ESF II project of the University of West Bohemia in Pilsen

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Thermal cycles (TC) and their evaluation

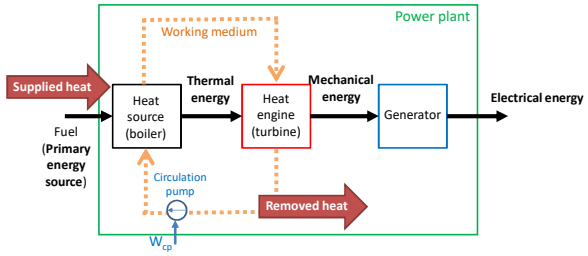
(Energy efficiency calculation)

Exercises 2 (KEE/TTE)

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

Thermal cycles (TC) and their evaluation

Power plant - used to transform the primary energy source into electricity



Thermal power plant - **indirect energy transformation** - heat release in heat source (boilers)

Thermal energy → Mechanical energy → Electrical energy

Repetition of physical quantities

Energy $E = (E_K + E_p) + U$

Kinetic energy + potential energy of the system = mechanical energy of the system

Exergy

= it can possibly be converted to other forms of energy

Anergy

= it cannot be converted into other forms of energy. It cannot be released

Internal thermal energy $u \ (J/kg)$

= it is the sum of all forms of energy that a given substance contains

$U = U_K + U_p$

Kinetic and potential energy of system particles

- It consists of kinetic and potential energy of the molecules of the system
- Its size changes only if the system receives additional energy from outside the energy system (mechanical or thermal energy).

Temperature change → change of **internal kinetic energy**
Volume change → change of **internal potential energy**

- **Changing the internal energy of the system** - by performing work, exchanging heat or both

Repetition of physical quantities

Enthalpy H *or* i (J/kg)

- Sum of internal thermal energy and mechanical energy of the substances

$$i = u + p \cdot v \quad (J/kg)$$

p: Pa; v: $\frac{m^3}{kg}$

Entropy s $(kJ/kg \cdot K)$

- The measure of a system's thermal energy per unit temperature that is unavailable for doing useful work
- Degree of energy degradation = ability to transform heat into another energy form
- Irreversible processes - friction, throttling → **increase of entropy**

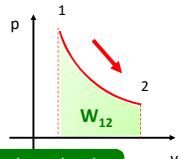
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Laws of the thermodynamics

The law of conservation of energy

- If the thermodynamic process takes place in a closed system between points 1 and 2, then **according to the law of conservation of energy**, the following equation applies:

$$Q_{12} = E_2 - E_1 + W_{12}$$



All heat supplied between states 1 and 2

Difference of total energies

Absolute work = the total work performed between states 1 and 2

The first law of the thermodynamics

= Expression of the law of conservation of energy for a homogeneous system

$$Q_{12} = U_2 - U_1 + W_{12}$$

= if we supply heat to a substance between states 1 and 2, its internal energy increases and the substance then performs external absolute work

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Laws of the thermodynamics

The first law of the thermodynamics

$$Q_{12} = U_2 - U_1 + W_{12} \Rightarrow \Delta U = Q + W \Rightarrow dq = du + dw$$

Differential form of the equation for 1 kg of substance

= the change in the internal energy of the termodynamic system is equal to the sum of the work performed by the surrounding bodies acting on the system by the forces and heat transferred by the surrounding bodies to the system.

- By heat exchange and work, the thermodynamic system can obtain energy from surrounding bodies or supply energy to surrounding bodies.
- The work performed by the system cannot be greater than the heat supplied, unless the internal energy of the system has changed - there is no perpetuum mobile of the first kind !!!

