5. J. A. Ackroyd, "A study of test time in reflected shock tunnels," ARC CP, No. 883 (1967).
6. T. Ikui and K. Matsuo, "Investigation of the aerodynamic characteristics of the shock tube," Bull. JSME, 15, No. 82 (1972).
7. M. Dawn, "Experimental investigation of high enthalpy flow in a shock tube," Raket. Tekh. Kosmon., No. 8, 9 (1969).
8. A. K. Oppenheim, P. A. Urtiew and A. J. Landerman, "Vector polar method for the evaluation of wave interaction processes," Arch. Budowy Masz., 11, No. 3 (1964).
9. H. O. Amann, "Experimental study of the starting process in a reflected nozzle," Phys. Fluids, Suppl. 1 (1969).
10. H. O. Amann, "Vorgänge beim Start einer ebener Reflexiondüse," Z. Flügwiss., 19, 393 (1971).
11. G. M. Rudakova and A. P. Shashkin, "Computation of some two-dimensional unsteady gas flows," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 3, Issue 1, 70 (1975).
12. R. F. Chisnell, "The motion of a shock wave in a channel, with application to cylindrical and spherical shock waves," J. Fluid Mech., 2 (1957).
13. L. Bernstein, "Equilibrium real-gas performance charts for a hypersonic shock-tube wind-tunnel employing nitrogen," ARC CP, No. 633 (1961).
14. R. A. Alpher and D. R. White, "Flow in shock tubes with area change at the diaphragm section," J. Fluid Mech., 3, 457 (1958).
15. W. Chester, "The diffraction and reflection of shock waves," J. Mech. Appl. Math., 7, Part 1, 57 (1954).

EXPERIMENTAL INVESTIGATION OF TOTAL FLOW AND DIRECTIONAL DIAGRAMS IN DISCHARGE OF GAS TO VACUUM THROUGH CAPILLARIES OF DIFFERENT LENGTHS

S. T. Barashkin, B. T. Porodnov, and M. F. Chemagin

UDC 533.6.011.8

An experimental investigation of discharge of gas into a vacuum through cylindrical channels over a wide range of source gas pressure is of interest, since this phenomenon finds wide application in both engineering and scientific research [1, 2]. In discharge of gas from a channel into vacuum different flow conditions are found, from viscous to free-molecular, and this makes the problem very different from the well-studied problem where gas flows with negligibly small pressure differences in comparison with the average pressure, and complicates theoretical study.

The flow of gas through cylindrical capillaries with different ratios of length to diameter l/d has been studied by various authors (e.g., [3-7]). In [3, 4] an unsteady flow method was used, in which the pressure drop in the channel is considerably less than the average pressure. A large pressure drop in the channel was allowed for in [5]. However, in that paper the author restricted his study to an intermediate flow regime. To describe the observed results, as a rule, one uses either semiempirical formulas [3, 4], or quite rigorous theoretical formulas, obtained for a limiting viscous flow regime [6]. At present there are no theoretical papers describing gas discharge into vacuum through a cylindrical channel under arbitrary flow conditions.

The directional diagrams (the angular distribution of the molecular beam intensity) have been investigated experimentally by various authors (e.g., [8-10]). A rather complete study of molecular beams was conducted in [11], where the directional diagrams were measured for an ammonia beam over a wide pressure range and for channels of different lengths. The results obtained agree satisfactorily with theoretical calculations made in [12]. Later, the problem of generating molecular beams was studied theoretically in [13].

The present paper presents results of a systematic experimental study of the influence of geometric dimensions of circular capillaries and the nature of the gas on the total molecular flow and the shape of the directional diagrams of molecular beams of hydrogen and carbon dioxide. The results obtained have been compared with available theoretical data.

Sverdlovsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 4, pp. 74-80, July-August, 1977. Original article submitted June 28, 1976.

