ESF II project of the University of West Bohemia in Pilsen,reg. č. CZ.02.2.69/0.0/0.0/18_056/0013239

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

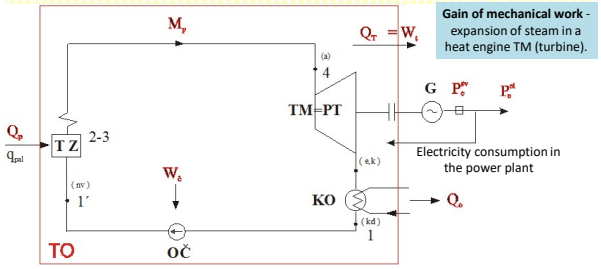
Exercises 3 (KEE/TTE)

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

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

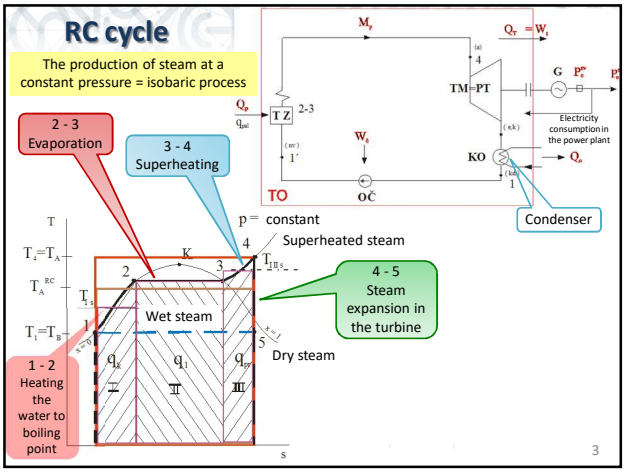
From a theoretical point of view, we can use any working substance in the RC cycle, but it is necessary that it has advantageous thermodynamic properties.



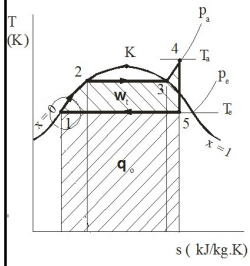
Gain of mechanical work - expansion of steam in a heat engine TM (turbine).

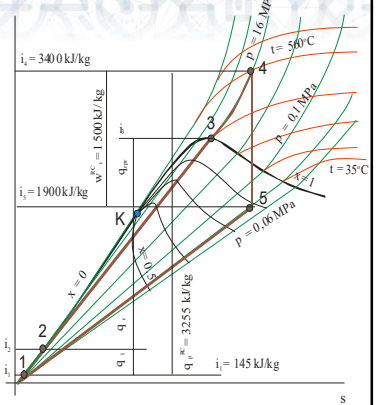
RC cycle

The production of steam at a constant pressure = isobaric process



RC cycle





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

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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)

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

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

$$Q = M \cdot di$$

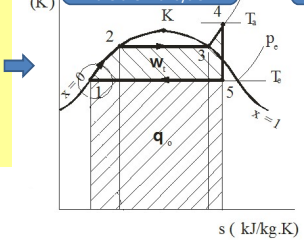
$$\frac{(kJ)}{(h)} = \frac{(kg)}{(h)} \cdot \frac{(kJ)}{(kg)}$$

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



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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):

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

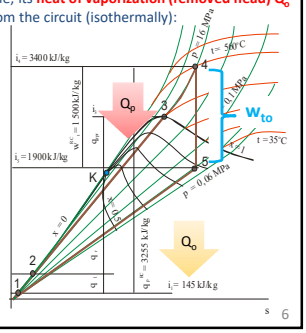
Emission steam enthalpy

Condensate enthalpy

X

Supplied heat - Q_p

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



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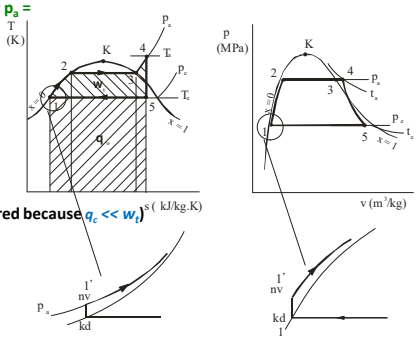
Calculation of an ideal RC cycle

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 $q_c << w_t$)

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

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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.

