THERMODYNAMICS OF THE FLOW

Abbreviations

- WF – working fluid
- w – flow speed

The features of thermodynamics for open systems

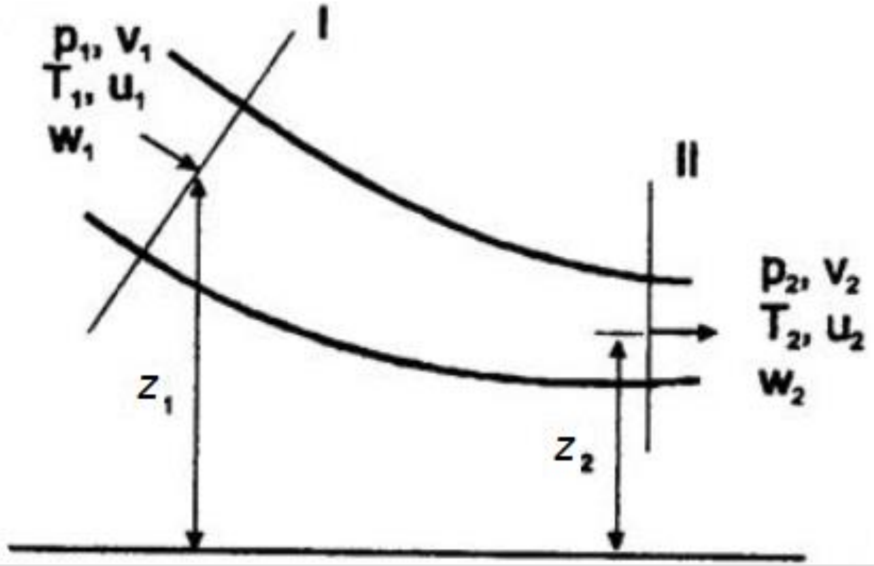
The energy conversion processes in the flow are widely used in engineering, when the working fluid moves from the area with some parameters p_1, v_1 in the area with different parameters p_2, v_2.

In the analysis of the processes in the flow, it is assumed to be **an enclosed volume of the working fluid.** All the basic concepts of thermodynamics can be used for this case.

The features of thermodynamics for open systems

The first law of thermodynamics

$$q = (u_2 - u_1) + l$$



u_1, u_2 are the specific internal energies of the working fluid at inlet and outlet of the unit, respectively

z is the coordinate axis of the fluid flow with respect to the height

w is the fluid flow speed

The flow expansion work *consists of several components*.

The features of thermodynamics for open systems

To derive the equation of the first law of thermodynamics for the flow, the change in the parameters in sections 1 and 2 should be investigated

Assumption:

Steady flow

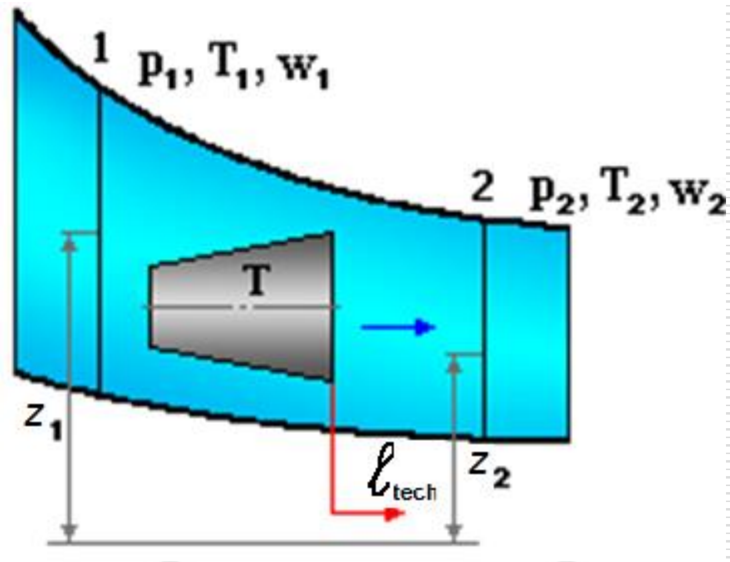
p_1, T_1= const; p_2, T_2 = const

unidirectional flow

w_1= const; w_2 = const;

Mass flow

G = const



While passing through moving surfaces (blades, piston), the flow of fluid performs technical work ℓ_{tech}.