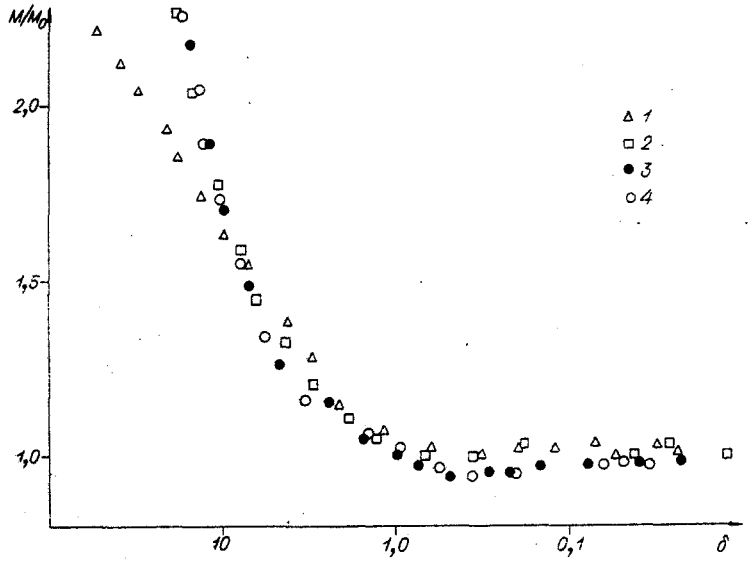

Fig. 1

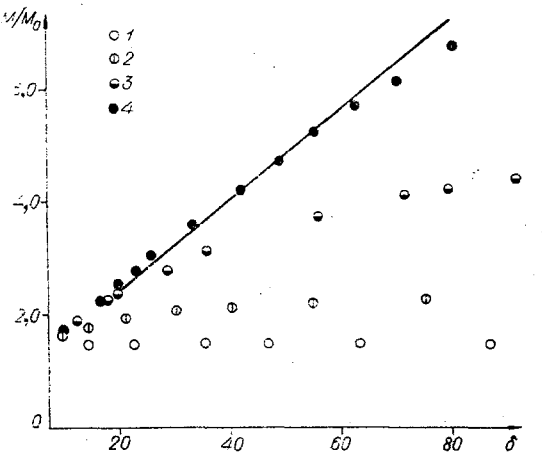

Fig. 2

Experimental Technique

The experiments were conducted in fused glass capillaries of radius 0.199 and 0.287 cm, with ratios of length to diameter l/d = 0.02, 0.980, 5.33, and 24.1, respectively. The test channel was welded to a source flange, fastened to a rotating plate. In the setting-up process the axis of the exit section of the channel was made coincident with the axis of rotation, and the channel axis was mounted perpendicular to the axis of rotation. Constant pressure was maintained in the source by means of a flowmeter, a glass vessel of constant section, located in a volume of gas and floating freely in diffusion oil. To avoid an appreciable change of gas pressure in the upper cavity of the volume above the glass, due to it becoming evacuated as the gas discharged, the cavity was joined to a vessel of capacity ∿130 liters.

The gas flow through the source channel was determined from the rate of evacuation of the glass. During the measurements the gas pressure in the source was maintained constant to within 1-1.5%. The error in measurement of total gas pressure was not greater than 2%.

The absolute pressure of the gas in the source was measured by a volumetric differential micromanometer with a digital sensitivity of $\sim 1.1 \cdot 10^{-6}$ torr/Hz [14]. The gas pressure above the glass of the flowmeter was measured by oil and mercury manometers. The gas discharged from the source was carried out into a vacuum cavity in which the gas pressure was held constant at 10^{-5}-10^{-6} torr. In order to measure the directional diagram of the molecular beam we used a modulation method of detection, described in [14]. The detector was an ionization converter with an inlet aperture of ∿2.7 mm, rigidly attached at a distance of ∿20 cm from the beam source. The signal was recorded using a digital voltmeter and autorecording potentiometer. The reproducibility of the results was not worse than 4-5% in the large-angle region (60-80°).

The investigations were carried out in carbon dioxide and hydrogen in the Knudsen number range (Kn = λ/R) from 50 to 0.003, at a source gas temperature of 293°K. The molecular mean free path λ was calculated from the viscosity coefficient for solid spherical molecules according to the gas pressure in the source.

