ESF II project of the University of West Bohemia in Pilsen

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Steam-gas cycle

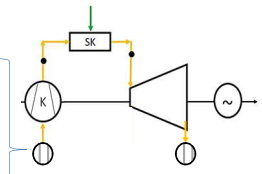
Exercises 8 (KEE/TTE)

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

Gas (Combustion) turbines

- **Working substance -** flue gases of gaseous or liquid fuels
  - **Disadvantage** - high exhaust gas temperature → reduction of thermal efficiency of the thermal cycle → utilization of exhaust gas heat in the steam generator for steam production in steam-gas circuits
- **Simplifying assumptions**

1) The mass flow of the working medium in the thermal cycles is constant
2) Pressure and heat losses are neglected
3) The working medium (flue gases) is considered to be an ideal gas with a specific heat capacity c_p = 1 kJ/kgK
4) Compression and expansion of the working medium are adiabatic processes



Combustion turbine open cycle (no losses)

Gas (Combustion) turbines

Combustion turbine open cycle (no losses)

✓ All simplifying assumptions apply

- **Thermal efficiency of the thermal cycle**

$$\eta_t = \frac{Q_p - Q_o}{Q_p} = \frac{P_g}{Q_p} = 1 - \frac{T_{4ad} - T_1}{T_3 - T_{2ad}} < 1$$

- **Mass flow of working medium (flue gas)**

$$M_{sp} = \frac{P_g}{(T_3 - T_{2ad}) \cdot c_p \cdot \eta_t} = \frac{P_g}{[(T_3 - T_{4ad}) - (T_{2ad} - T_1)] \cdot c_p}$$

- **Fuel mass flow (combustion chamber efficiency = 100%)**

$$M_{pal} = \frac{Q_p}{q_{pal}} = \frac{P_g}{\eta_t \cdot q_{pal}}$$

- **Internal power of the turbine (gain of technical work)**

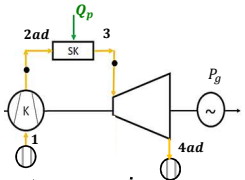
$$P_T = M_{sp} \cdot (i_3 - i_{4ad})$$

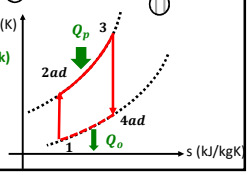
- **Generator power**

$$P_g = P_T - P_K = P_T - M_{sp} \cdot (i_{2ad} - i_1)$$

Compressor power input

$$\frac{T_A}{T_B} = \left(\frac{p_A}{p_B}\right)^{\frac{\kappa-1}{\kappa}}$$





Gas (Combustion) turbines

Combustion turbine open cycle (with losses)

- ✓ Compression and expansion of the working medium are not adiabatic (thermodynamic efficiency of the compressor and turbine) → reduction of the thermal efficiency of this cycle compared to the ideal thermal cycle of the combustion turbine

$$\frac{T_A}{T_B} = \left(\frac{p_A}{p_B}\right)^{\frac{\kappa-1}{\kappa}}$$

- **Thermodynamic efficiency of a turbine**

$$\eta_{td}^{T} = \frac{i_3 - i_4}{i_3 - i_{4ad}} = \frac{T_3 - T_4}{T_3 - T_{4ad}}$$

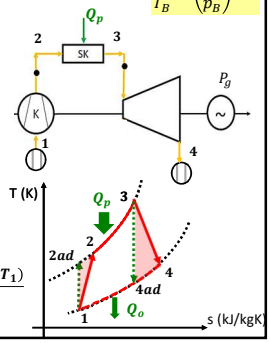
- **Thermodynamic efficiency of a compressor**

$$\eta_{td}^{K} = \frac{i_{2ad} - i_1}{i_2 - i_1} = \frac{T_{2ad} - T_1}{T_2 - T_1}$$

- **Internal thermal efficiency**

$$\eta_{ti} = \frac{Q_p - Q_o}{Q_p} = \frac{w_T - w_K}{i_3 - i_2}$$

$$\eta_{ti} = \frac{(T_3 - T_2) - (T_4 - T_1)}{T_3 - T_2} = \frac{(T_3 - T_4) - (T_2 - T_1)}{T_3 - T_2}$$



