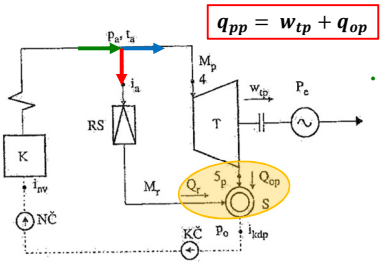
3

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

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

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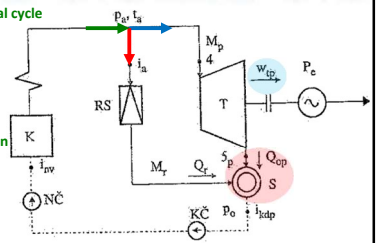
Thermal cycle with backpressure turbine

- **Thermal efficiency of the thermal cycle**

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

- **Efficiency of heating heat utilization**

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



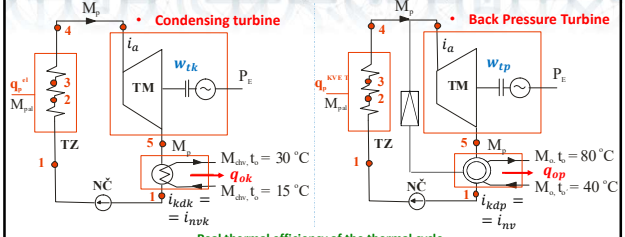
- **Total efficiency of the power plant with a backpressure cycle without losses**

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

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

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The difference between a condensing turbine and a backpressure 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

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

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

The difference between a condensing turbine and a backpressure turbine

- Condensing turbine
- Back Pressure Turbine

Power plant efficiency - gross

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

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

Heat supply efficiency

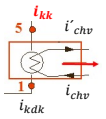
$= \eta_{tp}^{el} = 1$

Amount of cooling or service water

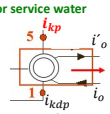
$$M_{pk} = \frac{3\,600 \cdot P_e}{(i_a - i_{ek})\eta_{td} \cdot \eta_m \cdot \eta_g} = \frac{3\,600 \cdot P_e}{(i_a - i_{kk})\eta_m \cdot \eta_g}$$

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

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

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

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

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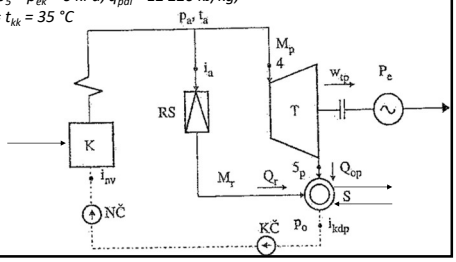
Example

- 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:

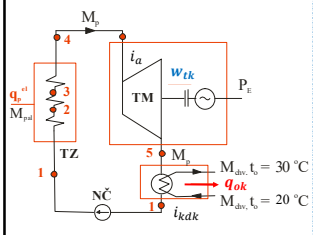
$p_4 = p_a = 3.5$ MPa, $p_5 = p_{ek} = 6$ kPa, $q_{pal} = 12\,220$ kJ/kg,
$t_4 = t_a = 435$ °C, $t_1 = t_{kk} = 35$ °C

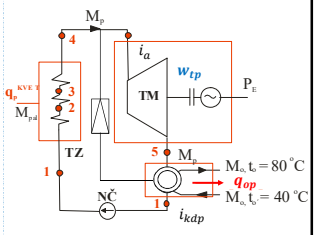
$\eta_k = 0.85$
$\eta_p = 0.99$
$\eta_m = 0.96$
$\eta_g = 0.97$
$\eta_{td} = 0.8$



Example - Solution

- Condensing turbine
- Back Pressure Turbine





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

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

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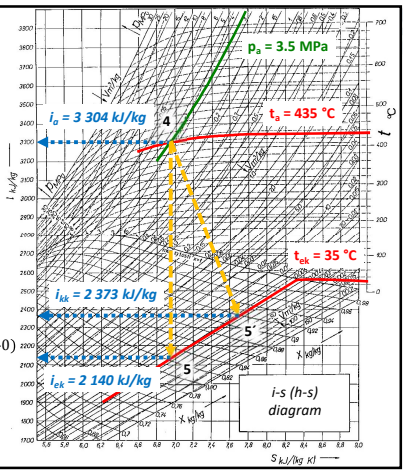
Example - Solution