Comparison of Results and Discussion

Figures 1 and 2 show the experimental data from measurement of total molecular flux of carbon dioxide and hydrogen through the channels investigated, expressed as the dimensionless flux M/M_0 as a function of the parameter

$$\delta = \frac{\sqrt{\pi}}{2} \frac{1}{\mathrm{Kn}},$$

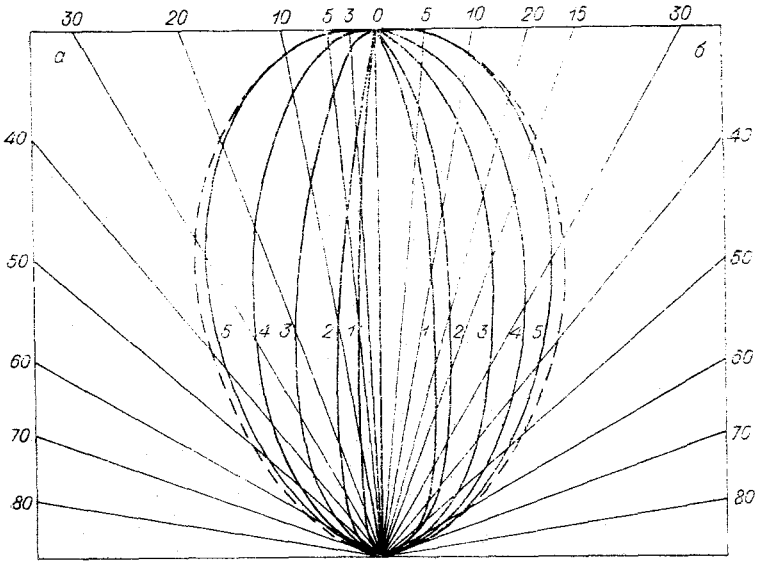

Fig. 3

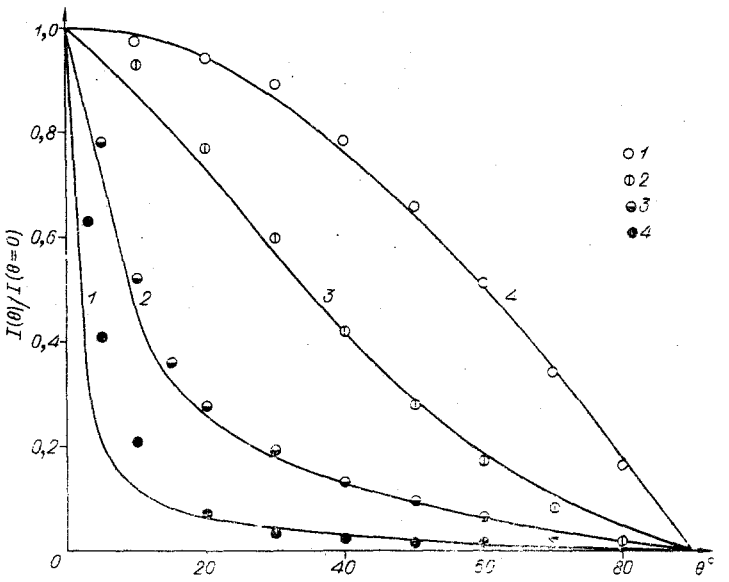

Fig. 4

where M is the experimental flux of molecules; M_0 is the flux as calculated from a formula for free-molecular gas flow in a channel of finite length of the form

$$M_0 = \frac{1}{4}\frac{p}{kT} v_t S W.$$

Here p is the gas pressure in the source; $v_t = (8kT/\pi m)^{1/2}$ is the average molecular velocity of the gas; S is the cross-sectional area of the channel; and W is the probability that molecules will pass through the channel. The probability W was found from [15] for capillaries with l/d = 0.98 and 5.33, and the values were 0.5188 and 0.1910, respectively. For a capillary with l/d = 24.1 the probability of passing was taken from [16] and was 0.0502.

As can be seen from Fig. 1 [1 and 2 refer to carbon dioxide, l/d = 0.98 and 5.33, respectively; and 3 and 4 refer to hydrogen and carbon dioxide (l/d = 24.1)], in the free-molecular limit the ratio M/M_0 becomes unity for all the channels (to within 3-4%). In the channel with l/d = 24.1 a slight minimum was seen in the gas flow rate in the range δ = 1-0.1, typical for long capillaries. In the other (short) capillaries no minimum flow rate was observed. Also, the values of M/M_0 for carbon dioxide and hydrogen for the channel with l/d =