$W > 0$ $Q > 0$



Gas receives energy when the surrounding bodies are doing work (compressing the gas) or by heating this gas.
W > 0, Q > 0 → ΔU > 0

$W < 0$ $Q < 0$



The gas transfers energy to the surroundings by doing work and giving off heat
W<0, Q<0 → ΔU<0

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Reversible changes of the ideal gas

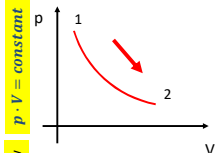
Equation of state of an ideal gas $p_1 \cdot V_1 = R \cdot T_1$

Molar gas constant

Isothermal proces – T (temperature) = constant

$Q_{12} = U_2 - U_1 + W_{12}$

$p \cdot V = constant$



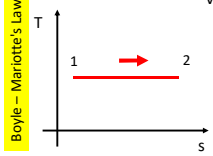
- The supplied heat does not change the internal energy of the substance, but one increases the mechanical work.

$\Delta T = 0 \Rightarrow \Delta U = 0$

$\Delta Q = \Delta W$

The heat received by an ideal gas is equal to the work that the gas does in this process.

Boyle – Mariotte's Law



Isothermal compression = Gas removes heat which is equal to the work expended on its compression.

dQ < 0 , dW < 0 – gas does not work

Isothermal expansion = all the heat is consumed for work - the volume increases and the pressure decreases

dQ > 0 , dW > 0 – gas works

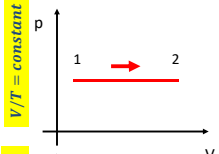
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Reversible changes of the ideal gas

Isobaric proces – p (pressure) = constant

- The volume of the gas is directly proportional to the temperature

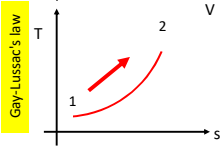
$V/T = constant$



- The received heat heats the gas, which increases U

The internal energy U of the gas is changed due to the supply of the heat and then the gas does the work.

Gay-Lussac's law



$\Delta Q = \Delta U + \Delta W = c_p \cdot m \cdot \Delta T$

Specific heat capacity of gas at constant pressure

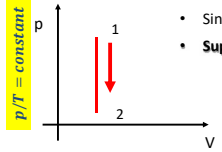
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Reversible changes of the ideal gas

Isochoric process - v (volume) = constant

- The pressure is directly proportional to its thermodynamic temperature

$p/T = constant$



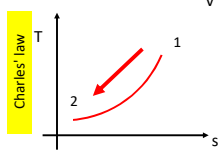
- Since the volume of gas is constant - **the gas does not work**
- **Supply heat = increase in internal energy of the gas**

$\Delta Q = \Delta U$

Specific heat capacity of a gas at a constant volume

$\Delta Q = c_v \cdot m \cdot \Delta T$

Charles' law



- The gas is cooled or heated

dQ > 0 či dQ < 0 a dW = 0

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Reversible changes of the ideal gas

Adiabatic process – change without heat exchange with the environment

= no heat energy is supplied to the gas and no heat is even removed from the gas

$\Delta Q = 0 \Rightarrow \Delta U = W$ Gas does work only "at the expense" of its internal energy

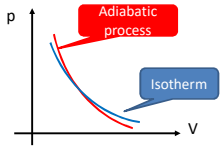
= Isoentropic change $(s = konst)$

Poisson's constant

$\kappa = \frac{c_p}{c_v}$

Poisson's law

$p \cdot V^{\kappa} = konst.$



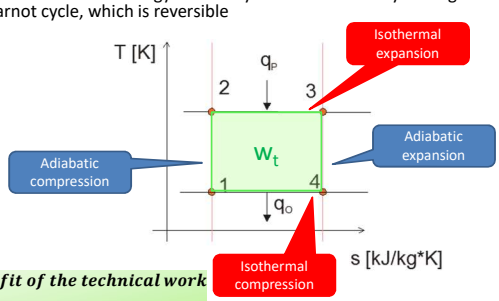
Adiabatic compression
- Compression of the gas in the container (work is done due to the action of an external force - the piston does work)
- The temperature of the gas and its internal energy increase

Adiabatic expansion
- Gas does the work (pushes on the piston)
- The temperature of the gas and its internal energy decrease

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Carnot cycle

= the maximum energy efficiency of the thermal cycle is given by the Carnot cycle, which is reversible