Components of the flow energy for stable flow

To enter the unit it is necessary to overcome pressure p_1, therefore, thrusting-in work will be involved:

$$l_{\text{thr}} = -p_1 \cdot v_1$$

Outthrust work:

$$l_{out} = p_2 \cdot v_2$$

Pushing work:

$$p_2 \cdot v_2 - p_1 \cdot v_1$$

Components of the flow energy for stable flow

Portion of the work is spent on

– the change in kinetic energy

– to overcome the friction forces

Then the specific work of expansion:

$$l = l_{tech} + (p_2 \cdot v_2 - p_1 \cdot v_1) + \left(\frac{w_2^2 - w_1^2}{2} \right) + l_{fric}$$

The features of thermodynamics for open systems

$$q = (u_2 - u_1) + l_{tech} + (p_2 \cdot v_2 - p_1 \cdot v_1) + \left(\frac{w_2^2 - w_1^2}{2} \right) + l_{fric}$$

Taking into account $h = u + p \cdot v$ and $l_{fric} = 0$

$$q = (h_2 - h_1) + l_{tech} + \left(\frac{w_2^2 - w_1^2}{2} \right)$$

The first law of thermodynamics for a flow of the working fluid

The heat supplied to the working fluid flow is:

– increase in enthalpy WF
– production of technical work
– increase in kinetic energy of the flow

Particular cases of the first law of thermodynamics for the flow

- With regard to various types of thermal and mechanical equipment, the following special cases may be considered

Particular case I

Heat exchange equipment, in which flowing liquid or gaseous medium exchange heat

- 1. No technical work is performed, $l_{tech} = 0$
- 2. Flow speed does not change, $w_1 = w_2$

Then

$$q = (h_2 - h_1) + l_{тр}.$$

Since frictional work is completely converted into frictional heat ($l_{frict} = q\ l_{frict}$), in the equation they are mutually cancelled, and the equation is further simplified:

$$q = (h_2 - h_1) \quad \text{or} \quad dq = dh.$$

- This expression is true not only in the isobaric process, but also frictional processes, when pressure of the medium decreases due to resistance

Particular case II

Caloric engines, where the working body performs technical work due to decrease in enthalpy, or

Compressors, where technical work in the adiabatic process is spent on gas enthalpy increase

- 1. No heat exchange, adiabatic flow, $q = 0$.
- 2. Flow speed does not change, $w_2 = w_1$.

Then

$$l_{tech} = (h_1 - h_2) + l_{fric}, \qquad l_{\mathrm{tech}} = (h_1 - h_{2\mathrm{t}})$$

or

$$dl_{tech} = -\,dh$$

Particular case II

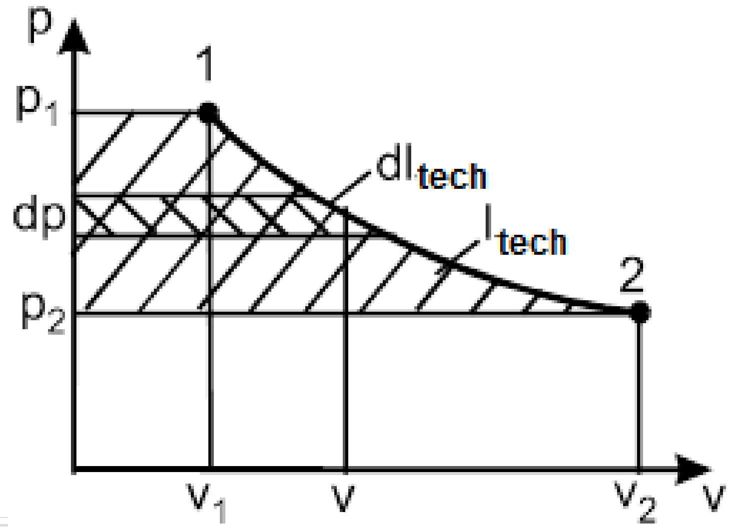
On the other hand, according to the first law of thermodynamics