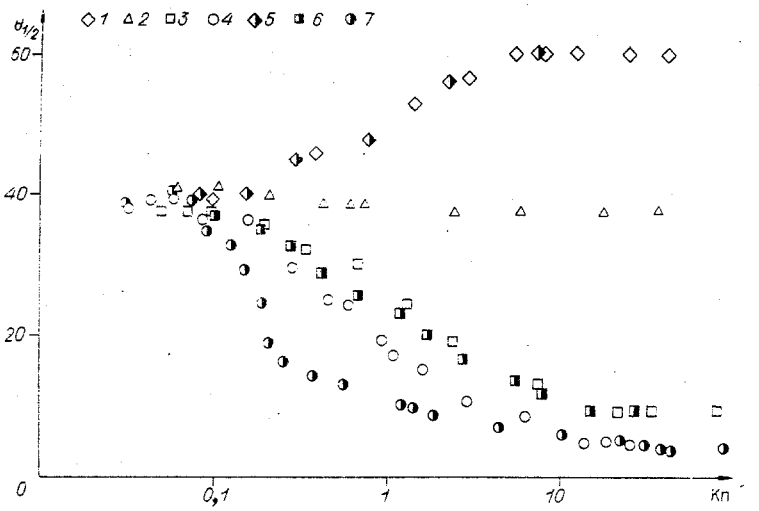

Fig. 5

24.1 coincide within the limits of experimental error over the whole range of δ investigated, which is evidence that the flow rate is independent of the kind of gas.

Figure 2 shows the experimental dependence of the ratio M/M_0 for carbon dioxide as a function of δ in a viscous flow regime with slip (1-4, l/d = 0.02, 0.98, 5.33, and 24.1, respectively; the solid line corresponds to the theoretical formula obtained in [17] under the assumption that the pressure drop is small compared with the average pressure). It can be seen that for an aperture (l/d = 0.02) in the region δ > 10, the ratio M/M_0 remains constant within the experimental error, which is evidence that the volumetric gas flow rate is independent of the pressure in the source, i.e., that the gas discharge through the aperture has reached sonic conditions (the so-called Euler limit). With increase of l/d the dimensionless flow rate M/M_0 increases. The rate of increase M/M_0 with increase of δ diminishes in the short capillaries with δ = 20-40, and for the long capillaries (l/d = 24.1) it remains practically constant over the whole test range δ > 10. However, in the case with δ > 80 a reduction in the rate of increase M/M_0 is observed. One would expect that for the long capillaries sonic conditions for gas discharge into vacuum would occur. Unfortunately, the experimental technique and the method of measurement did not allow us to study this gas discharge regime.

Figures 3 and 4 show the directional diagrams of the molecular beam of carbon dioxide in the form of relative beam intensity $I(\theta)/I(\theta = 0)$ as a function of the angle θ. The angle θ is reckoned from the axis of symmetry of the molecular beam. Figure 3 shows the experimental shape of the directional diagram of the molecular beam of carbon dioxide as a function of Knudsen number for capillaries with l/d = 24.1 (Fig. 3a, 1-5, Kn = 25.7, 6.12, 1.10, 0.271, and 0.0324, respectively) and l/d = 5.33 (Fig. 3b, 1-5, Kn = 33.0, 7.46, 1.31, 0.34, and 0.0496, respectively). It can be seen that the directional diagrams expand to a limit with decrease in Knudsen number (the dashed line in Fig. 3a, b), calculated from a Troitskii formula [12], of the form

$$I(\theta)/I(\theta = 0) = \cos^{5/2}\theta.$$

A comparison of the results in the different channels shows that while the directional diagrams for channels of different l/d differ appreciably at large Knudsen numbers (free-molecular limit) (for a channel with l/d = 24.1 the molecular beam has a clearly marked direction), in the viscous flow regime the directional diagrams are identical and close to the limit.

Figure 4 compares the theoretical and experimental directional diagrams for carbon dioxide in a flow regime close to free-molecular (Kn > 20) for the different channels (1-4, l/d = 0.02, 0.98, 5.33, and 24.1, respectively). Curves 1-3 were calculated from a formula proposed in [13], and curve 4 corresponds to a cosine law for distribution of molecular beam intensity, describing free-molecular discharge of a gas into a vacuum through a perfect orifice.

In contrast with the short capillaries, for the long capillary ($l/d = 24.1$) a noticeable difference is observed between the experimental and theoretical directional diagrams (curve 1), particularly in the small angle region ($\theta < 20$). Evidently, the reason for this difference is that the theoretical calculations are predicated on free-molecular conditions, both along the radius and along the channel, and also that there are no intermolecular collisions in the beam itself. However, in the experiment the free-molecular flow condition (Kn > 20) is achieved only along the capillary radius.