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}**

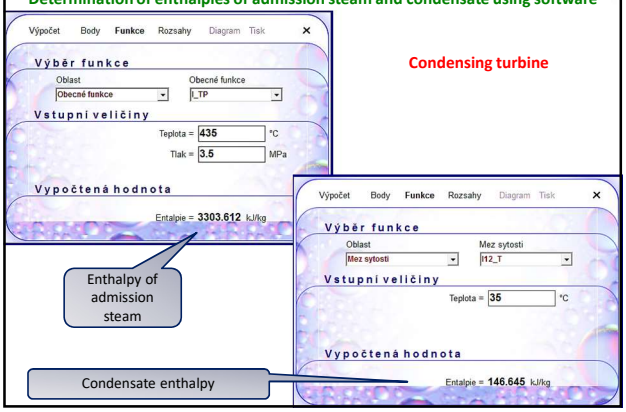
$$i_{kk} = i_a - \eta_{td} \cdot (i_a - i_{ek})$$

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



Example - Solution

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



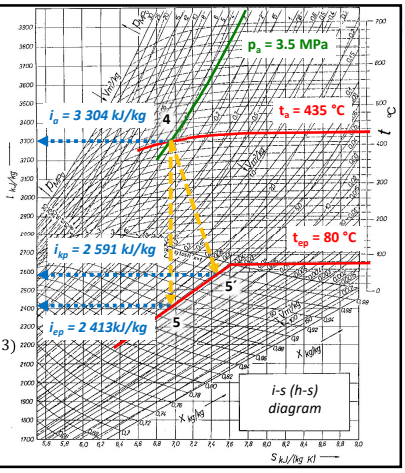
Example - Solution

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}**

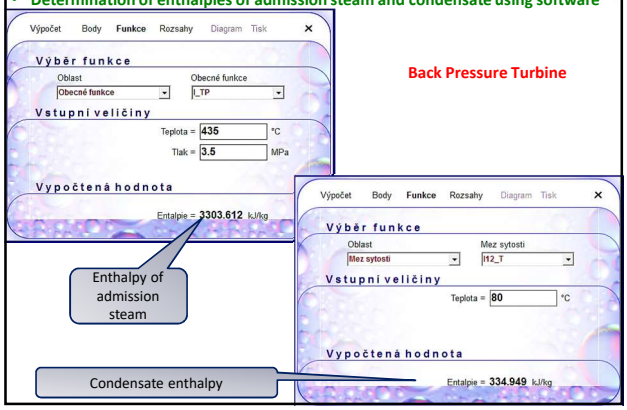
$$i_{kp} = i_a - \eta_{td} \cdot (i_a - i_{ep})$$

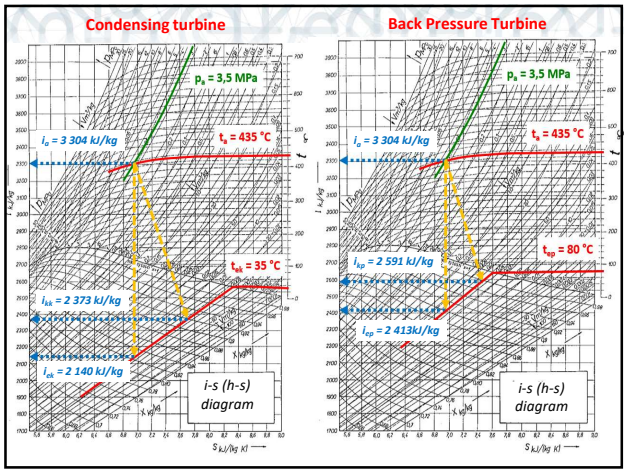
$$i_{kp} = 3\,304 - 0.8 \cdot (3\,304 - 2\,413) = \mathbf{2\,591.2\ kJ/kg}$$