Profit of the technical work

$w_t = q_p - q_o$

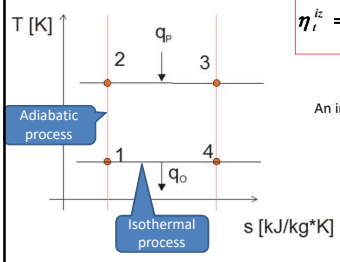
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The ideal thermal efficiency of the thermal cycle

= Ratio profit of technical work to the supplied heat

Carnot cycle

- ideal thermal efficiency of the thermal cycle (lossless = adiabatic = isentropic)



$$\eta_t^{iz} = \frac{W_t}{Q_p} = \frac{Q_p - Q_o}{Q_p} = 1 - \frac{Q_o}{Q_p}$$

An increase in energy efficiency is achieved only by increasing temperatures

An attempt to create a thermal cycle which is similar to the **Carnot cycle**

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The ideal thermal efficiency of the thermal cycle

For a working substance1 kg , which goes through the thermal cycle (mass flow of working substance), we can replace the total (absolute) values of energy flows with quantities in the proportional units, which are related to 1 kg of working substance:

$$\eta_t^{iz} = 1 - \frac{q_o}{q_p}$$

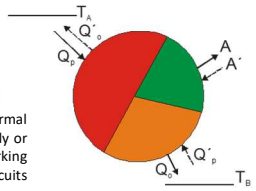
The value of heat in the working substance at the output of the heat engine (turbine) is given by the ambient parameters (temperature, pressure)

Thermal cycles in a clockwise direction

- Thermal cycle used to obtain technical work
- We take mechanical energy

Thermal cycles in counterclockwise direction

- Work (mechanical energy) is supplied to the thermal cycle. They can therefore be used for heat supply or for heat dissipation (removed) from the working substance, ie cooling circuits and heating circuits (heat pumps).



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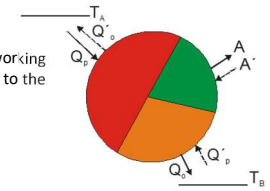
Heating and cooling factor

Cooling cycles can be compared energetically (degree of perfection) using the cooling factor

Cooling factor

= how much heat we removed to the working substance of the thermal cycle in relation to the delivered technical work

$$\varepsilon_{CH} = \frac{Q_p'}{A_t'}$$



Heating factor

= how much heat we get from the working substance of the thermal cycle in relation to the delivered work

$$\varepsilon_T = \frac{Q_o'}{A_t'}$$

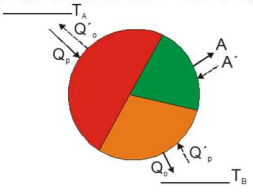
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Degree of perfection of the thermal cycle

$$W = W',\ Q_p = -Q_o',\ Q_o = -Q_p'$$

$$\varepsilon_{CH} = \frac{Q_p'}{A_t'} = \frac{1-\eta_t}{\eta_t} = \eta_t - 1$$

$$\varepsilon_T = \frac{1}{\eta_t}$$



- The perfection of each thermal cycle can be expressed as the ratio of the real cycle to the Carnot cycle

$$\eta_t^{CO} = 1 - \frac{T_B}{T_A},\ \varepsilon_T^{CO} = \frac{T_A}{T_A - T_B},\ \varepsilon_{CH}^{CO} = \frac{T_B}{T_A - T_B}$$

Degree of perfection of the thermal cycle $= \frac{\eta_t}{\eta^{CO}},\ = \frac{\varepsilon_T}{\varepsilon_T^{CO}},\ = \frac{\varepsilon_{CH}}{\varepsilon_{CH}^{CO}}$

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First law of thermodynamics

- Adding heat to a substance increases its internal energy and the substance performs external mechanical work.

$$dQ = dU + dW$$

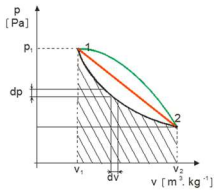
$$dW = pdV$$

- Pressure is a function of volume and temperature



- Absolute work is not a state variable - we must know the integration path between states 1 and 2

$$q_1 - q_2 = q_{12} = u_2 - u_1 + \int_{v_1}^{v_2} p dv$$



$$di = du + d(p \cdot v) = du + p \cdot dv + v \cdot dp$$

$$dq = du + p \cdot dv = di - v \cdot dp$$

$$dq|_{p=konst.} = di$$

$$q = i_2 - i_1$$

The profit of technical work is given by the difference enthalpies = adiabatic thermal gradient

$$dw_{tl} = -v \cdot dp$$

$$dq = di - v \cdot dp = di + dw_{tl}$$

$$dq = 0 \Rightarrow dw_{tl} = -di$$

$$w_{tl} = i_1 - i_2$$

Second law of thermodynamics

= It is an expression of energy conversion efficiency

- All forms of energy can be converted to thermal energy without restriction, but thermal energy can be converted to other forms of energy only to a limited extent.

$$dq = Tds$$

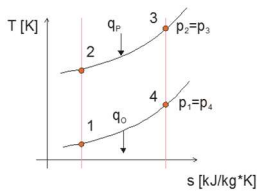
- The amount of heat that a substance receives to its heating from a temperature 1 to temperature 2, it is its specific heat = the amount of heat required to heat 1 kg of a substance by the appropriate temperature difference depends on its heat capacity (specific heat).

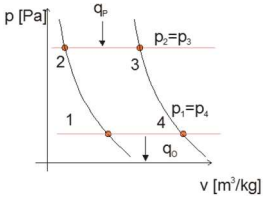
$$c = \frac{dq}{dT} \Rightarrow dq = cdT = di$$

- Gas cycles, where the working substance is air, which can be considered as an ideal gas, can be calculated on the basis of knowledge of the **absolute temperatures T [K].**

Example 1

Calculate the profit of technical work and energy efficiency of the thermal circuit. If it is a lossless (ideal) thermal cycle working with air between two adiabats (dq = 0) - isoentropes (s = constant) and two isobars ($p_1 = 10^5$ Pa, $p_2 = 8{,}3 \cdot 10^5$ Pa). The temperature at the inlet to the heat engine (turbine) is $t_3 = 700$ °C and the ambient temperature is $t_1 = 20$ °C. The heat circuit is open.

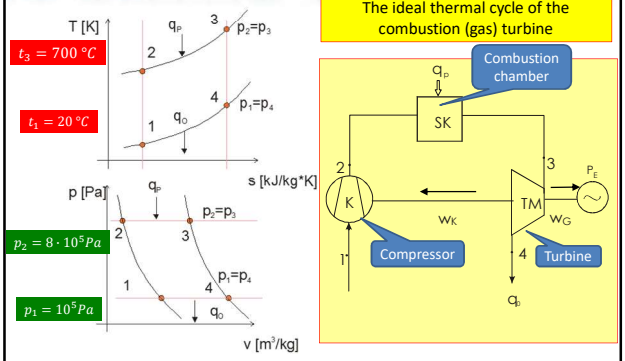




- **The working substance is an air ⇒ it can be considered an ideal gas**

Example 1 – Solution

The ideal thermal cycle of the combustion (gas) turbine



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Example 1 – Solution

- **Calculations of the temperatures**
  - Open thermal cycle - working substance is air = the ideal gas

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

The Poisson's constant expresses the ratio of specific or molar heat capacities of a gas:

$$\kappa = \frac{c_p}{c_v}$$

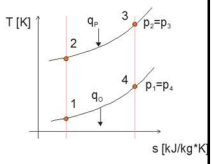
The following parameters apply to an ideal incompressible gas: $\kappa = 1{,}4$ a $c_p = 1kJ \cdot kg^{-1} \cdot K^{-1}$

$T_1 =$

$T_3 =$

$T_2 =$

$T_4 =$



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Example 1 – Solution

- **Heat supplied to the thermal cycle**

  ⇒ **I. TZ** $dq = du + dw$

  Isobaric process (pressure p = const.)