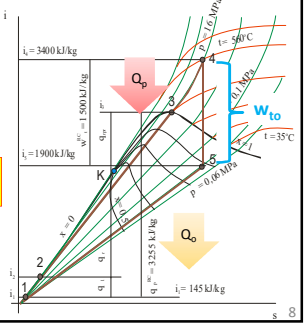
- **Ideal thermal efficiency while neglecting losses for unitary flow:**

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

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

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

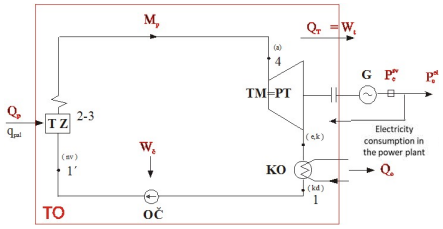
- **Ideal adiabatic (isoentropic) expansion in the turbine:** $h_{ad} = i_a - i_e$



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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.



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Example 1 - Solution

- Steam parameters after ideal expansion

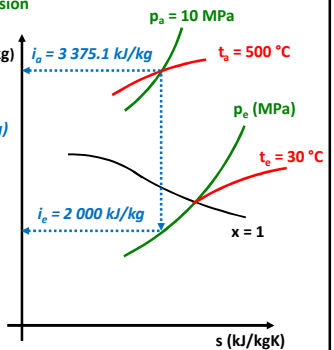
Specified parameters:
t_a = 500 °C
p_a = 10 MPa
t_e = 30 °C

Enthalpy of admission steam i_a (kJ/kg)

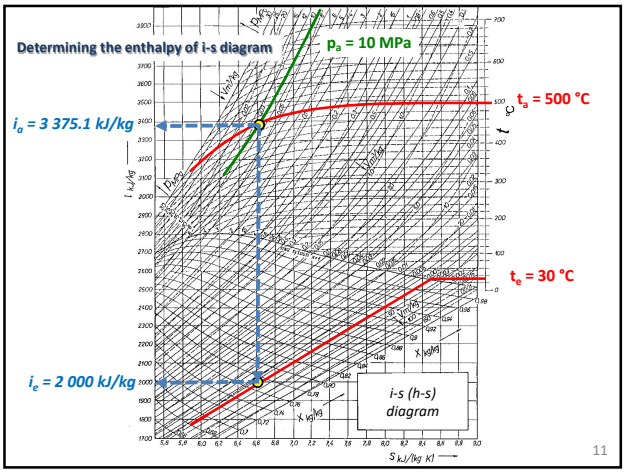
i_a = 3 375.1 kJ/kg

Emission steam enthalpy i_e (kJ/kg)

i_e = 2 000 kJ/kg



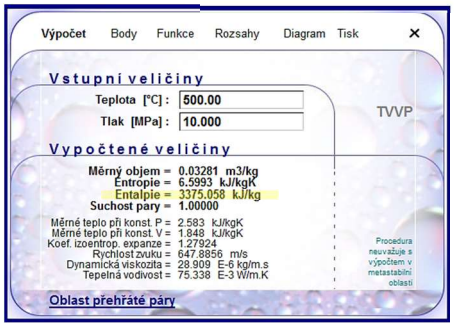
p_e = 0.004247 (MPa)
– reading from the intersection of the emission steam temperature and the right limit curve



