flow condition is called the critical flow condition. Thus, by substituting the critical pressure ratio of *Formula 515* in Formula 101 and Formula 334, formulas can be obtained for the narrowest point of the nozzle when the critical pressure ratio is reached or overcome, see *Formula 516.*

$$c^*=\sqrt{\frac{2\cdot\kappa}{\kappa+1}p_{ic}v_{ic}};\quad \dot{m}^*=A^*\sqrt{\frac{p_{ic}}{v_{ic}}}\chi_{max}$$

$$\chi_{max}=\left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}}\sqrt{\frac{2\cdot\kappa}{\kappa+1}};\quad i^*=i_{ci}-\frac{c^{*2}}{2}$$

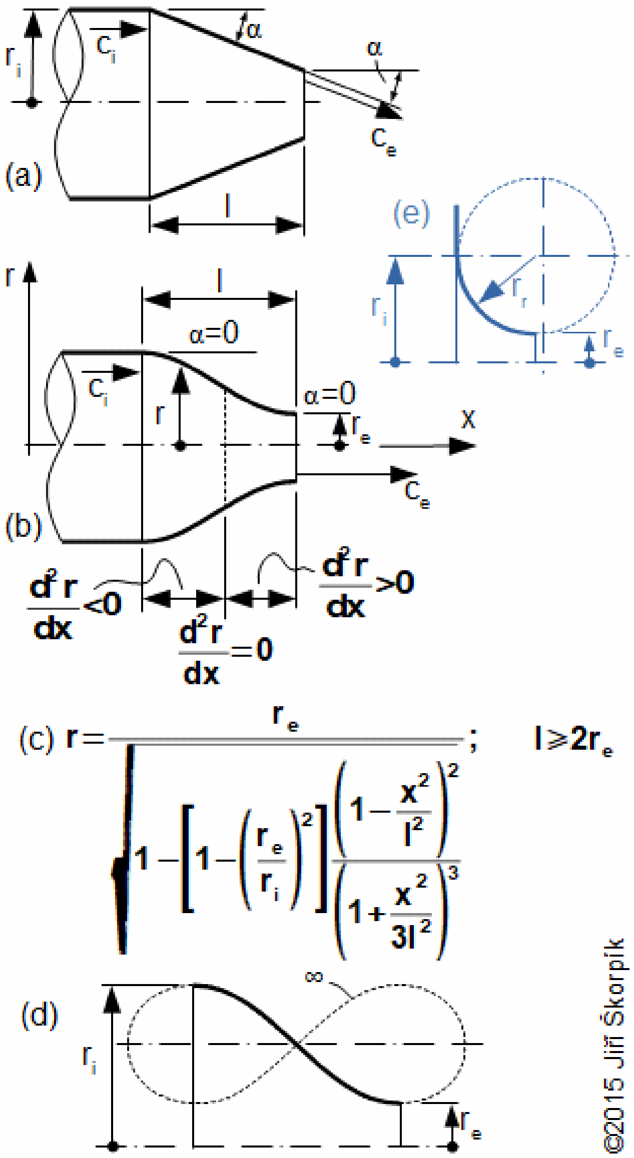
516 *The equations of the critical flow in narrowest area of the nozzle*
These quantities are called critically (critical velocity, critical mass flow rate, critical pressure ratio...). χ_{max} these constants are listed in a tables according type of gases and pressure ratio at $c_i=0$; **i*** [$J\cdot kg^{-1}$] critical enthalpy (at critical enthalpy reaches isentropic expansion the critical velocity).

3D plot of the equation for mass flow rate of gas as function the inlet pressurea and the back-pressure is called flow rate cone of the nozzle.

Problem 102
The air flows through a nozzle, its velocity is $250\ m\cdot s^{-1}$, its pressure is $1\ MPa$, its temperature is $350\ °C$ at the inlet of the nozzle. Surroundings pressure behind the nozzle is $0{,}25\ MPa$. The narrowest area of the nozzle has $15\ cm^2$. (a) find if the flow through the nozzle is critical flow. (b) calculate the outlet velocity and (c) the mass flow rate of air. The properties of air are: $c_p=1{,}01\ kJ\cdot kg^{-1}\cdot K^{-1}$, $r=287\ J\cdot kg^{-1}\cdot K^{-1}$, $\kappa=1{,}4$. You do not solve a situation behind the nozzle. The solution of this problem is shown in the *Appendix 102*.

• Ideal contour of converging nozzle

An ideal contour of the nozzle is smooth, parallel with streamlines (on the inlet even the exit to avoid not a rise of turbulence through sudden change of direction of flow velocity at the wall), on the exit must be uniform velocity field (this condition is confirmed by experiments [4, p. 319]). It means the outlet velocity should be in axial direction of the nozzle. This condition must also satisfy the streamlines at the wall of the nozzle. *Figure 475* shows the usual converging nozzle contour that can also be applied to non-circular channels and blade channels.

