PRODUCTION AND INVESTIGATION OF SUPERSONIC JETS OF RAREFIED GAS

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A brief description is given of the facility, measuring instruments and experimental technique. Experimental data is presented on hypersonic jets of rarefied gas, obtained by discharge of a gas from Laval nozzles, micro-nozzles and porous plates.

The investigation was carried out in a low-density wind tunnel, with maximum pumping speed of 57,000 l/sec in the pressure range 10^{-2}-10^{-3} torr. The facility (Fig. 1) was equipped with a remote-controlled, three-position traverse mechanism 25, capable of being positioned to an accuracy of 0.01 mm by means of a type KM-8 indicator. Flow visualization was accomplished by means of a glow discharge generated in the space between two metal plates to which a voltage of 5 to 6 kV was applied. The working gases used were N_2, CO_2 and He which were supplied to the fore-chamber through the inflow system, comprising the filters 11 and 12 and the drier 13. Heating of the gas to avoid condensation was accomplished by means of an ohmic tubular heater [1]. The gas flow rate in the inflow system was recorded by type RS-3 rotameters 14. The flow stagnation pressure was measured in terms of the fore-chamber pressure as a function of the readings on the following instruments:

a) a standard class 0.6 manometer 3 with a measurement range 0-4 kg/cm^2;

b) the U-tube manometers 5, 4, filled with dibutyl phthalate with specific weight γ = 1.041 g/cm^2 at 20°C, or with mercury;

c) the standard vacuum gauge 2.

The total pressure in the jet behind the shock was measured by means of a flat-faced cylindrical gauge 24. For measurement of total pressure in the range 0.1-5 torr a U-tube manometer 23, was used filled with dibutyl phthalate. In the pressure range 10^{-1}-10^{-2} torr a type LT-2 thermocouple gauge 22 and a type VT-2A vacuum gauge 21 were used. The displacement of the meniscus of the liquid column from its initial position was measured with a cathetometer to an accuracy of 0.01 mm. In the experiments heads with exterior diameters of 8, 5, 3, and 2 mm were used, all with ratio of external to internal diameter of 0.75. A correction to the flow density was computed in terms of the parameter Re_d/M according to the method described in [2]. The static pressure in the stream was measured by means of a conical gauge with cone semi-angle of 10°. The stagnation temperature was assumed to be the gas temperature in the fore-chamber, which was measured by means of a chromel—alumel thermocouple 15 and recorded by a type EPV-2 potentiometer 1. The fore-chamber pressure was measured by means of a thermocouple 17 and ionization gauge 18, and recorded by means of a type VIT-2 vacuum gauge 19. Coarse measurements of the fore-chamber vacuum were taken by means of the standard vacuum gauge 20. The usual source of supersonic homogeneous isentropic flow of rarefied gas was a Laval nozzle. The usual method of calculating nozzles was employed to construct an ideal nozzle, and the profile subsequently corrected for displacement thickness.

In order to calculate an ideal nozzle from the equations relating the mass flow to the gas parameter at the throat, one can use the following expression for the mass flow of air through a nozzle [3]:

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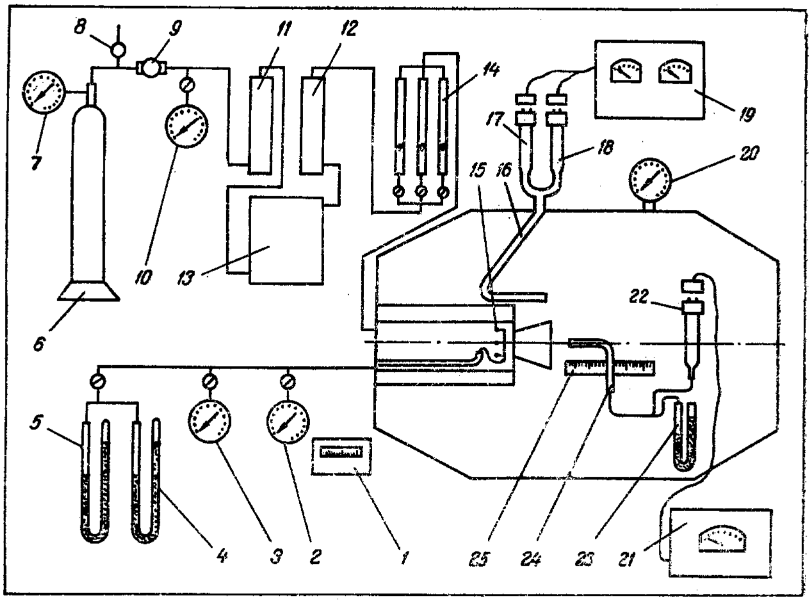