Gas (Combustion) turbines

Combustion turbine open cycle (with losses)

$$\frac{T_A}{T_B} = \left(\frac{p_A}{p_B}\right)^{\frac{\kappa-1}{\kappa}}$$

- **Terminal thermal efficiency of the thermal cycle**

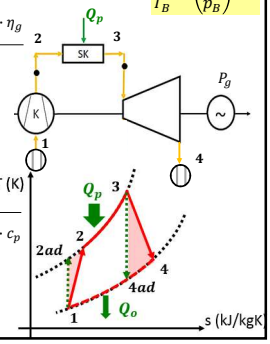
$$\eta_{tsv} = \frac{\left[\eta_{td}^{T} \cdot \eta_m^{T} \cdot (T_3 - T_{4ad}) - \frac{1}{\eta_{td}^{K} \cdot \eta_m^{K}} (T_{2a} - T_1)\right] \cdot \eta_g}{T_3 - T_1 - \frac{T_{2ad} - T_1}{\eta_{td}^{K}}}$$

- **Mass flow of working medium (flue gas)**

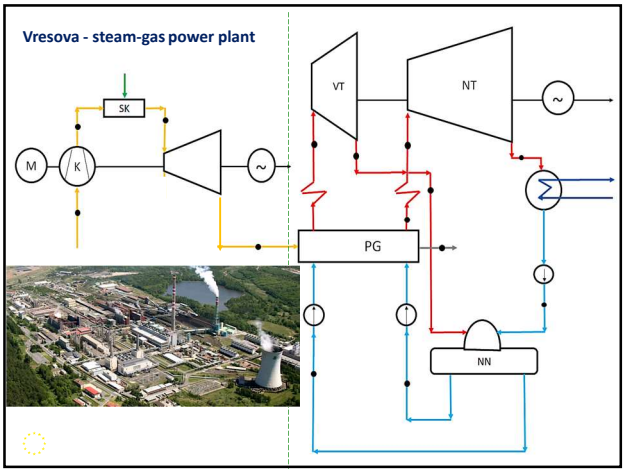
$$M_{sp} = \frac{P_g}{(T_3 - T_2) \cdot c_p \cdot \eta_{tsv}} = \frac{P_g}{\left[\eta_{td}^{T} \cdot \eta_m^{T} \cdot (T_3 - T_{4ad}) - \frac{1}{\eta_{td}^{K} \cdot \eta_m^{K}} (T_{2ad} - T_1)\right] \cdot \eta_g \cdot c_p}$$

- **Fuel mass flow**

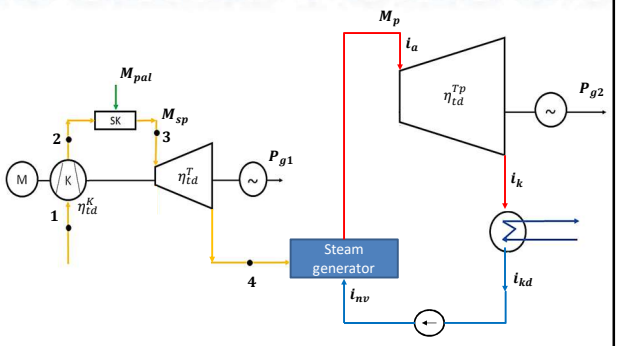
$$M_{pal} = \frac{Q_p}{\eta_{SK} \cdot q_{pal}} = \frac{P_g}{\eta_{tsv} \cdot \eta_{SK} \cdot q_{pal}}$$



Vresova - steam-gas power plant



Steam-gas cycle



Steam-gas cycle

Gas part of the thermal cycle

- **Heat power required for the gas part**

$$Q_{p1} = \frac{P_{g1}}{\eta_{tsv1}} = M_{sp} \cdot c_p \cdot (T_3 - T_2)$$

- **Internal thermal efficiency of the gas part of the cycle**

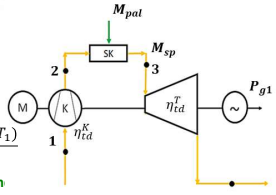
$$\eta_{ti} = \frac{(T_3 - T_2) - (T_4 - T_1)}{T_3 - T_2} = \frac{(T_3 - T_4) - (T_2 - T_1)}{T_3 - T_2}$$

- **Terminal thermal efficiency of the gas part of th circuit**

$$\eta_{tsv} = \frac{\left[\eta_{td}^{T} \cdot \eta_m^{T} \cdot (T_3 - T_{4ad}) - \frac{1}{\eta_{td}^{K} \cdot \eta_m^{K}} (T_{2a} - T_1)\right] \cdot \eta_g}{T_3 - T_1 - \frac{T_{2ad} - T_1}{\eta_{td}^{K}}}$$

- **Mass flow of working medium (flue gas)**

$$M_{sp} = \frac{P_{g1}}{\left[\eta_{td}^{T} \cdot \eta_m^{T} \cdot (T_3 - T_{4ad}) - \frac{1}{\eta_{td}^{K} \cdot \eta_m^{K}} (T_{2ad} - T_1)\right] \cdot \eta_g \cdot c_p}$$



Steam-gas cycle

Steam part of the thermal cycle

- **Real thermal efficiency of part of the steam cycle**

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

- **Heat power consumed for steam production**

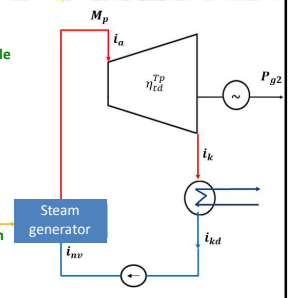
$$Q_{p2} = \frac{P_{g2}}{\eta_{tsv2}} = M_p \cdot (i_a - i_{nv})$$

- **Terminal thermal efficiency of part of the steam cycle**

$$\eta_{tsv2} = \frac{P_{g2}}{Q_{p2}} = \frac{M_p \cdot (i_a - i_k) \cdot \eta_{g2} \cdot \eta_{m2}}{M_p \cdot (i_a - i_{nv})} = \eta_t \cdot \eta$$

- **Mass flow of the working medium of the steam cycle**

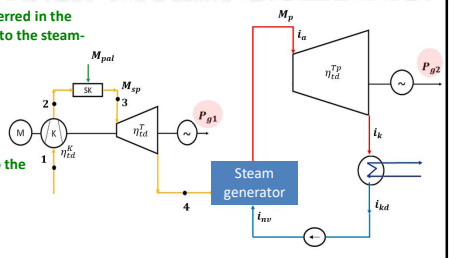
$$M_p = \frac{P_{g2}}{(i_a - i_k) \cdot \eta_{g2} \cdot \eta_{m2}}$$



Steam-gas cycle

- Total heat flow transferred in the combustion chamber to the steam-gas cycle

$$Q_{pc} = Q_{p1} + Q_{p2} = \\ = \frac{P_{g1}}{\eta_{tsv1}} + \frac{P_{g2}}{\eta_{tsv2}}$$



- Mass flow of fuel into the combustion chamber

$$M_{pal} = \frac{Q_{pc}}{\eta_{SK} \cdot q_{pal}}$$

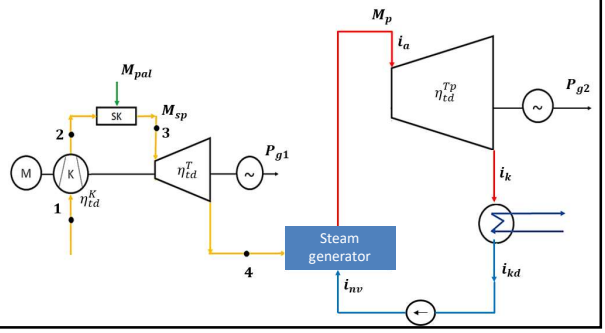
- Total thermal efficiency of the steam-gas cycle related to the generator terminals

$$\eta^c_{tsv} = \frac{P_{g1} + P_{g2}}{Q_{p1} + Q_{p2}}$$

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Example

- Solve the steam-gas cycle (parallel circulation CC), which is shown in the figure. Calculate the required fuel mass flow, the mass flows of the working media at the steam and gas sections and the individual efficiencies and the overall efficiency of the thermal cycle.

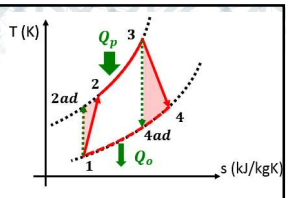


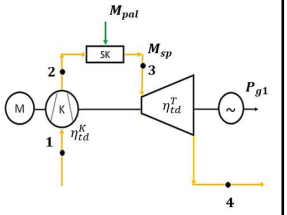
Example - Solution

Gas part of the thermal cycle

- Entered parameters

Data	
Parameter	Value
t_1 (°C)	10
t_3 (°C)	950
$p_1 = p_4$ (MPa)	0.1013
$p_3 = p_2$ (MPa)	0,7
P_{g1} (MW)	65
$\eta_{TD}{}^K$ (%)	85
$\eta_{TD}{}^T$ (%)	89
c_p (kJ/kg.K)	1
$\eta_m{}^{komp}$ (%)	96
$\eta_m{}^{Tur}$ (%)	98
η_g (%)	97
η_{sk} (%)	100
q_{pal} (kJ/kg)	40 000