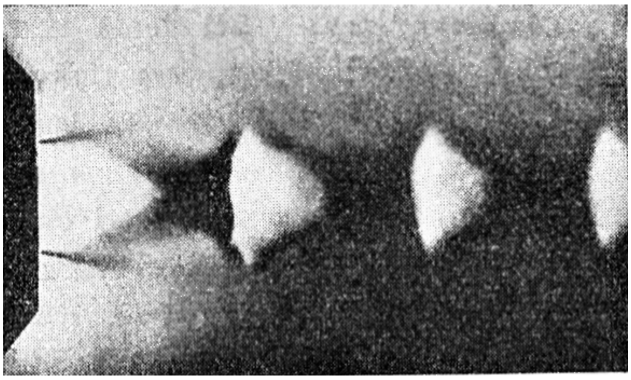


475 *Influence contour of the nozzle on the direction of the outlet velocity*
(a) cone nozzle; **(b)** ideal contour of nozzle; **(c)**, **(d)**, **(e)** usually contours of nozzles; **(c)** so called Vitoshinsk nozzle or Vitoshinsk converging nozzle [4, p. 320], [16, p. 13] (use for reduction passage between two passages with different diameter or as blower nozzle of wind tunels); **(d)** contour of nozzle by lemniscate ∞; **(e)** contour of nozzle for outlet of bottles ($r_r\approx 1{,}5\cdot r_e$ [5, p. 80]); **r** [m] radius of nozzle; **l** [m] length of nozzle. The cone nozzle has lower a mass flow coefficient than ideal contour nozzle (see *Formula 23*).

● State at exit of converging nozzle

From the above it is clear that at the outlet of the nozzle into the free surrounding two conditions can occur and the pressure ratio is higher or just critical ($p_e \geq p^*$), or the pressure ratio is less than critical ($p_e < p^*$).

If the pressure ratio is greater than the critical, the jet at the nozzle outlet gradually begins to brake and mix with the surrounding gas. At a certain distance from the orifice, the velocity and temperature of the effluent gas will be balanced with the surrounding - it will be in thermodynamic equilibrium with the surrounding.



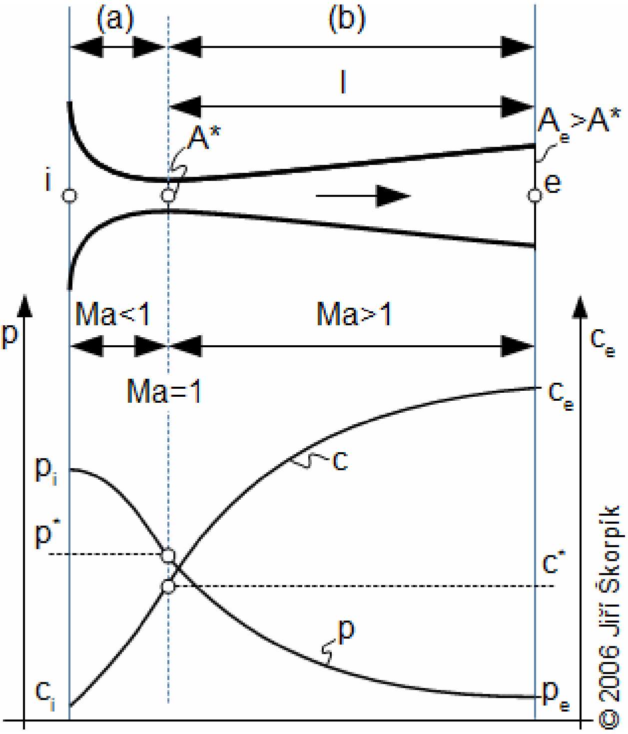
984 *The outflow from a converging nozzle at the critical pressure ratio*
Photo from [3, p. 5].

If the pressure ratio is less than critical, then beyond the nozzle orifice, the gas further expands and its velocity increases according to *Formula 101, p. 1* to supersonic. The gas stream area be must increased according Hugoniot condition. The divergent gas stream forms oblique shock waves on border between the stream and the surroundings gas. These shock waves are reflected to the core of gas stream and they are decreased an efficiency of expansion (they cause pressure drop). The expansion is ended when the pressure is equal the surroundings pressure and a next process is similar the previous case (gradually mixes with the surrounding gas).

● ● ●

De Laval nozzle (converging-diverging nozzle)

For better efficiency of gas expansion behind the narrowest area of the converging nozzle (it is the case $p^* > p_e$) is necessary made the appropriate conditions. It means a divergent channel must be added to the converging nozzle behind narrowest flow area of the nozzle (so called critical flow area, because the speed of sound is reached here) – this design is called as De Laval nozzle:



103 *De Laval nozzle (CD nozzle)-direction of expansion*
(a) converging section of nozzle; **(b)** divergent section of nozzle. **Ma** [-] Mach number; **l** [m] lengh of diverging section of nozzle. The velocity of gas is subsonic *Ma<1* in the converging section, and is sonic *Ma=1* in the narrowest area (throat), is supersonic *Ma>1* in the diverging section.

The exit velocity of the Laval nozzle is supersonic, and as it flows into the free space, the flow immediately begins to create shock waves - braking the supersonic jet by the surrounding gas: