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FORMATION OF SUPERSONIC MOLECULAR BEAMS BY MEANS OF A SKIMMER

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One of the main problems in forming a molecular beam from a supersonic stream of low-density gas by the method in [1] is eliminating the distortions that arise from the interaction of the (forward) flowing stream with the skimmer.

Most investigations (see surveys [2, 3]) have been devoted to studying distortions of the intensity (density) of the molecular beam, while at the same time there has been almost no study in the literature of the effect of the skimmer interaction on the molecular velocity distribution function or its normalized moments (velocity of the flow and the forward-moving temperature). This reflects the narrow focus of the above studies, the principal purpose of which was to obtain molecular beams with extreme parameters: maximum intensity and minimum divergence [4].

One important recent trend is the investigation of relaxation processes in supersonic streams using a molecular beam [5, 6]. Thus, the study of mechanisms leading to distortions of velocity distribution functions and the search for conditions under which such distortion will not occur are prerequisite to expanding the scope of such investigations.

The present work is devoted to analysis and generalization of the results of experimental studies of the effect of skimmer interaction on the velocity distribution function conducted by the authors on a low-density gasdynamic tube at the Institute of Thermophysics of the Siberian Department of the Soviet Academy of Sciences equipped with a molecular-beam system [7]. The system has an apparatus providing for measurement of both parallel $T_{\parallel}$ (time-of-flight method of [8]) and perpendicular $T_{\perp}$ (electron-beam method of [9]) temperature. In all of the experiments, the working gas was commercially pure nitrogen.

1. The aim of the first series of measurements was to find the conditions under which the forward-moving temperature T would not be distorted by the interaction of the flowing stream with the skimmer. We made measurements of transverse profiles of the density of the molecular beam with a wide range of nozzle-skimmer distances x/d_*, stagnation pressure p_0, and the diameters of the inlet cross section of the skimmer d_s. In this work, the stagnation temperature was $T_0 = 293°K$, the diameter of the nozzle throat d_* was 2.11 mm. The design and dimensions of the skimmers used are detailed in [7]. We used the transverse profiles to determine density on the axis of the molecular beam n_b and the velocity relation $S_{\perp}$. The perpendicular temperature $T_{\perp}$ was computed from $S_{\perp}$ on the assumption that the hydrodynamic velocity was equal to the limiting velocity of the flow for known stagnation conditions.

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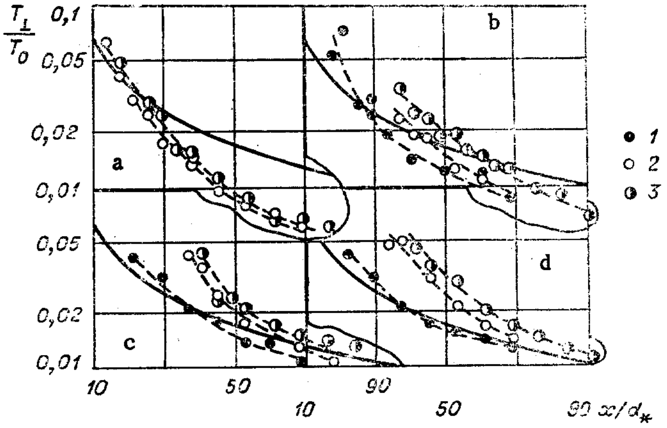

Fig. 1

Figure 1a-d shows the change in the resulting values of $T_\perp$, normalized for stagnation conditions T_0, in relation to distances x/d_* for four stagnation pressures: p_0 = 50, 246, 450, and 550 mm Hg, respectively. The solid line shows isentropic values of temperature (henceforth, estimates were made using the heat capacity ratio $\varkappa = 1.4$). The measurements at all values of p_0 were made under reproducible conditions using three skimmers of diameter d_s = 0.18, 0.81, and 1.54 mm (points 1-3, respectively). The exception was a mode with p_0 = 50 mm Hg, in which no measurements were made with d_s = 0.18 mm. As can be seen from the graph, the empirical curves have a steeper slope and intersect the theoretical curve further from the nozzle, the greater the value of p_0. At pressures of 550 mm Hg or more, throughout the entire measurement range the empirical curves asymptotically approach the theoretical nowhere intersecting the latter. On the other hand, the results show a clear dependence on the skimmer cross section: The measured values of temperature are systematically lower for a skimmer of lesser diameter.

