INVESTIGATION OF FLOW OF A DUST-LADEN STREAM IN A LAVAL NOZZLE

G. A. Komov

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An experimental investigation has been made of the influence of the presence of solid particles in an air stream flowing in a Laval nozzle on the degree of expansion in the nozzle and on the noncalculability, i.e., the degree to which the discharge from the nozzle cannot be calculated, for particle mass fractions varying in the range 0.2–0.5. Shadow photographs are presented of the compression shocks at the outlet section of the nozzle in a dust-laden stream composed of air and solid particles.

In the design of certain elements of power machinery, the peculiarities of the discharge from a Laval nozzle of a dust-laden stream composed of gas and solid particles must be taken into account. A study must be made, in particular, of the influence of the particles on the degree of expansion in the nozzle and of the degree to which the discharge from the nozzle cannot be calculated.

Because of the lack of results of such investigations in the literature, special tests were carried out on the equipment shown in Fig. 1a.

Air (T = 288–290° K) from the main supply line 3 reaches the powder dispenser 5, where the particles are introduced into the stream. The resulting saturated stream arrives at the test Laval nozzle and exits into chamber 10, which is equipped with a throttle valve 11.

The injection of particles into the air stream in the dispenser is accomplished as follows. The air stream passes through the openings in the rotating disc 7 of the dispenser, these being covered with wire mesh. The disc continuously supplies powder to the stream which entrains particles from the mesh. The dispenser nozzles 6, which are in the form of slits, may be rotated and moved up and down, thus allowing control of powder flowrate. A determination of the powder mass flowrate was accomplished by continuously measuring the weight of the dispenser while the powder was being dispensed.

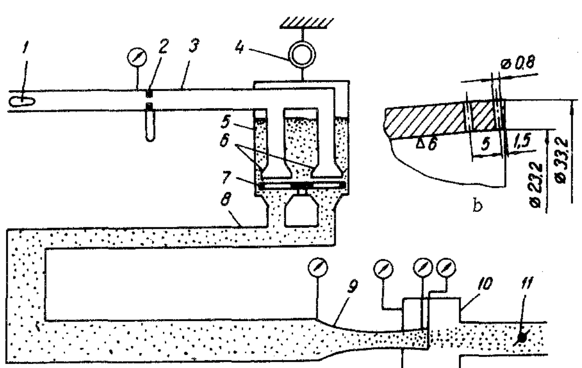

Fig. 1. a) Diagram of the experimental equipment, and b) of the exit part of the Laval nozzle.

For this purpose it was suspended from strain gauge ring 4 and connected to the supply lines by flexible couplings 3 and 8.

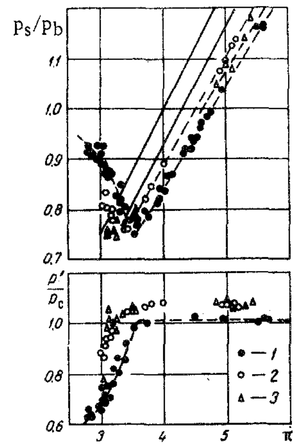

Fig. 2. Dependence of the degree of noncalculability p_s/p_b and of the ratio p'/p_s on π, with m = 0.4, and π_{min} = 3.55: 1) for air; 2) air and Al particles (d_m = = $14 \cdot 10^{-6}$ m); 3) air and Fe particles (fraction 40); the two upper lines are p_s/ /pB for equilibrium mixtures of air—Al and air—Fe, respectively.

Before each experiment the dispenser was calibrated by loading it with weights simulating the weight of the powder, and a calibration curve was drawn. The air flowrate was measured by means of diaphragm 2.

The pressure p* upstream of the test nozzle was measured with a standard manometer having a range from 0 to 10^6 N/m^2. The pressure at the exit section of the nozzle, p_s, and upstream of the exit section, p', were measured with vacuum gages having a range from -10^5 N/m^2 to 0. The pressure in the chamber p_b was measured with a vacuum manometer having a range from -10^5 N/m^2 to $+1.6 \cdot 10^5$ N/m^2.

The readings of all the instruments during the experiment were photographed, the times of the photographs being noted on the strip of a chart recorder which recorded dispenser weight, and on the record of an oscillograph which simultaneously recorded pressures.

The experiment was carried out as follows. Air was supplied to the lines, and then the assigned back pressure was established in the chamber 10 by means of throttle 11. The camera and the recording instruments were switched on, as well as the electric motor driving the disc of the dispenser, so that powder began to feed into the stream. The air mass flowrate during the experiment was held constant independently of whether or not powder was being fed in, this being attained by creating a critical air flow regime in the tubing ahead of measuring disc 2. For this purpose a specially profiled body 1 was located in the supply line. A cyclone in which about 99% of the powder was caught was located at the exit from the equipment.