Example 1 - Solution

- Enthalpy of admission steam

Determination of enthalpy values from Steam Tables and software

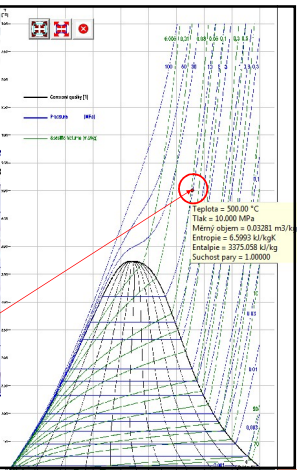


Example 1 - Solution

- Enthalpy of admission steam

Determination of enthalpy values from Steam Tables and software

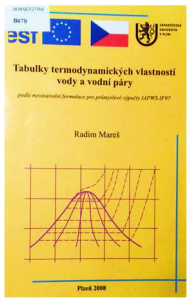


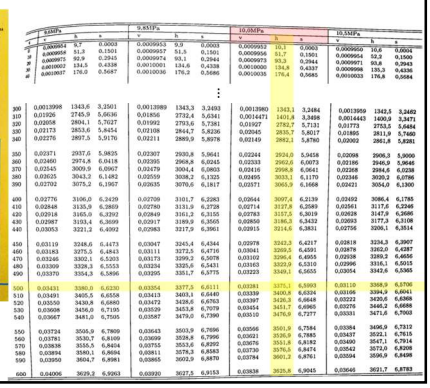


Example 1

Determination of enthalpy values from Steam Tables

- Enthalpy of admission steam





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

$q_o =$

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Example 1 - Solution

- Ideal thermal efficiency of the thermal cycle

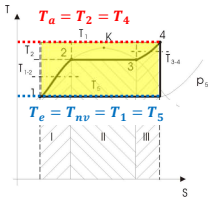
η_{to} =

η_{to} =

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

η_t^{CO} =

η_t^{CO} =



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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

$h_{ad} = w_{to}$

$h_s = w_t$

Turbine losses = $h_{ad} - h_s$

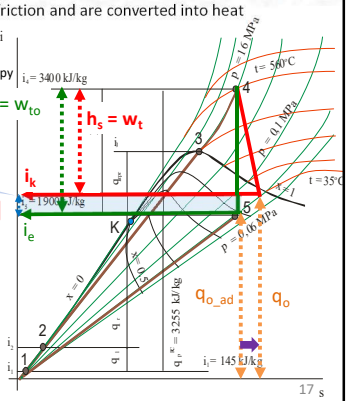
i_k

Enthalpy of real expanded steam

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

$i_{nv} = i_{kd}$

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



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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)

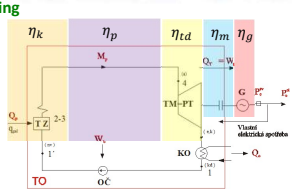
$$\eta_m = \frac{P_{sp}}{P_i}$$

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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

$\mathbf{1\ kWh = 3\ 600\ kJ}$

- Thermal efficiency of the power plant at the generator terminals

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

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

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

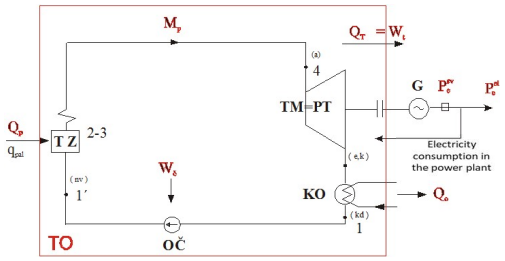
$$M_p(i_a - i_k) \cdot \eta_g \cdot \eta_m \cdot \eta_k \cdot \eta_p = 3\,600 \cdot P_e$$

- 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

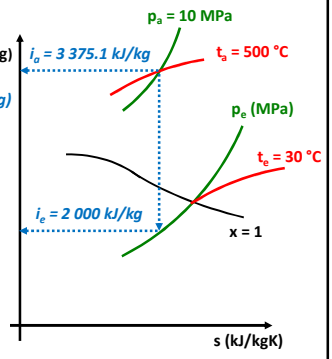
Enthalpy of admission steam i_a (kJ/kg)

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



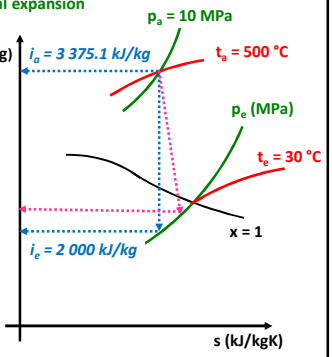
22

Example 2 - Solution

- **Emission steam parameters after real expansion**

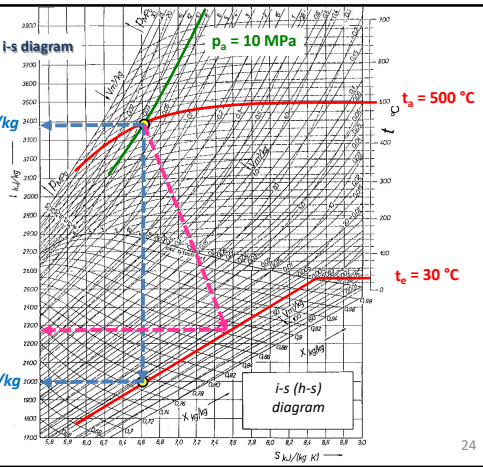
Specified parameter: η_{td} = 0.8

Emission steam enthalpy i_k (kJ/kg)



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Presentation in i-s diagram



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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**

$\boldsymbol{\eta_t =}$

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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**

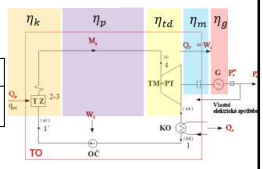
$\boldsymbol{\eta_t^e =}$

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

$\boldsymbol{\eta_t^{el} =}$

- **Comparison of results with Example 1**

$\boldsymbol{\eta_t^{CO}}$	$\boldsymbol{\eta_{to}}$	$\boldsymbol{\eta_t}$	$\boldsymbol{\eta_t^e}$	$\boldsymbol{\eta_t^{el}}$



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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**

$M_p =$

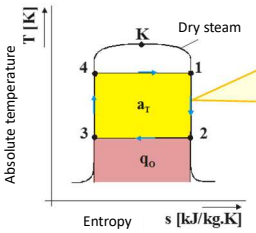
- **Specific steam consumption**

$m_p =$

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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

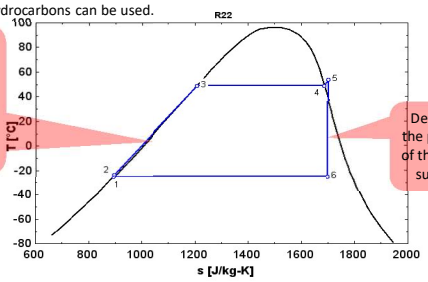
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Real working substances

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

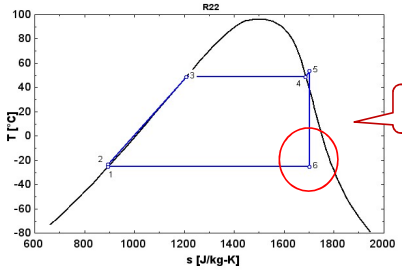


Determines the properties of the working substance

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Wet working substances

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

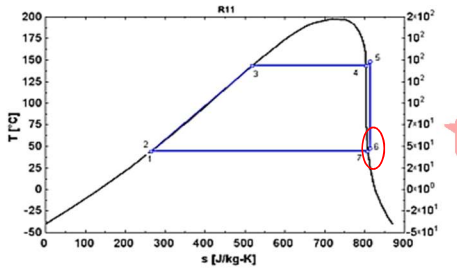


FREON 22

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Isoentropic working substances