$$dq = dh - v\,dp,$$

Then if $q=0$ $\quad -dh = -v\,dp,$ $\quad dl_{tech} = -v\,dp$

$$l_{\text{tech}} = -\int_1^2 v\,dp$$

This corresponds to technical work plotted in the pv-diagram



Particular case III

Nozzles and diffusers (specially profiled channels for flow acceleration or deceleration)

- 1. No heat exchange , adiabatic flow, $q = 0$
- 2. No technical work is performed, $l_{tech} = 0$

Then the energy equation of adiabatic flow is

$$w_2^2/2 - w_1^2/2 = (h_1 - h_2) + l_{fric},$$

or $d(w^2/2) = -dh$, i.e. $w dw = -dh$

Taking into account that at $q=0$ $dh = -v dp$,

we obtain

$$d(w^2/2) = -v dp, \qquad w dw = -v dp$$

Particular case III

$d(w^2/2) = - v dp, \qquad w dw = - v dp.$

This shows that dw and dp (dh) always have opposite signs.

The flow speed can be increased in the channel (dw > 0) only when the pressure and enthalpy are decreased (dp < 0, dh < 0).

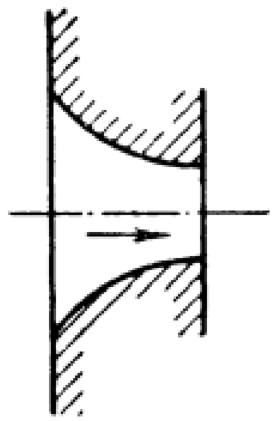
On the contrary, the flow deceleration (dw<0) is followed by increased pressure and enthalpy (dp > 0, dh > 0).

- The form $(w^2/2) = - v dp$, considering $- v dp = dl_{tech}$, gives grounds to assert that the gas flow with the kinetic energy stored can potentially perform technical (useful) work over an external object, i.e. move a device, for example, rotate a turbine rotor.

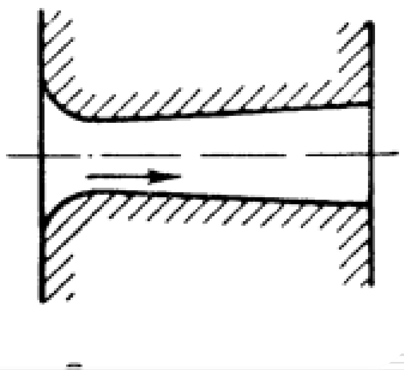
Nozzle flow

A nozzle is a channel that is specifically contoured to increase the speed of gases to a predetermined value and in a given direction.

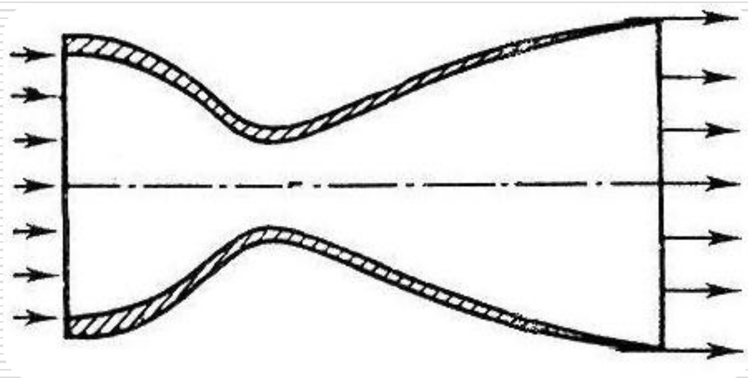
The types of nozzles



Tapered nozzle



Divergent nozzle



A de Laval nozzle

The equation of continuity of the flow

The continuity condition of the flow is the same value of the mass flow of the working fluid in any cross section:

$$G = \frac{F \cdot w}{v} = const$$

G is the flow rate per second of WF, kg/s; w is speed of the flow, m/s; v is specific volume, m³/kg; F is the area of the cross section, m².