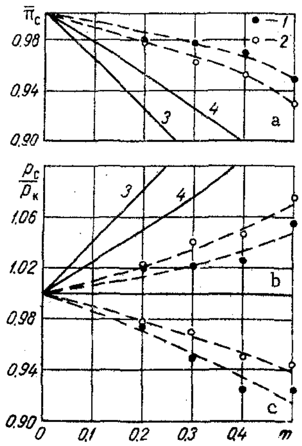

Fig. 3. Influence of particle mass fraction m on nozzle operation: a) on $\overline{\pi}$; b) and c) on p_s/p_b, respectively, in underexpanded and overexpanded conditions; 1–4) see 2–5 in Fig. 2.

The nozzle used in the investigation was a straight axisymmetric one with an area ratio, throat to exit section, appropriate to discharge of the air with M number of 1.71. The length of the convergent part of the nozzle, contoured according to the Vitoshinskii formula [1], was equal to 200 mm. The length of the expanding conical part (total cone angle 0.032 rad) was 100 mm. The diameters of the entrance section, throat, and exit section were 80 mm, 20 mm, and 23.2 mm, respectively.

The ratio of areas of the nozzle throat to entrance section in the test nozzle was 0.0625, and therefore the static pressure in the nozzle entrance section was practically equal to the total pressure. Thus, the total pressure ahead of the nozzle was determined without introducing heads that might cause obstruction. The ratio of diameter of chamber 10 to that of the nozzle exit section was 6. The air pressure upstream of the nozzle varied in the range $(3\text{–}3.5)\cdot 10^5$ N/m^2. The following particles were used in the experiments: a) spherical aluminum particles with mean diameter (determined by measuring the specific surface area in a PSX-2 instrument) of about $14\cdot 10^{-5}$ m; b) low-carbon iron particles, near spherical in shape (fraction 40); the powder was sifted through a sieve with cell size 0.04×0.4 mm, and retained on a sieve with size 0.3×0.3 mm.

Moreover, a series of experiments was carried out in which the system of compression shocks formed in the dust-laden stream behind the nozzle exit section was photographed by the shadow technique.

Chamber 10 was then withdrawn, and the dust-laden stream discharged into the atmosphere (with subsequent collecting of the jet into the cyclone.

In these tests the nozzle used differed from that described as regards the length of the expanding section, which was 40 mm (the area ratio of the exit section to the throat was the same). Moreover, the nozzle had a sharp rim at the exit section, and not an annular surface (Fig. 1b).

Experimental results: The flow regime in a supersonic nozzle may be determined from graphs of the dependences of the degree of noncalculability and of the ratio p'/p_s on the total degree of expansion π. These dependences were obtained in our investigation for air and for the dust-laden stream at values of mass fraction of particles from 0.2 to 0.5. The graph of one of these (for m = 0.4) is given in Fig. 2.

The figure also shows theoretical curves determined on the assumption that the velocities and temperatures of the air and the particles are equal (equilibrium mixture). Under these assumptions the mixture is regarded as a "virtual" gas with adiabatic exponent determined according to the formula [2]

$$k' = [(1-m)c_p + m\,c]/[(1-m)c_V + m\,c].$$

The calculation was carried out according to the formula

$$\frac{p_s/p_c}{\pi} = \left(1 - \frac{k'-1}{k'+1}\lambda^2\right)^{\frac{k'}{k'-1}}.$$

The reduced velocity of the equilibrium mixture,

$$\lambda = w \Big/ \sqrt{\frac{2k'}{k'+1}(1-m)RT^*}$$

is found from the expression [1]

$$\frac{F_{\min}}{F_c} = \left(\frac{k'+1}{2}\right)^{\frac{1}{k'-1}} \left(1 - \frac{k'-1}{k'+1}\lambda^2\right)^{\frac{1}{k'-1}} \lambda.$$

The flow of an equilibrium mixture is a limiting case of an actual dust-laden flow, in which the particles lag behind the gas, and the particle temperature is, in general, not equal to that of the gas. The equilibrium mixture formulas are used in gasdynamic design of machine elements [2].

In the region of large values of π the experimental points (Fig. 2) correspond very well to straight lines. This means that the back pressure has no influence on the flow parameters inside the nozzle. The place where the points begin to deviate from the linear relation determines the minimum value of total degree of expansion $\pi_{\min}$ for which there is no back pressure influence. We also note that at this place there is a change in the nature of the dependence of the ratio of p'/p_s on π (Fig. 2).

