Theory of turbocompressors

A course of lectures. 3 semester.

Group 63238/10

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Theory of turbocompressors. *Lecture 4.*

CONTENT

Thermodynamic and gas dynamic basics of turbocompressors theory.

- **Real three dimensional unsteady flow character and its schematization: time-averaged steady flow, guasi three dimensional flow, two dimensional flow, one dimensional flow.**
- **Static and total (delayed) gas parameters.**
- **Energy-conservation equation in mechanical form (Bernoulli's equation). Per-unit mechanical work – “head”.**
- **General equation for turbomachines (Euler's equation).**
- **Equation of condition, gas imperfection accounting.**
- **Process equation. Pictures of compression and expansion processes in turbomachines in *T-s* and *i-s* diagrams. Adiabatic, polytrophic and isothermal compression and expansion work.**

Real three dimensional unsteady flow character and its schematization.

The flow changes its parameters in three dimensional direction of coordinate axes (***z***, ***r***, ***u***), the flow is **three dimensional**.

The flow is **unsteady**, in other words its parameters depend on time ***t***.

Real three dimensional unsteady flow character and its schematization.

In general:

$$\vec{c}\,,(\vec{w}), p, T = f(z, r, u, t)$$

Real three dimensional unsteady flow character and its schematization.

When solving engineering problems and general analyze of working processes a lot of simplifying methods are used:

1. Steady-state modes are under consideration, but periodic **unsteadiness** is not taken into account. **Steady-state flow** is under consideration. Time-averaged flow parameters are taking place in the calculations:

$$\vec{c}\,,(\vec{w}),p,T=f(z,r,u)$$

Real three dimensional unsteady flow character and its schematization.

2. On the first step of analyze, calculation and design the flow is considered as **one-dimensional**. Flow parameters are considered as constant on control sections surfaces and change only from one section to another.

$$\vec{c}\,, (\vec{w}), p, T = f(l)$$

Real three dimensional unsteady flow character and its schematization.

3. **Two-dimensional flow** – the flow is consedered on some middle height of the blade axisymmetric flow surface. Two-dimensional flow coordinates:

AC – z, u (r = const);

CC – u, r (z = const).

4. **Quasi threedimensional flow** – two-dimensional flow assembly.

Static and total (delayed) gas parameters

Terms "**delayed parameters**" or "**total parameters**" are connected with value p^* of gas, which is moving with velocity «*c*» when its delaying to the zero velocity with no external heat exchange and input (output) of mechanical work.

Static and total (delayed) gas parameters

$$p^* = p + \frac{\rho c^2}{2}$$ - delayed pressure

$$T^* = T + \frac{c^2}{2c_p}$$ - delayed temperature

p and T - static pressure and temperature

General equation for turbomachines. “Head”. Bernoulli's equation

Term “head”

$$H = N / \bar{m}$$ (J/kg)

- “head” – per-unit work, mass of the gas referred to the unit mass

H – head for the whole compressor
h – head for one stage

"Head"

Bernoulli's equation in words:

Mechanical work which is transmitted by the impeller of turbocompressor is wasted on compression and moving of gas, increasing of its kinetic energy and doing work against resistance to motion.

Bernoulli's equation

Bernoullis's equation

$$h_i = h_p + h_d + h_r \quad \text{(J/kg)}$$

h_i – **inner "head"** – mechanical work, which is passed to the unit-mass of gas while it is moving through the impeller

Bernoulli's equation

$$h_p = \int_1^2 v dp = \frac{n}{n-1} R T_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

- polytrophic “head”

- work, which is needed to pressure increase (compression) and moving unit-mass of gas from the field with p_1 pressure to the field with p_2 pressure.

Bernoulli's equation

$$h_d = 0,5(c_2^2 - c_1^2)$$

- dynamic “head” -

- gas unit-mass kinetic energy changing when it is moving through the control sections “1” and “2”

h_r – mechanical work, which is needed for unit-mass of gas for doing work against resistance to motion in the flow passage between sections “1” and “2”.