Fig. 1. Switching circuit for measuring instruments: 1) type EPV-2 potentiometer; 2) vacuum reference gauge; 3) reference manometer; 4) mercury U-tube manometer; 5) oil U-tube manometer; 6) bottle; 7) manometer; 8) gauge for measuring inflow from atmosphere; 9) reducing valve; 10) manometer; 11, 12) filters; 13) drier; 14) type RS-3 rotameters; 15) thermocouple rake; 16) chamber pressure measurement tube; 17) type LT-2 gauge; 18) type LM-2 gauge; 19) type VIT-2 vacuum gauge; 20) standard vacuum gauge; 21) type VT-2A vacuum gauge; 22) type LT-2 gauge for measuring the total pressure P_0'; 23) oil U-tube manometer for measuring pressure P_0; 24) Pitot tube; 25) traverse unit.

$$G = \frac{0.4 P_0 F g(M)}{\sqrt{T_0}}, \tag{1}$$

where

$$g(M) = M\left(\frac{k+1}{2}\right)^{\frac{k+1}{2(k-1)}} \Big/ \left(1+\frac{k-1}{2}M^2\right)^{\frac{k+1}{2(k-1)}}, \tag{2}$$

Taking into account that for air at T = 300 K,

$$G = 1.55\cdot 10^{-6} N, \tag{3}$$

we obtain

$$F = 2.85\cdot 10^{-3}\,\frac{S_p C \dfrac{P}{P_0}\sqrt{T_0}}{g(M)}, \tag{4}$$

where

$$C = \frac{P_p}{P} = \frac{P_p}{P_d}\,\frac{P_d}{P_c}\,\frac{P_c}{P} = C_1 C_2 C_3. \tag{5}$$

Here $C_1 = P_p/P_g$ is determined by the losses in the pipe leading from the facility to the pumps, $C_2 = P_d/P_c$ is the pressure increase in the diffuser, and $C_3 = P_c/P$ is the discharge factor. If we neglect the pipe losses, take the discharge coefficient to be 1, and omit the diffuser, C = 1. After finding F, we determine the throat area from the isentropic expansion formula [3]:

TABLE 1. Nozzle Parameters

M	T°, °K	300	500	800	1000
2	D, mm	227	315	353	374
	d_{crit} mm	203	230	257	273
	P_0, torr	$3{,}9\cdot10^{-2}$	$3{,}9\cdot10^{-2}$	$3{,}9\cdot10^{-2}$	$3{,}9\cdot10^{-2}$
	T, °K	167	277	445	555
4	D, mm	159	180	201	214
	d_{crit} mm	49	55,4	62	65,8
	P_0, torr	0,76	0,76	0,76	0,76
	T, °K	71,4	119	190	236
8	D, mm	82,5	92,5	107,5	112,5
	d_{crit} mm	5,98	6,7	7,75	8,15
	P_0, torr	50	50	50	50
	T, °K	21,6	36,0	57,60	72
10	D, mm	67,5	75,0	85	92,5
	d_{crit} mm	2,9	3,22	3,65	3,98
	P_0, torr	200	200	200	200
	T, °K	14	24	28	47
15	D, mm	33,2	43	54,3	60,7
	d_{crit} mm	0,452	0,585	0,684	0,825
	P_0, torr	667	667	667	667
	T, °K	6,6	11	17	22

$$\frac{F}{F^*}=\frac{1}{M}\left[\frac{2}{k+1}\left(1+\frac{k-1}{2}M^2\right)\right]^{\frac{1}{2}\frac{k+1}{k-1}}. \tag{6}$$

Values of D, d_{crit}, p_0 and T were calculated for various Mach numbers and stagnation temperatures, for $P_p = P = 5\cdot10^{-3}$ torr and S_p = 57,000 l/sec which corresponds to conditions for ideal pumping of the vacuum system with mass flow G = 0.5 g/sec. The results are shown in Table 1.

