EFFECT OF THE CONE ANGLE AND THE DEGREE OF CONTRACTION OF A SONIC NOZZLE ON THE GEOMETRICAL STRUCTURE OF THE FIRST ROLL OF AN UNDEREXPANDED JET

A. P. Aleshin, I. N. Denisov,
N. M. Rogachev, and V. F. Sivirkin

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The results of an experimental investigation into the effect of the cone angle and the degree of contraction of a contracting nozzle on the geometrical structure of the first roll of an underexpanded jet are presented.

In many cases of practical importance the outlet systems of jet assemblies operate under conditions of underexpansion. For the successful design and operational analysis of such devices it is essential to know the geometrical structure of the underexpanded jet and especially that section of the latter which has been given the name of the first roll. The boundaries of this section and the characteristic lines of the shock structure may be determined by using the method of characteristics and various empirical and semiempirical relationships. On this basis methods have been devised for calculating the first roll of underexpanded jets emerging from supersonic and contracting profiled nozzles [1-4].

In actual practice from constructional and technological considerations sonic nozzles are often made conical. The structures of underexpanded jets emerging from such nozzles may differ very considerably in quantitative respects from the structures of jets emerging from profiled sonic nozzles [5]. This limits the validity of existing methods of calculating the first roll of the underexpanded jets arising from conical sonic nozzles. Published experimental data as to the influence of the geometry of contracting nozzles on the structure of the first roll of an underexpanded jet mainly concern nozzles with relatively small cone angles α. Nozzles with α values approaching 90° are nevertheless of particular practical interest. In the present investigation we therefore studied a wide range of α values extending from 5 to 90°. In addition to this, we varied another important parameter of the nozzle, the degree of contraction m, equal to the ratio of the areas of the inlet to the outlet cross sections F/F_a. In this paper m varies from 1.1 to 4.0.

In order to obtain an underexpanded air jet we used compressed air directed from the compressor through a receiver into the prenozzle chamber, which served to equalize the flow before passing into the actual nozzle. The retarding pressure in the prenozzle chamber P_c^* was monitored by means of a standard manometer, the error being no greater than 0.3%. The atmospheric pressure P_i was also measured.

The nozzles under consideration had the geometry indicated in Fig. 1a. The diameter of the cylindrical part was 8 mm in every case.

The jets were photographed by means of an IAB-451 shadow apparatus with a photographic attachment based on the Zenith-3 camera. The exposure time was determined by the length of the light pulse from the IFK-120 light source; it amounted to $0.5 \cdot 10^{-4}$ sec, giving very clear shadow pictures of the jet.

The photographic films were analyzed quantitatively by means of a UIM-23 measuring microscope. The geometrical parameters of the first roll (to which the measurements were related) are shown in Fig. 1b. We measured the distance from the tip of the nozzle to the Mach disk l_D, the length of the first roll

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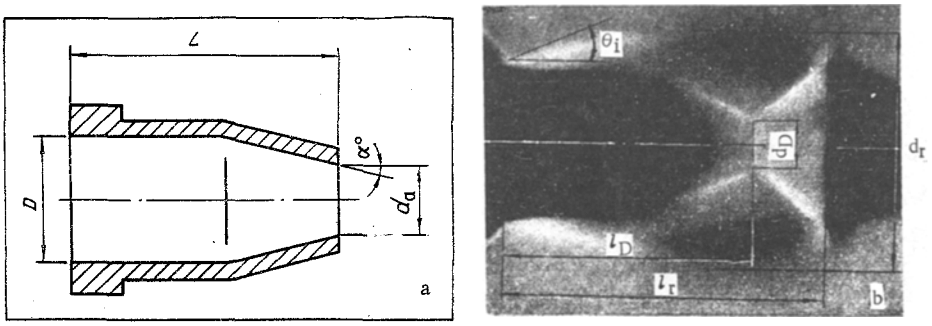

Fig. 1. Sketch of the nozzle (a) and scheme of measurements relating to the geometrical parameters of the first roll (b).

l_r, the maximum diameter of the first roll d_b, the diameter of the Mach disk d_D, and the initial slope of the shadow boundary to the jet axis θ_i.

In order to increase the accuracy of our determination of the parameters we recorded three photographs for each of the operating conditions studied and averaged the results. The greatest stability was that of the dimensions l_D, d_D, and l_r. The parameters d_r and θ_i appeared less sharply in the photographs owing to the mixing of the jet with the ambient, forming a boundary layer; these had a greater statistical spread.

Experiments were carried out for two values of the wastage factor $n = P_a/P_i = 2.04$ and 2.56.

Figure 2 shows the dimensionless values (i.e., values referred to the automodel — self-sustaining — parameters $d_a\sqrt{kn}$) of the distance to the Mach disk $\overline{l}_D$, the diameter of the Mach disk $\overline{d}_D$, the maximum diameter of the first roll $\overline{d}_r$, and the initial inclination of the outer boundary to the axis of the jet θ_i, as functions of the nozzle cone angle α.

Attention should be drawn to the fact that there is a weakly expressed minimum on the $\theta_i(\alpha)$ curve at $\alpha = 60$–$80°$, while on the $l_D(\alpha)$ curve there is a sharply expressed maximum at approximately $\alpha \approx 50°$. In order to understand these characteristics we should take account of certain facts associated with the effluence of an underexpanded jet from a contracting nozzle.