The experiments have shown that the degree of expansion of the gas phase of a dust-laden stream

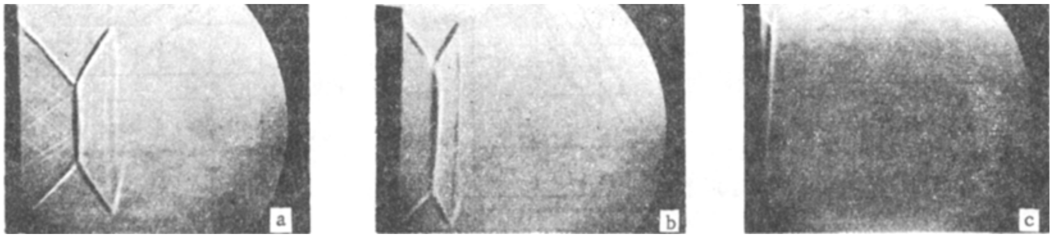

Fig. 4. Compression shocks with $\pi = 2.9$ ($\pi_{min} = 2.7$): b and c) in the dust-laden stream with $m = 0.3$ (400 fraction Fe particles), and with $m = 0.5$ (40 fraction Fe particles).

is less than that of the gas in the same nozzle. This difference increases (Fig. 3, a) as the particle fraction in the stream increases.

The results shown in Fig. 3 allow a conclusion to be drawn regarding the influence of flow velocity nonuniformities associated with lag of the particles behind the gas on the quantities investigated.

When larger and heavier iron particles are introduced into the stream, and lag behind more than the aluminum particles, the parameters of the dust-laden flow (Fig. 3) differ less from those of the gas without particles than in the case with aluminum particles, which are more forcibly entrained by the gas. In the limiting case of particle entrainment (particle velocity equals gas velocity), the change in flow parameters relative to their values in the gas without particles is the greatest (calculated curves in Fig. 3).

The observed connection of the flow parameters with lag of particles from the gas is evidently explained by the fact that a large amount of energy must be expended by the gas in causing the large entrainment of particles (for constant particle mass fraction).

If the calculated operating conditions in the Laval nozzle ($p_s = p_b$) in which the dust-laden stream is flowing are determined without allowance for the presence of particles in the gas, then the nozzle will, in fact, operate in the underexpanded regime (the region $p_s/p_b > 1$ in Fig. 3). When the theoretical regime is determined using equilibrium mixture formulas, the nozzle will operate in the overexpanded regime (the region $p_s/p_b < 1$ in Fig. 3).

Figure 4 shows photographs of compression shocks behind the nozzle in a flow of air without particles and in a dust-laden stream obtained with identical total degree of expansion. It may be seen that a bridge-type shock occurs in both the dust-laden and single-phase flows.

The bridge-type shock in the dust-laden stream (with equal total pressures in the single-phase and dust-laden streams, at the nozzle entrance section) is located further upstream than in the single-phase flow. The reason is, apparently, that in the entrance section of the nozzle, the velocity of the gas phase of the mixture is less than that of the gas without particles.

It is clear that this difference will be greater, the greater the particle mass fraction, and the more vigorously the particles are entrained by the gas (the smaller the particles). The photographs obtained confirm this. Thus, in the flow more heavily laden ($m = 0.5$) with smaller (fraction 40) particles (Fig. 4c), the shock location differs more from its value in the flow without particles (Fig. 4a), than in the less laden ($m = 0.3$) flow with larger (fraction 400) particles (Fig. 4b).

NOTATION

p^*—total pressure upstream of nozzle; p_b—back pressure; p_s and p'—static pressure at nozzle exit section and at section ahead of exit section; $\pi = p^*/p_s$—degree of expansion in nozzle; $\pi = p^*/p_b$—total degree of expansion; π_{min}—minimum value of π at which p_b has no influence on p_s; $\bar{\pi}_s$—ratio of degree of expansion of gas phase of mixture to degree of expansion of air; p_s/p_b—degree of noncalculability; M_a and M_p—mass flowrate of air and particles, respectively; $m = M_p/(M_a + M_p)$—mass fraction of particles in flow; d_m—mean particle diameter; c_p, c_v, and c_K—specific heat of air (at constant pressure and constant volume) and of particles, respectively; ω—velocity of equilibrium mixture; λ—ratio of flow velocity to critical velocity; F—geometrical area of nozzle cross section; R—gas constant of gas phase of dust-laden stream; T^*—stagnation temperature of equilibrium mixture.

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Baranov Central Aircraft Engine Institute, Moscow