It can be seen from Table 1 that the exit diameter of an ideal nozzle falls off rapidly with increase in M, and depends appreciably on the stagnation temperature T_0. We used this method to calculate and construct two conical nozzles for M = 4 (D = 180) and M = 8 (D = 94), with opening angles of 90° in the subsonic part, and 30° in the supersonic part. These nozzles were used for a series of experiments to study the effect of the gas parameters in the fore-chamber on the flow, the effect of cooling of the nozzles with water near the throat and cooling by means of liquid nitrogen in the supersonic region. A Pitot tube was used to study the distribution of total pressure along the axis and over various cross sections of the jet. Figure 2 shows the dimensionless pressure profiles P_0'/P_0, taken at the nozzle exit for M = 8. Here curve 1 corresponds to discharge of air with stagnation temperature T_c = 300°K, and curve 2 corresponds to stagnation temperature T_0 = 600°K. Curve 3 refers to discharge of air with stagnation temperature T_0 = 600 °K, with the nozzle walls cooled to T_0 = 100°C. In all three cases the size of the isentropic core remained practically unchanged, but with cooling of the nozzle walls it was observed that the total pressure field in the isentropic core became more uniform. With cooling of the nozzle walls (M = 4) an increase in diameter of the isentropic core of roughly 10% was observed, along with the improvement in the core pressure profile. The results indicated that the jet core diameter remained practically unchanged over a significant length of the jet and was of the order 42% of the nozzle exit diameter at M = 4, and 39% for M = 8. The Mach number distribution was calculated from the pressure fields measured. The results show that the transverse Mach number gradient was negligibly small, and the horizontal gradient dM/dx was of the order 0.05 per cm. The nozzles were investigated under different conditions. In the experiments with the M = 8 nozzle the fore-chamber pressure (P_0) was varied from 20 to 59 torr, the chamber pressure (P_c) was varied from $5\cdot10^{-3}$ to $1.4\cdot10^{-2}$ torr, and the mass flow rate G from 0.2 to 0.6 g/sec, while the variation in M did not exceed 0.2. Similar results were obtained for the M = 4 nozzle. In the region selected for the tests, the jets with mass flow rate G = 0.5 g/sec, produced in the Laval nozzles, had the parameters shown in Table 2. Here

$$\mathrm{Kn}_\delta = \frac{\bar{l}}{\delta} \cong \frac{M}{\sqrt{\mathrm{Re}}}. \tag{7}$$

Further increase in the Mach number of jets obtained using Laval nozzles would require a substantial increase in the flow rate, entailing an increase in the power of the pumping system. This can be

TABLE 2. Nozzle Jet Parameters with G = 0.5 g/sec; T_0 = 600°K

D, mm	d_{crit} mm	x, mm	y, mm	P_0, torr	Re_{cm}	$\bar{M}$	$\frac{d\bar{M}}{dx}$, 1/cm	$\frac{d\bar{M}}{dy}$, 1/cm	Kn_δ
180	52	150 $x<190$	$-40<y<40$	0,71	173	4	0,02	0	0,3
96	6	$90<x<130$	$-30<y<30$	63	250	8	0,04	0,02	0,5

TABLE 3. Parameters of Jets from Micro-Nozzles with G = 0.5 g/sec; T_0 = 600°K

P_{crit}, mm.	x, mm	y, mm	P_0, torr	Re_{cm}	$\bar{M}$	$\frac{d\bar{M}}{dx}$, 1/cm	$\frac{d\bar{M}}{dy}$, 1/cm	Kn_δ
1	$100<x<150$	$-30<y<30$	255	314	14	0,4	0,21	0,787
2	$100<x<250$	$-40<y<40$	645	490	17	0,14	0,1	0,77
3	$50<x<150$	$-20<y<20$	1980	1170	19	0,8	0,5	0,557

TABLE 4. Parameters of Jets from Porous Plates with G = 0.5 g/sec; T_0 = 600°K

Porous plate	K, Darcy	x, mm	y, mm	P_0, torr	Re_{cm}	$\bar{M}$	$\frac{\Delta\bar{M}_{max}}{\Delta y}$, 1/cm	$\frac{d\bar{M}}{dx}$, 1/cm	Kn_δ
I	0,066	$100<x<200$	$-40<y<40$	1054	475	22	0,1	0.3	1,01
II	0,64	$100<x<200$	$-40<y<40$	655	350	20	0,1	0,3	1,07
III	30	$100<x<150$	$-35<y<35$	41	100	10	0,1	0,26	1

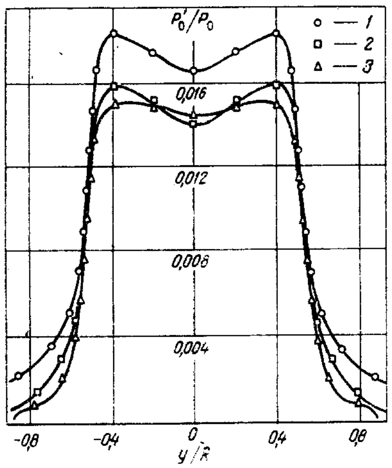

Fig. 2

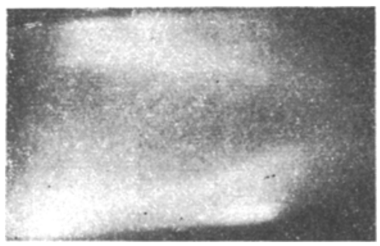

Fig. 3

Fig. 2. Dimensionless stagnation pressure profile at the nozzle exit for M = 8: 1) at T_0 = 300°K; 2) 600°K; 3) 600°K with liquid nitrogen cooling of the sublayer.