Bernoulli's equation

If the Bernoulli's equation is used in steady canals (diffusers and guide vanes, inlet and outlet elements of turbocompressor), then

$$h_p + h_d + h_r = 0,$$

or $\Delta p^*/\rho = -h_r$ at such canals the pressure could increase by means of velocity decrease, and resistance is overcame by means of total pressure decrease.

Bernoulli's equation

“Head” H is a sum of stage “heads” h of the multistage compressor, at which consequential compression is realized:

$$H = \sum_{1}^{z} h$$

General equation for turbomachines (Euler's equation).

Euler’s equation in words:

Mechanical work, which is passed by impeller to gas unit-mass, is equal to the multiplication of circular part of absolute gas velocity at the outlet of the impeller blades, minus the same multiplication before the inlet to the impeller blades.

Euler's equation.

Euler’s equation:

$$h_{\text{т}} = c_{u2}u_2 - c_{u1}u_1$$

$h_{\text{т}}$ – theoretical “head”

When there is no swirl c_{u1} on the inlet of the impeller:

$$h_{\text{т}} = c_{u2}u_2$$

General equations for processes in turbocompressors description

$$h_i > h_T > h_P$$

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Equation of gas condition. Compression of gas accounting.

Equation of condition connects pressure, temperature, and specific volume (density) of gas:

$$pv = p/\rho = zRT,$$

where z – dimensionless compression coefficient $z \geq 1$ take into account the reality of gases. For perfect gas $z = 1$.

Process equation.

Mechanical work consumption on overcome of the moving resistance of gas unit-mass is a wasted “head” h_r – it is transmitted to heat q_r, which is dispersed at this mass of gas: $h_r = q_r$ (h and q – specific value, refered to the gas unit-mass).

The process of parameters of frictionless gas changing when external heat exchange is absent ($q_{ex} = 0$, $q_r = 0$) is **isentropic (adiabatic)**: gas entropy is constant $s=const$.

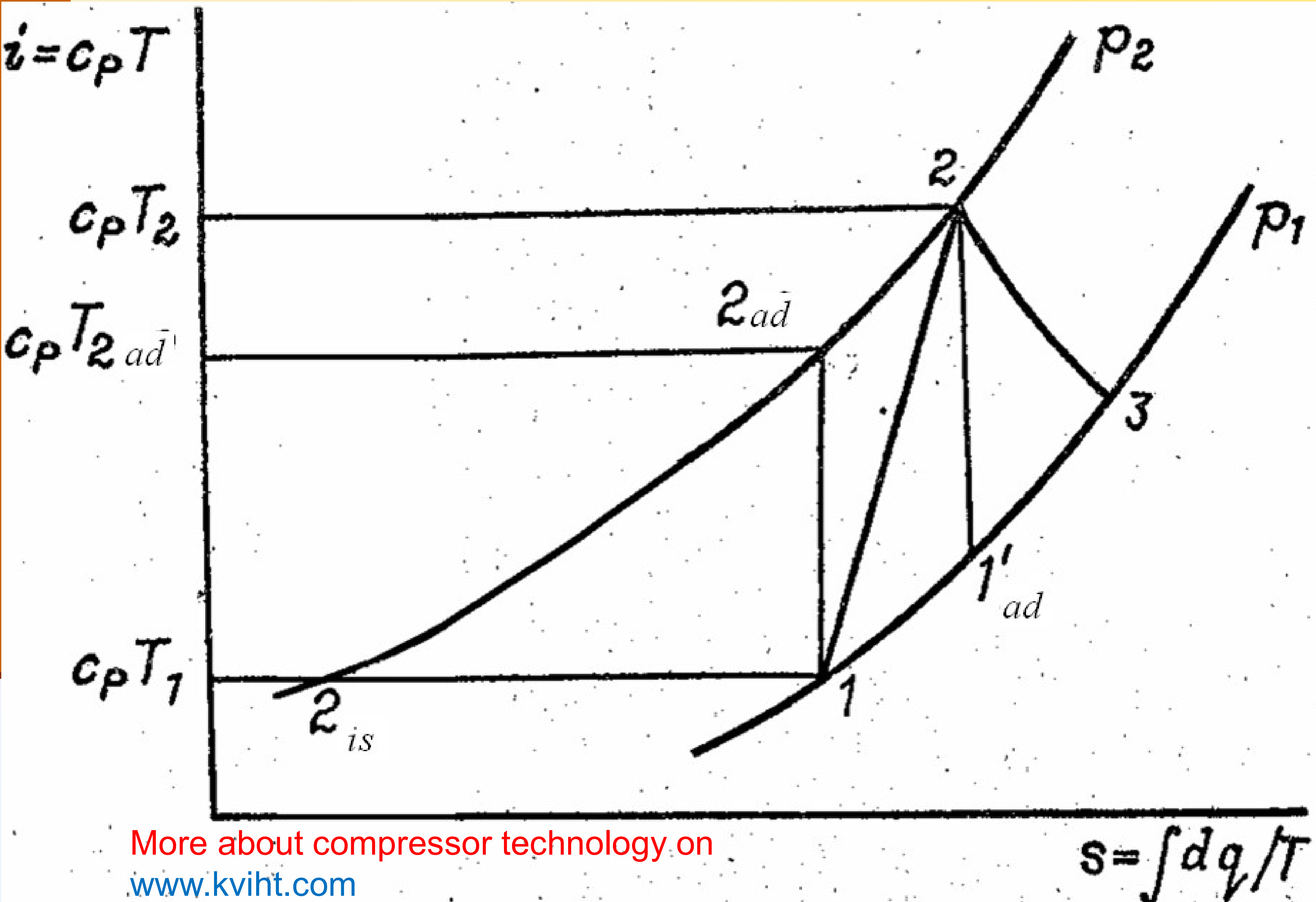
Process equation.