Figure 5 shows the hemispherical directional diagram of a molecular beam $\theta_{1/2}$ as a function of Knudsen number for the various channels (1-4, carbon dioxide, $l/d = 0.02$, 0.98, 5.33, and 24.1, respectively; 5-7, carbon dioxide). The hemispherical diagram is determined by the angle $\theta_{1/2}$ for which the beam intensity is one-half of its intensity on the axis. A comparison of the results shows that while the hemispherical directional diagram decreases for channels with $l/d > 1$ with increase of Knudsen number (the diagram contracts), it increases for channels with $l/d < 1$ (the diagram expands). For all the channels for $Kn \to 0$ (the viscous limit) the half-width tends to the limit [12], equal to 38-40°.

In the analysis of the results obtained it was observed that the shape of the directional diagram (and also the half-width) for a long capillary ($l/d = 24.1$) depended on the nature of the gas. This difference in the diagrams is greatest in the intermediate flow regime, where the diagrams for hydrogen are narrower than for carbon dioxide. The difference in the diagrams for hydrogen and carbon dioxide is shown in Fig. 5. It should be noted that no such deviation was observed for the short capillaries. Apparently, this difference in the diagrams is due both to interaction of the gas with the channel walls and also to collisions of gas molecules with each other in a rather narrow beam formed by a long channel. A qualitative examination of the influence of intermolecular collisions on the shape of the molecular beam confirms this observed fact. In fact, at the same gas density in the beam and, therefore, at the same number of intermolecular collisions per unit volume, the directional diagram will evidently be wider for the gas which has a larger cross-sectional area for molecular scatter.

LITERATURE CITED

1. N. F. Ramsay, Molecular Beams, Oxford University Press (1956).
2. A. M. Brodskii and V. S. Leonas, Investigations with Molecular Beams [in Russian], Mir, Moscow (1969).
3. L. M. Lund and A. S. Berman, "Flow and self-diffusion of gases in capillaries," J. Appl. Phys., 37, Part 1, 2489 (1966).
4. A. M. Lund and A. S. Berman, "Flow and self-diffusion of gases in capillaries," J. Appl. Phys., 37, Part 2, 2496 (1966).
5. A. K. Sreekanth, "Slip flow through long circular tubes," in: Rarefied Gasdynamics, Vol. 1, New York—London (1969).
6. R. W. Hanks and H. L. Weissberg, "Slow viscous flow of rarefied gases through short tubes," J. Appl. Phys., 35, 142 (1964).
7. A. K. Sreekanth, "Transition flow through short circular tubes," Phys. Fluids, 8, 1951 (1965).
8. G. R. Hanes, "Multiple-tube collimator for gas beams," J. Appl. Phys., 31, 8171 (1960).
9. J. C. Johnson, A. T. Stair, and J. L. Pritchard, "Molecular beam formation by long parallel tubes," J. Appl. Phys., 37, 1551 (1966).
10. J. A. Giordmain and T. C. Wang, "Molecular beams formed by arrays of 3-40 diameter tubes," J. Appl. Phys., 31, 463 (1960).
11. A. I. Naumov, "Experimental investigation of the directivity of a molecular beam of ammonia," Zh. Tekh. Fiz., 33, No. 11, 127 (1963).
12. V. S. Troitskii, "Directivity of a molecular beam formed by discharge of a gas from a channel," Zh. Tekh. Fiz., 32, No. 13, 488 (1962).
13. I. G. Neudachin, B. T. Porodnov, and P. E. Suetin, "Formation of narrow molecular beams by cylindrical channels," Zh. Tekh. Fiz., 42, No. 15, 1069 (1972).
14. A. A. Tarin, S. T. Barashkin, B. T. Porodnov, and P. E. Suetin, "Use of a modulation method to detect molecular beams," Zh. Tekh. Fiz., 46, No. 1, 162 (1976).
15. W. G. deMarcus, The Problem of Knudsen Flow, UCNC K-1302, Oak Ridge, Tennessee (1956).
16. A. S. Berman, "Free-molecule transmission probabilities," J. Appl. Phys., 36, 3356 (1965).
17. S. K. Loyalka, "Thermal transpiration in a cylindrical tube," Phys. Fluids, 12, 2301 (1969).