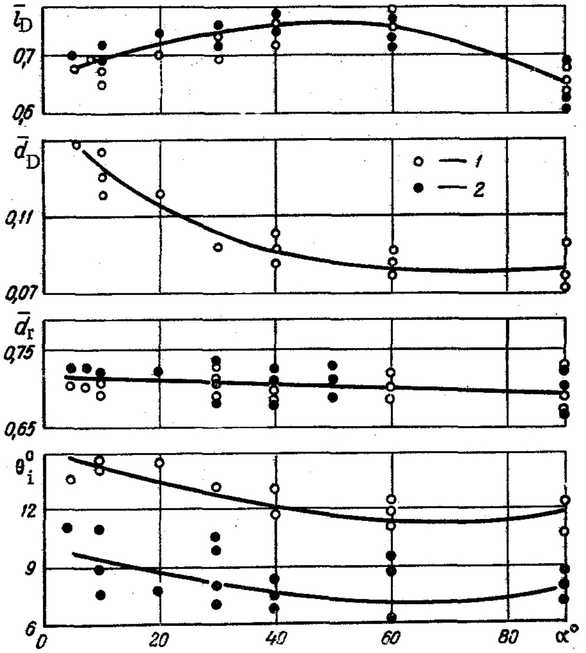

Fig. 2. Geometrical parameters of the first roll as functions of the cone angle of the nozzle: 1) n = 2.56; 2) 2.04.

Firstly, the surface corresponding to the transition of the flow from subsonic to supersonic conditions (sonic surface) has the form of a "tongue" extending downward along the flow [6, 7]. Under otherwise equal conditions the "tongue" increases in length with increasing α, which delays the formation of the shock structure and leads to an increase in $\bar{l}_D$.

Secondly, owing to the influence of the boundary layer, for small α the effective diameter of the critical cross section d_{eff} is smaller than the geometrical diameter of the exit cross section d_a [7]. The difference between these values rapidly diminishes with increasing α. Hence, the use of d_a instead of d_{eff} for calculating l_D in the case of small α reduces the value of $\bar{l}_D$.

Thirdly, for large α the contraction of the jet due to the radial velocity components of the peripheral gas jets becomes very considerable. This contraction increases with increasing α, leading to a reduction in the effective diameter and hence a fall in $\bar{l}_D$ owing to the use of d_a instead of d_{eff} when determining $\bar{l}_D$.

Fourthly, the extension of the sonic surface along the flow with increasing α signifies an intensification of the nonuniformity of the velocity profiles in the cross sections of the jet, which leads to an increase in the viscous dissipation of mechanical energy and a loss of total pressure within the bounds of the actual jet.

The combined influence of these several factors constitutes the cause of the maximum on the $l_D(\alpha)$ curve. The $l_r(\alpha)$ curve, not shown in Fig. 2, behaves in a similar way.

The relative diameter of the Mach disk $\bar{d}_D$ diminishes rapidly as α increases from 5 to 60°, and remains constant for α = 60–90°.

The fall in $\bar{d}_D$ with rising α is due to the fact that the sonic surface is extended downward along the flow, and the compression of the paraxial regions of gas also increases. Both factors promote a reduction in the degree of rarefaction, and hence, reduce the gas velocities in the paraxial part of the jet between the end of the nozzle and the Mach disk. This leads to a reduction in the intensity and dimensions of the forward leap (the Mach disk) with increasing α. The influence of viscosity due to the nonuniform nature of the velocity profiles has a similar effect.

Our experiments revealed no appreciable influence of α on $\bar{d}_r$.

The relationship between θ_i and α contains a minimum. With increasing cone angle θ_i first diminishes, because, firstly, the radial components of the peripheral gas jets directed toward the axis increase, and, secondly, the sonic surface extends downward along the flow. This latter means that the region of subsonic acceleration of the flow between the end of the nozzle and the sonic surface becomes more and more extended. Since the transverse cross sections of the stream tubes diminish during subsonic acceleration, this leads to a reduction in the intensity with which the thickness of the jet as a whole increases, i.e., ultimately to a reduction in θ_i. For large cone angles an increase in α leads to an increase in θ_i, which agrees with the character of the changes taking place in $\bar{l}_r$ and $\bar{d}_r$.

The value of the angle θ_i is smaller than that calculated by the Prandtl–Mayer theory for a nozzle with a plane sonic surface.

The extent to which the degree of contraction of the contracting nozzle m affected the structure of the underexpanded jet was comparable with the experimental scatter of the points measured in accordance with the technique adopted in the present investigation. There was accordingly no point in analyzing these results further.

The influence of the wastage factor n on the characteristic linear dimensions of the first roll agrees qualitatively with the results of calculations based on existing methods for profiled contracting nozzles.

On the basis of the foregoing analysis, we may conclude that the conical angle of the contracting nozzle has a major influence on the geometrical structure of the first roll of the free underexpanded jet.

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NOTATION

θ_i	is the initial inclination of the shadow boundary to the axis of the jet;
α	is the cone (conical) angle of the nozzle;
m	is the degree of contraction;

n	is the wastage factor;
P_a	is the pressure at the end of the nozzle;
P_i	is the atmospheric pressure;
P_c^*	is the retardation pressure in the prenozzle chamber;
l_r	is the length of the first roll;
l_D	is the distance from the tip of the nozzle to the Mach disk;
d_r	is the maximum diameter of the first roll;
d_D	is the diameter of the Mach disk;
D	is the diameter of the cylindrical part of the nozzle;
d_{eff}	is the effective diameter of the critical cross section;
d_a	is the geometrical diameter of the exit cross section;
F	is the area of the entrance section;
F_a	is the area of the exit section;
k	is the adiabatic index.

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