Entropy is a characteristics of thrmodynamic process, which is specified by the equation:

$$ds = \frac{dq}{T}, \quad dq = dq_{ex} + dq_r .$$

When it is isentropic process (at the technical literature such a process usually is called adiabatic, what is not correct, but generally accepted):

$$dq_{ext} = 0, \; dq_r = 0.$$



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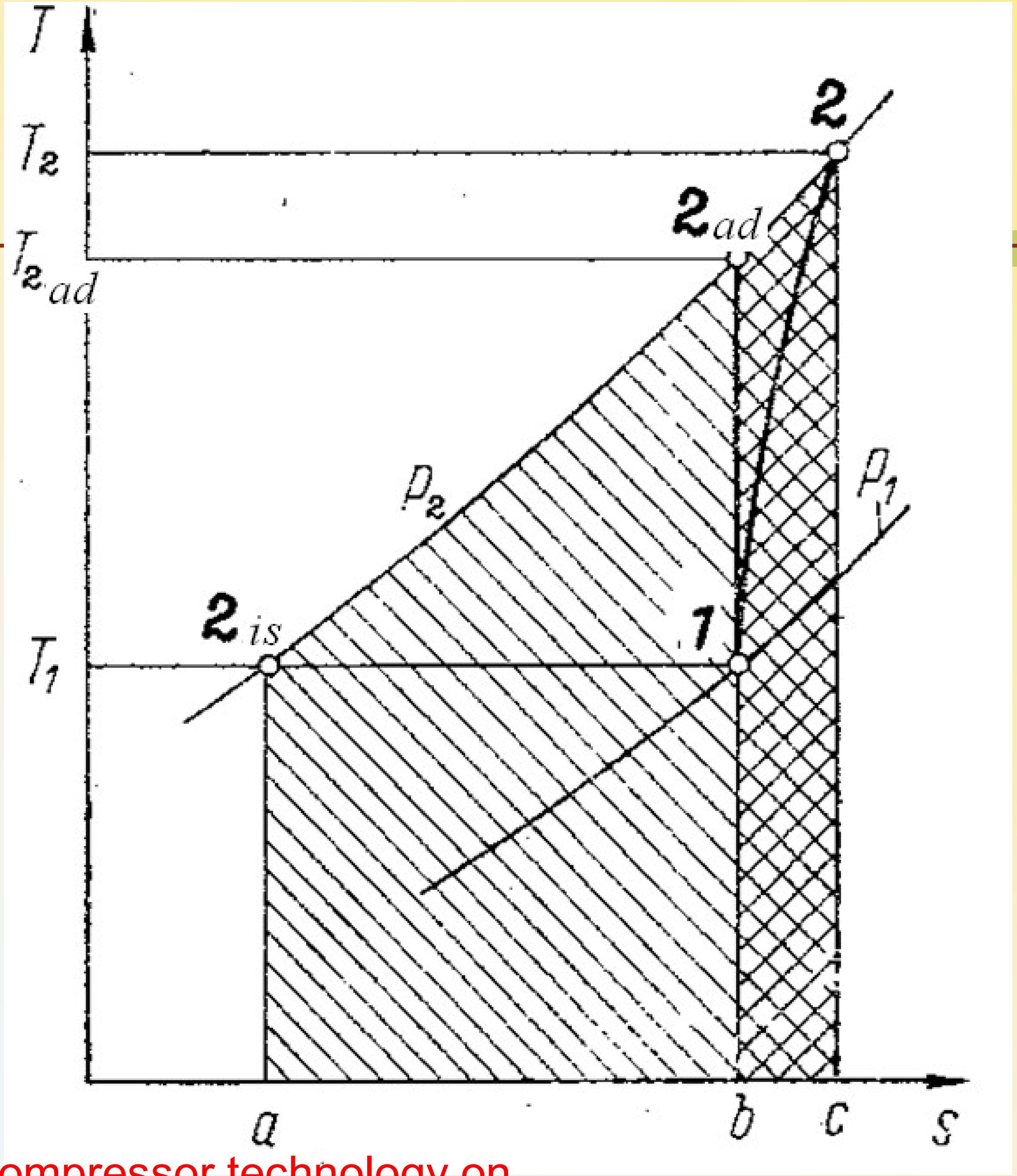

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Process equation.

Gas parameters changing is conform the dependence when it is isentropic (adiabatic) process:

- Isentropic process equation

$$pv^k = p/\rho^k = const,$$

where $k = c_p/c_v$ - isentropic exponent (adiabatic). Adiabatic process is **reverse**

Process equation.

Work of isentropic compression when pressure increases from p1 to p2 is equivalent to the square *a-2is-2ad-b* and could be calculated by the formula:

$$h_{ad} = \frac{k}{k-1} R T_1 \left(\pi^{\frac{k-1}{k}} - 1 \right),$$

where $\pi = p_2/p_1$ - pressure ration

Polytrophic process equation:

$$pv^n = p/\rho^n = \text{const},$$

Process exponent when ($h_r = q_r > 0$) is more than adiabatic exponent: $n > k$. This difference is as strong as more loses of mechanical work for overcoming resistance is provided the working process.

Process equation.

On the T-s diagram the polytrophic process of compression is shown by line 1-2, work of the polytrophic compression is equivalent to square $a\text{-}2_{is}\text{-}2\text{-}1\text{-}b$ and could be calculated with formula:

$$h_{\text{п}} = \frac{n}{n-1} R T_1 \left(\pi^{\frac{n-1}{n}} - 1 \right).$$

Process equation.

At the **isothermal** process heat is abstracted from gas, which is equal by the value to added work. Therefore, at the isothermal process gas is specified as perfect, or without temperature which increases the molecules cooperation. The polytrophic exponent for perfect gas is $n = 1$

$$pv = p/\rho = \text{const}$$

Process equation.

The process of isothermal compression is sown on the T-s diagram by line $1\text{-}2_{is}$, and work of polytrophic compression is equivalent to square $a\text{-}2_{is}\text{-}1\text{-}b$ and could be calculated with the help of this formula:

$$h_{is} = RT_1 \ln \pi$$

Process equation.

$$h_P > h_{ad} > h_{is}$$

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