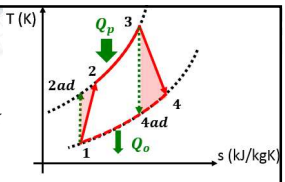




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Example - Solution

Gas part of the thermal cycle



- Temperatures calculation

$T_1 = t_1 + 273{,}15 = 10 + 273.15 = 283.15\ K$

$T_3 = t_3 + 273{,}15 = 950 + 273.15 = 1\,223.15\ K$

$T_{2ad} =$

$T_{4ad} =$

$T_2 =$

$T_4 =$

$$\eta_{td}^{T} = \frac{i_3 - i_4}{i_3 - i_{4ad}} = \frac{T_3 - T_4}{T_3 - T_{4ad}}$$

$$\eta_{td}^{K} = \frac{i_{2ad} - i_1}{i_2 - i_1} = \frac{T_{2ad} - T_1}{T_2 - T_1}$$

- Internal thermal efficiency of the gas part of the cycle

$$\eta_{ti} = \frac{(T_3 - T_4) - (T_2 - T_1)}{T_3 - T_2} =$$

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Example - Solution

Gas part of the thermal cycle

- Terminal thermal efficiency of the gas part of the circuit

$$\eta_{tsv1} = \frac{\left[\eta_m^T \cdot (T_3 - T_4) - \frac{1}{\eta_m^K}(T_2 - T_1)\right] \cdot \eta_g}{T_3 - T_2}$$

$\eta_{tsv1} =$

- Mass flow of working medium (flue gas)

$$M_{sp} = \frac{P_{g1}}{(T_3 - T_2) \cdot c_p \cdot \eta_{tsv1}} =$$

- Heat power required for the gas part

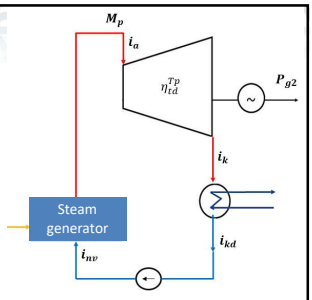
$$Q_{p1} = \frac{P_{g1}}{\eta_{tsv1}} = M_{sp} \cdot c_p \cdot (T_3 - T_2) =$$

Example - Solution

Steam part of the thermal cycle

- Entered parameters

Data	
Parameter	Value
t_a (°C)	460
p_a (MPa)	4
P_{g2} (MW)	35
η_{TD} (%)	80
c_p (kJ/kg.K)	4.19
p_e (kPa)	4
η_m^{Tur} (%)	98
η_g (%)	97



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Example - Solution

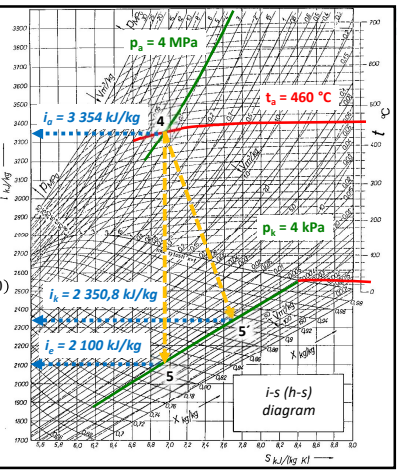
Condensing turbine

- **Determination of steam and condensate parameters**
  - ✓ p_a = 4 MPa, t_a = 460 °C
  - ✓ p_e = 4 kPa, $\eta_{td} = 0.8$
- **Enthalpy calculation i_k**

$$i_k = i_a - \eta_{td} \cdot (i_a - i_e)$$

$$\boldsymbol{i_k} = \\ = 3\,354 - 0.8 \cdot (3\,354 - 2\,100) \\ = \mathbf{2\,350.8\ kJ/kg}$$

$$\boldsymbol{p_k \rightarrow t_k = 29\ °C} \\ \boldsymbol{\rightarrow i_{nv} = 121.4\ kJ/kg}$$



Example - Solution

Steam part of the thermal cycle

- **Real thermal efficiency of part of the steam cycle**

$$\eta_t =$$

- **Mass flow of the working medium of the steam cycle**

$$M_p = \frac{P_{g2}}{(i_a - i_k) \cdot \eta_{g2} \cdot \eta_{m2}} =$$

- **Heat power consumed for steam production**

$$Q_{p2} = \frac{P_{g2}}{\eta_{tsv2}} = M_p \cdot (i_a - i_{nv}) =$$

- **Terminal thermal efficiency of part of the steam cycle**

$$\eta_{tsv2} = \frac{P_{g2}}{Q_{p2}} = \frac{M_p \cdot (i_a - i_k) \cdot \eta_{g2} \cdot \eta_{m2}}{M_p \cdot (i_a - i_{nv})}$$

Example - Solution

- **Total heat flow transferred in the combustion chamber to the steam-gas cycle**

$$Q_{pc} =$$

- **Mass flow of fuel into the combustion chamber**

$$M_{pal} = \frac{Q_{pc}}{\eta_{SK} \cdot q_{pal}} =$$

- **Total thermal efficiency of the steam-gas cycle related to the generator terminals**

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

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