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

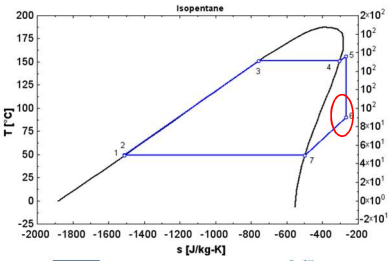


FREON 11

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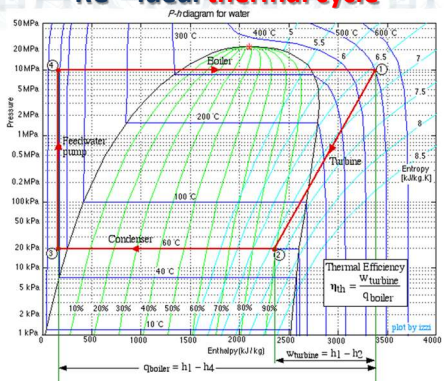
Dry working substances

- 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



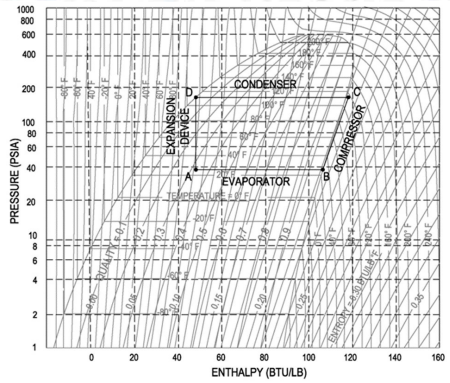
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RC – ideal thermal cycle



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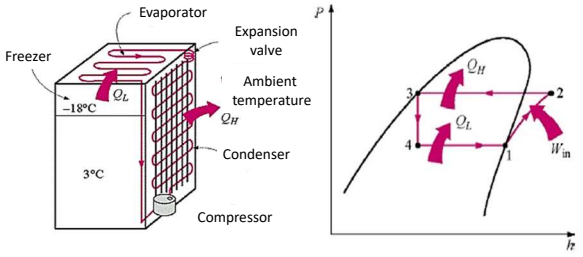
ORC – ideal cooling cycle



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Example 3

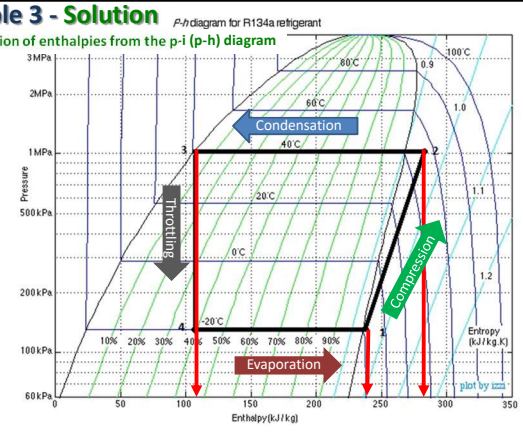
- Calculate the cooling factor (COP_R) and its maximum value ($COPR_{,CO}$) for an ideal compression cooling circuit. The working substance of the thermal cycle is the refrigerant R -134a, which has a temperature of -20 °C at the output of the evaporator. The mass flow is 3 kg / min. The ambient temperature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



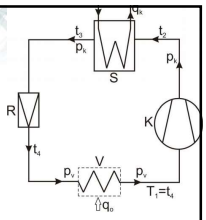
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Example 3 - Solution

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



Example 3 - Solution



- **Work done by the compressor**

  $w_k = i_2 - i_1 =$

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

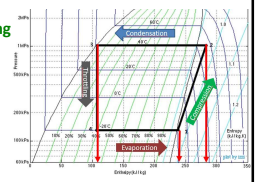
  $q_k = i_2 - i_3 =$

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

  $i_3 = i_4 =$

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

  $q_o = i_1 - i_4 =$



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Example 3 - Solution

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

- **Cooling factor**

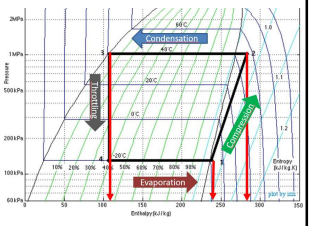
  $\varepsilon_{CH} = \frac{Q_0}{W_t} =$

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

- **Cooling performance**

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

$P_{CH} =$



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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

Carnotization of the thermal cycle
and
RC cycle with reheat

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