The equation of flow continuity in a differential form

- Using logarithmation and differentiion, we obtain :

$$\ln F + \ln w - \ln v = 0$$

$$\frac{dF}{F} = \frac{dv}{v} - \frac{dw}{w}$$

The second flow rate at the expiry

$$G = F_2 \cdot \frac{1}{v_1} \cdot \beta^{\frac{1}{k}} \cdot \sqrt{\frac{2k}{k-1} \cdot p_1 \cdot v_1 \cdot \left(1 - \beta^{\frac{k-1}{k}}\right)}$$

The second flow rate of WF for an ideal gas

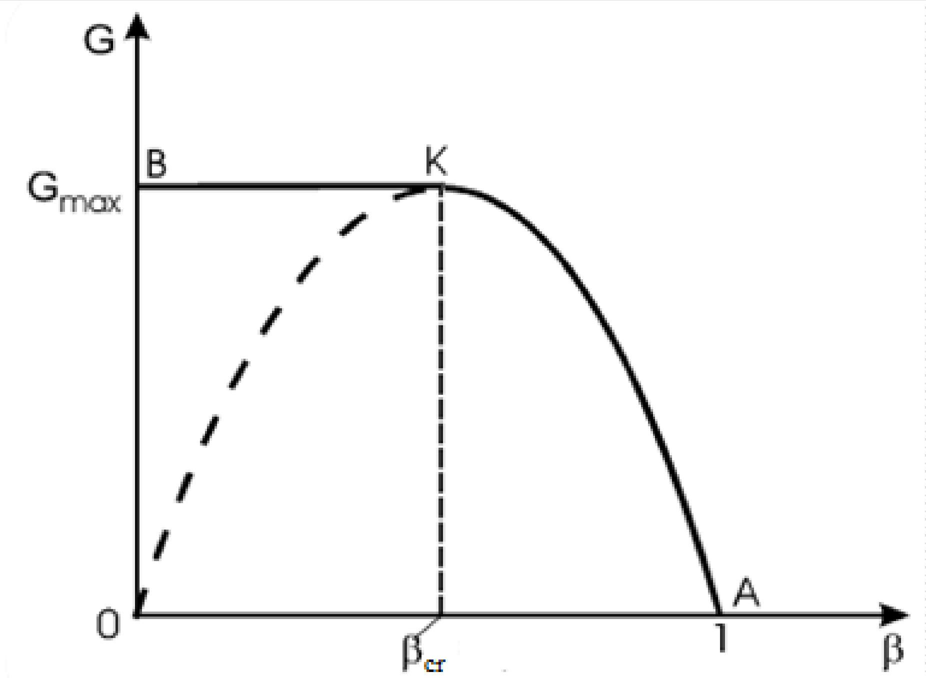
where k *is* the ratio of specific heats

- *k* = 1.4 is for gases
- *k* = 1.29 is for superheated steam
- *k* =1.035+0.1·x is for wet steam
- *k* = 1.135 is for dry steam

$$\beta = \frac{p_2}{p_1}$$

Critical pressure ratio

The diagram shows the dependence of the second mass flow G on β_1:



When ↓ p_2 $(\beta<1) \rightarrow G\uparrow$

G reaches the maximum value in case of the so-called critical pressure ratio:

$$\beta_{cr} = \frac{p_{cr}}{p_1}$$

When↓ p_2 и $G\downarrow \rightarrow \beta=0$

Critical pressure ratio

The analysis shows that the maximum of the second mass flow is achieved when:

$$\beta_{cr} = \frac{p_{cr}}{p_1} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$$