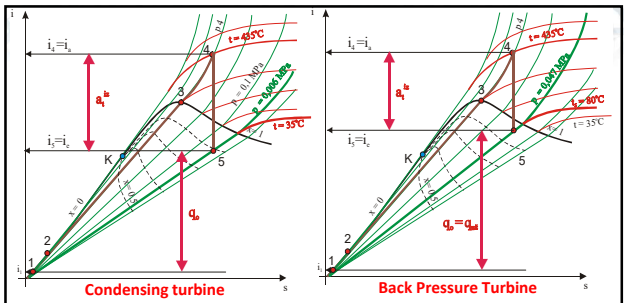


Example - Solution

- Determination of enthalpies of admission steam and condensate using software







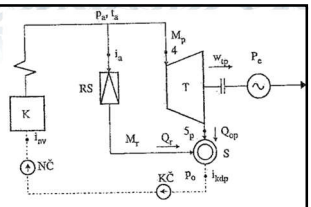
	Point	Temperature (°C)	Pressure (MPa)	Enthalpy (kJ/kg)
Condensing turbine	4	435	3.5	3 304
	5	35	0.006	2 140
	5´	35	0.006	2 373
	1	35	0.006	147
Back Pressure Turbine	4	435	3.5	3 304
	5	80	0.047	2 413
	5´	80	0.047	2 591
	1	80	0.047	335

Example - Solution

- Ideal thermal efficiency of the thermal cycle
- Condensing turbine

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

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



- Back Pressure Turbine

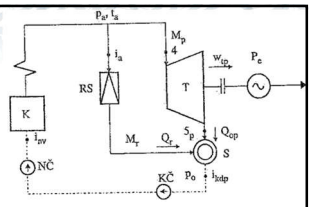
$$\eta_{top} = \frac{w_{tp}}{q_{pp}} = \frac{i_a - i_{ep}}{i_a - i_{kdp}}$$

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

Example - Solution

- Real thermal efficiency of the thermal cycle
- Condensing turbine

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



- Back Pressure Turbine

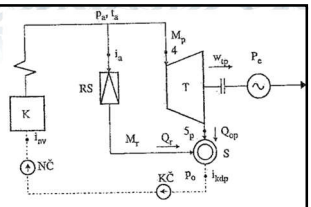
$$\eta_{tp} = \frac{w_{tp}}{q_{pp}} = \frac{i_a - i_{kp}}{i_a - i_{kd}}$$

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

Example - Solution

- Efficiency of heating heat utilization

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



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

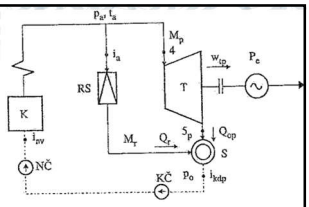
$\boldsymbol{\eta_{tk}^{el}} =$

- Back Pressure Turbine

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

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

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

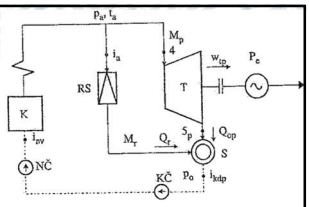
- Back Pressure Turbine

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

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Example - Solution

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



- Condensing turbine

$M_{pk} =$

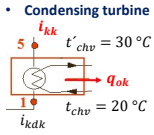
- Back Pressure Turbine

$M_{pp} =$

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Example - Solution

- Mass flow of cooling water and service water
- Condensing turbine

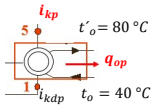


$t'_{chv} = 30\ °C$

$t_{chv} = 20\ °C$

$M_{chv} =$

- Back Pressure Turbine



$t'_o = 80\ °C$

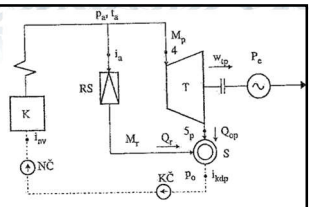
$t_o = 40\ °C$

$M_o =$

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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**

$$M_{palp} =$$

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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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