$di = du + d(p \cdot v)$ ⇒ $dq = di = c \cdot dT$

$q_p = c_p \cdot (T_3 - T_2)$

$q_p =$

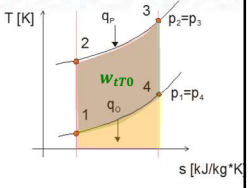
- **Heat removed from the thermal cycle**

$q_o =$

- **Profit of technical work of the thermal cycle**

$w_{tTO} =$

$w_{tTO} =$



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Example 1 – Solution

- **Compressor work**

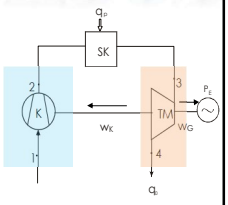
$w_k =$

$w_k =$

- **Profit of technical work of the turbine**

$w_{TM} =$

$w_{TM} =$



- **Profit of technical work of the thermal cycle** - the second variant of the calculation

$w_{tT0} =$:

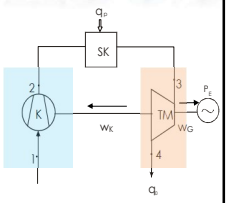
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Example 1 – Solution

- **Energy efficiency of the ideal thermal cycle**

$\eta_{T0} =$

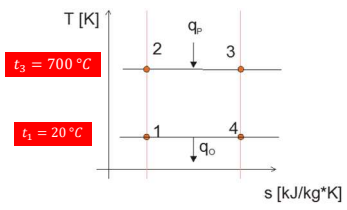
$\eta_t =$



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Example 2

Determine the efficiency of the ideal Carnot cycle and the degree of perfection of the thermal cycle from Example 1. The Carnot cycle is composed of two adiabats and two isotherms.



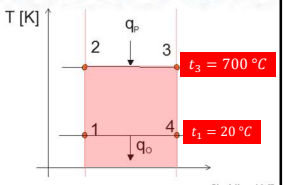
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Example 2 – Solution

- Energy efficiency of the Carnot cycle

$\eta_t^{CO} =$

$\eta_t^{CO} =$



- Energy efficiency of the thermal cycle from the Example 1

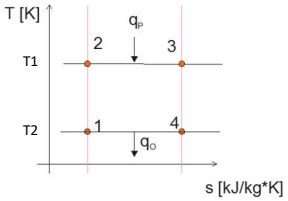
- Degree of perfection of the thermal cycle

$\frac{\eta_t}{\eta_t^{CO}} =$

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Example 3

In an ideal Carnot cycle between the temperatures t_1 = 550 °C and t_2 = 35 °C, an amount of air circulates of 30 kg / s. The power P = 250 kW is taken from the cycle. How much heat do we have to supply to the working medium and how much heat is removed from this thermal cycle?



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Example 3 – Solution

- Calculation of the temperatures

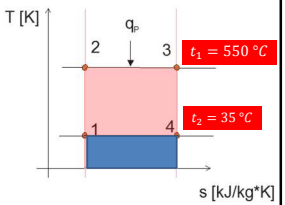
$T_1 =$

$T_2 =$

- Energy efficiency of the Carnot cycle

$\eta_t^{CO} =$

$\eta_t^{CO} =$



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Example 3 – Solution

- **Amount of the heat supplied into the thermal cycle**

TO

Q (kJ)

P = 250 kW

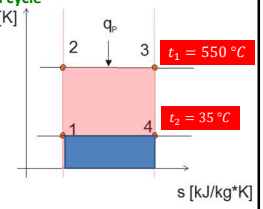
$input = output$

$M \cdot dq = P$

kg/s

kJ/kg

kW



$w = dq$ ⟹ $w =$

$\eta_t^{co} = \frac{w_t}{q_p}$ ⟹ $q_p =$

- **Amount of the heat removed from the thermal cycle**

$w = q_p - q_o$ ⟹ $q_o =$

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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

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

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