Thus, $\beta\kappa p$ depends only on k, that is, on the nature of the working fluid

$$G_{\max} = F_2 \cdot \sqrt{2 \cdot \frac{k}{k+1} \cdot \frac{p_1}{v_1} \cdot \left(\frac{2}{k+1}\right)^{\frac{2}{k-1}}}$$

The second flow rate for critical condition

βcr = 0.577 is for dry saturated steam
βcr = 0.546 is for superheated steam

Critical speed

The speed at the nozzle outlet, corresponding to critical pressure, is also called *critical*:

$$w_{cr} = \sqrt{2 \cdot \frac{k}{k+1} \cdot p_1 \cdot v_1} = \sqrt{k \cdot p_{cr} \cdot v_{cr}}$$

The expression coincides with the known formula for speed of sound "a" from physics.

The speed of sound is the speed of propagation in the environment of small perturbations, therefore, the critical speed is *the maximum* speed at the outlet of the tapered nozzle.

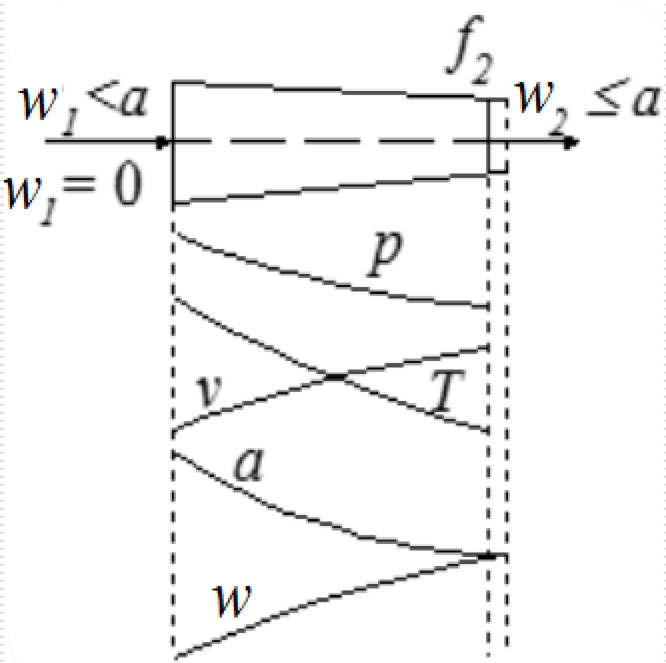
Conditions for obtaining the speed above the critical one

1) **A tapered nozzle** is used to increase the speed of subsonic flows ($w_0<a$ or $w_0=0$). At the outlet of the tapered nozzle $w_1 \leq a$, to obtain supersonic speed is impossible.

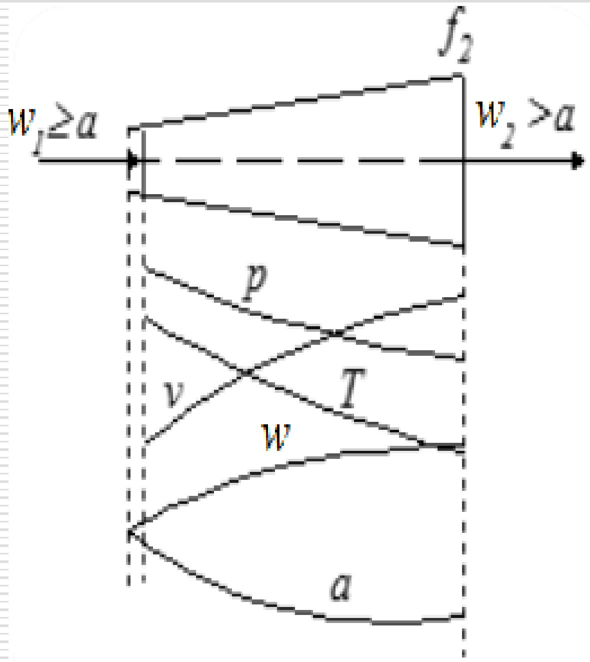
2) **A divergent nozzle** is used to increase the speed of sound or supersonic flows.