Fig. 3. Visualization of an under-expanded jet of nitrogen discharging from a micro-nozzle with d_{crit} = 3 mm (P_0 = 255 torr; T_0 = 600°K)

avoided by turning to other methods of obtaining hypersonic jets. One method for obtaining low density high Mach number flow is to use free underexpanded jets. In this event the jet discharges either through an aperture in a thin wall, or through a micro-nozzle. In the experiments here micro-nozzles were used with throat diameters of 3, 2, and 1 mm. The general configuration of the jets and the nature of geometry of the shocks were investigated by a visualization method. A typical luminous picture of an underexpanded jet of nitrogen discharging through a micro-nozzle with d_{crit} = 3 is shown in Fig. 3. The longitudinal and transverse Mach number gradients in the jets are rather large, the maximum value being on the order of 1/cm. However, near the Mach disk there is a zone of smallest gradients. In the regions chosen for the tests the jets obtained from micro-nozzles had the parameters shown in Table 3.

The next step was to investigate jets obtained with discharge through porous plates. We investigated three types of porous plates, I, II, and III, with different permeabilities. The investigations showed that a discharge through a porous plate is similar in nature to an underexpanded jet, with characteristic barrel-shaped suspended shock waves and a Mach disk.

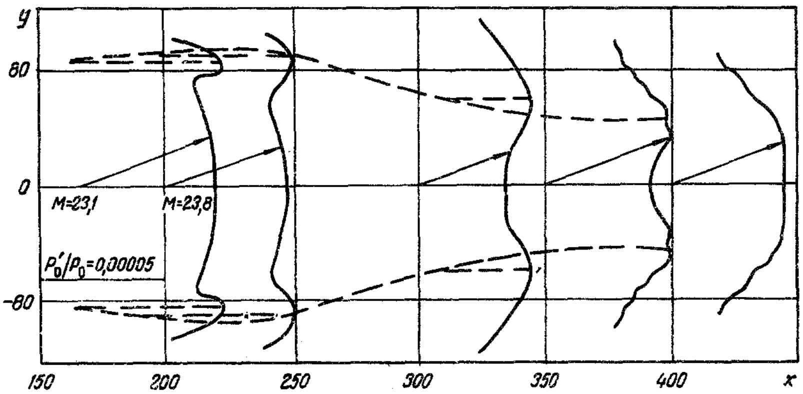

Fig. 4. Discharge of nitrogen from porous plate I with P_0 = 1055 torr; T_0 = 600°K (x, y in mm).

Figure 4 shows a typical distribution of the total pressure field in a discharge from porous plate I. The results show that the maximum diameter of the isentropic part of the jet is about 140 mm, and the distance to the Mach disk is about 350 mm. The porous plates II and III with larger permeabilities were also investigated. The results are shown in Table 4. It can be seen that a porous plate can be used to obtain quite a uniform flow with a considerable region of isentropic core.

Comparing the results one can conclude that to obtain supersonic flow at small M (M < 10) without gradients, the Laval nozzle is the most suitable. To create hypersonic flow of a rarefied gas it is expedient to use an underexpanded jet or discharge from porous plates, and the flow downstream of porous plates gives smaller gradients of M in the jets than for discharge from micro-nozzles.

NOTATION

Re_d, Reynolds number, referred to the external diameter of the Pitot tube; D, nozzle diameter; δ, boundary layer thickness; P_0, stagnation pressure; T_0, stagnation temperature; T_w, temperature of nozzle wall in the supersonic part; F, area of nozzle exit section; S_p, pumping speed at the pump inlet points; N, volume flow rate, referenced to a pressure of 1 torr; P_p, pressure at the pump inlet orifices; P_d, pressure in the diffuser; P_c, chamber pressure; F^*, area of nozzle throat; P_0', stagnation pressure behind normal shock; Re_{cm}, Reynolds number referred to 1 cm; $\overline{M}$, x average of axial Mach number for a given section of the jet; l, mean free path; dM/dy, transverse Mach number gradient for a given jet section, averaged over x and y; dM/dx, longitudinal Mach number gradient for a given jet section, averaged over x and y; Kn_δ, Knudsen number, referenced to δ; ΔM_{max}, maximum variation in M in the core for a y variation of 10 mm; h, thickness of porous plate; d_{pl}, plate diameter; K, porosity of plate; k, ratio of specific heats; R, nozzle exit radius.

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