3) **The Laval nozzle** is used to increase the speed to subsonic values $w_1>a$. In the minimum section of the nozzle, the speed of flow is the speed of sound.

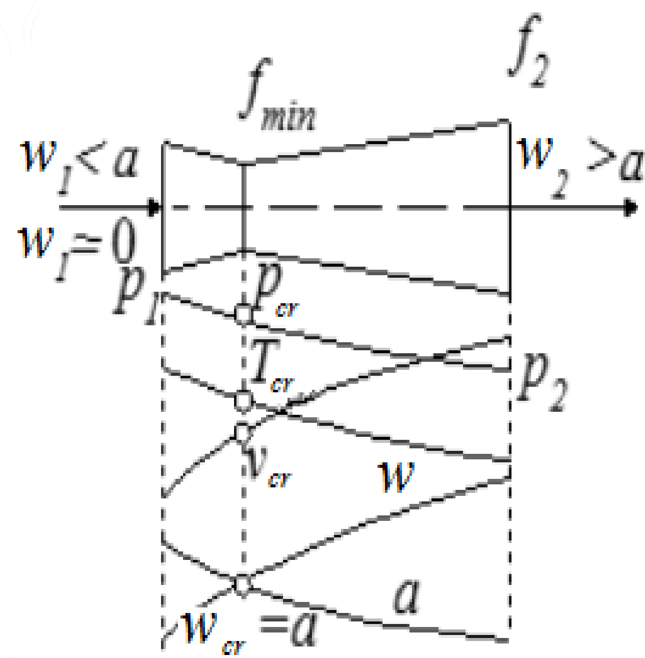
Conditions for obtaining the speed above the critical one



Tapered nozzle



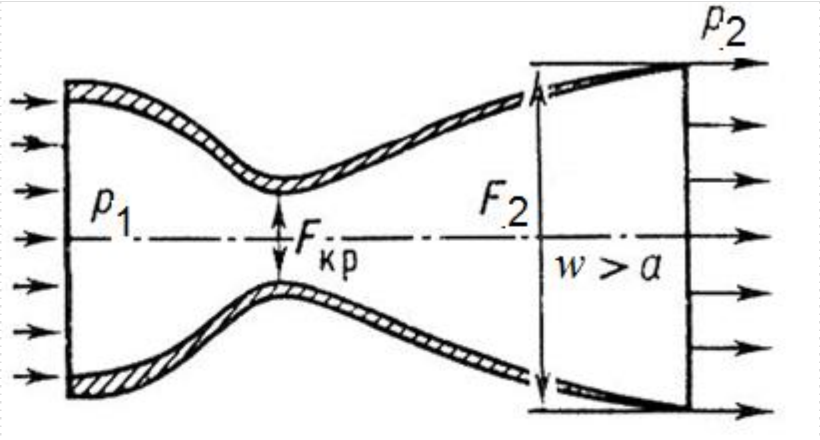
Divergent nozzle



A de Laval nozzle

A de Laval nozzle

Combo nozzle consisting of tapered and widening parts (named after the Swedish engineer)



When designing a Laval nozzle is taken into account, that the taper angles more than 10-12° cause separation of flow from the channel walls (irreversible energy loss).

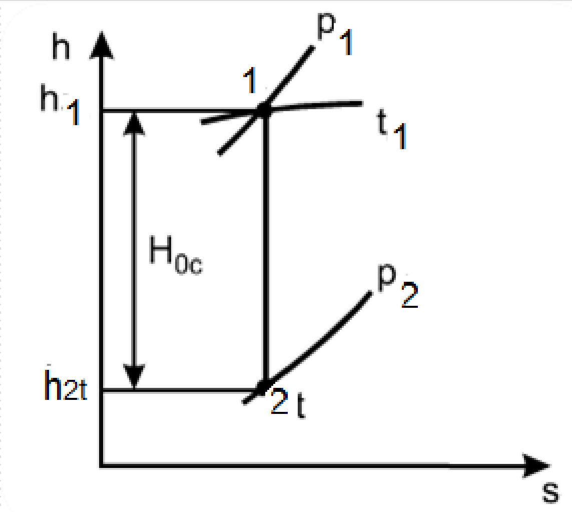
$$F_{cr} = \frac{G_{\max} \cdot v_{cr}}{w_{cr}}$$

The area of the minimum cross section of the Laval nozzle

Calculation of water vapor outflow from the nozzle **by using *hs*-diagram**

Typically, the initial speed of flow is much less than the theoretical speed of flow at the nozzle outlet ($w_1 \ll w_{2t}$). Therefore, the formula to calculate the speed of adiabatic gas flow at the nozzle outlet is simplified:

$$w_{2t} = \sqrt{2 \cdot (h_1 - h_{2t})} = \sqrt{2 \cdot H_{0c}}, \; м/с$$



Adiabatic expiration in *hs* – diagram

Heat drop is equal to:

$$H_{0c} = h_1 - h_{2t}, \; Дж/кг$$

H_{0c} can be found using the *hs*–diagram

Real process of the flow from the nozzle

The actual speed of flow w_1 is less than the theoretical w_{1t} due to friction losses, therefore, in engineering practice, an empirical correction for friction φ – ***nozzle velocity coefficient*** is used.

$$w_2 = \varphi \cdot w_{2t}$$

Kinetic energy loss:

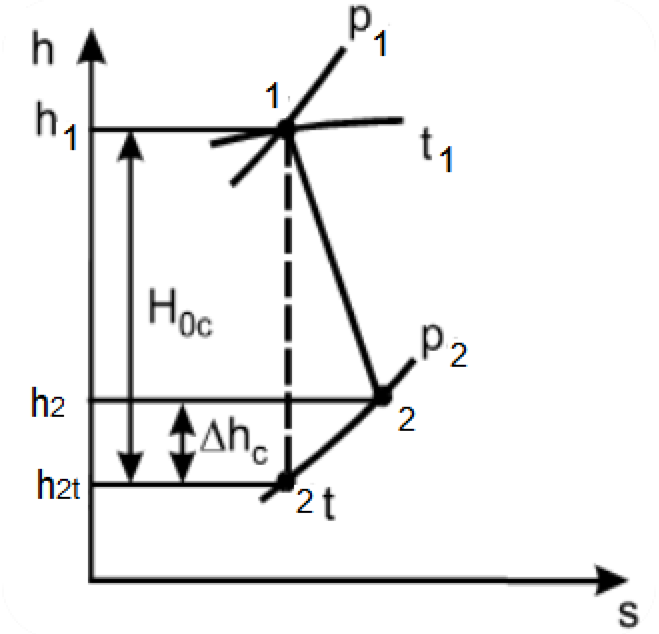
$$\Delta h_c = \frac{w_{2t}^2 - w_2^2}{2} = \xi \cdot \frac{w_{2t}^2}{2}, \ Дж / кг$$

Here, the factor $\xi = 1 - \varphi^2$ is called *the energy losses coefficient* in the nozzle

This part of the kinetic energy of the flow due to friction is converted into heat.

Actual process of outflow from the nozzle

The actual process of **outflow** deviates from the isentrope



Actual process of **outflow** from the nozzle

The speed of flow from the nozzle subject to friction is equal to:

$$w_2 = \varphi \cdot \sqrt{2 \cdot (h_1 - h_{2t})}$$

At the present level of technological advancement, the nozzle friction coefficient is equal to:

φ=0.95÷0.97

Energy loss: ξ=0.10÷0.04