Such a change in perpendicular temperature may be explained by the presence of two effects: skimmer interaction, and freezing of the forward-moving degrees of freedom of the molecules. The effect of skimmer interaction should be considered with increasing stagnation pressure and as the nozzle is approached. It is also evident that this effect will be more pronounced for larger-diameter skimmers. Freezing of the relaxation process, according to the data obtained for monatomic gases [10], leads to separation of the forward-moving temperature into parallel and perpendicular temperatures. Here, the perpendicular temperature deviates downward from the isentropic estimate, i.e., it decreases more rapidly with an increase in the distance from the nozzle edge. With an increase in pressure in the nozzle prechamber, freezing of the relaxation process occurs at large values of x/d_*.

The results shown in Fig. 1 can be explained within the framework of these two effects. At high values of local density in the flow, the skimmer interaction effect predominates. In the other limiting case, at low densities, the main difference in the measured temperature from the calculated isentropic temperature is due to freezing of forward-moving relaxation.

As is known, a change in the intensity of the molecular beam under the influence of skimmer interaction is described by means of the criterion Kn_s/M, where the Knudsen number Kn_s characterizes the degree of dispersion of the beam molecules in the region of the inlet section of the skimmer, while Mach number M characterizes the sensitivity of the recording system to this dispersion [11]. According to the results shown in Fig. 1, it should be expected that the effect of skimmer interaction on the forward-moving temperature as well can be successfully described by means of a certain Knudsen number, computed from the local length of the free path of the molecules normalized for a geometric dimension characteristic of skimmer interaction. The diameter of the inlet section of the skimmer can serve as such a characteristic dimension for this case also. This dimension is more convenient to use for generalizing that the relaxation process in the flow may be independent of it. Actually, such a generalization was obtained in [12] for the perpendicular velocity relation $S_\perp$ relative to Kn_s. It was found that with a fixed stagnation pressure, i.e., under conditions identical with respect to the relaxation process (as noted above, d_*, T_0 = const), the empirical points for all investigated skimmer diameters lay on a generalized curve.

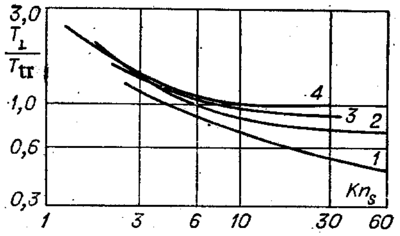

Fig. 2

Figure 2 shows an example of the dependence of perpendicular temperature $T_\perp$, normalized for the corresponding theoretical values T_{isen}, on the number Kn_s for several values of stagnation pressure. Curves 1-4 represent averages of empirical data for three skimmer diameters: d_s = 0.18, 0.81, and 1.54 mm. As can be seen from the graph, curves 2-4 (p_0 = 246, 450, and 550 mm Hg, respectively) converge with a decrease in Knudsen number, i.e., with an increase in skimmer interaction. Curve 1 (p_0 = 50 mm Hg) lies somewhat below the others. For maximum p_0, perpendicular temperature approaches the isentropic value with an increase in Kn_s. At $Kn_s \geq 10$, perpendicular temperature follows the isentropic curve, with empirical scatter not exceeding 5%. Separation of the curves at large Knudsen numbers is due to a difference in the relaxation process for different stagnation pressures. Actually, the lower the pressure p_0, the lower the number Kn_s at which the deviation from the general curve takes place. Finally, for p_0 = 50 mm Hg, freezing of forward-moving relaxation is evidently substantial even within the region of strong skimmer interaction.

Freezing of relaxation is slight for curve 4 within the entire measurement range. In this case, the deviation of the measured values of perpendicular temperature from the calculated isentropic temperatures is due to the effect of skimmer interaction alone. The latter, in turn, becomes insignificant at $Kn_s > 10$. Thus, the molecular beam method has been used to determine the condition under which undistorted information is obtained on forward-moving temperature.

The resulting condition significantly limits the range of applicability of the method in studies of nonequilibrium processes in supersonic streams, since even with skimmers with an inlet-hole diameter ~0.1 mm we cannot make measurements within the region of densities above ~10^{15} cm^{-3}. There are serious technical problems connected with further reductions in the diameter of the inlet hole. We will therefore examine other ways of expanding the applicable range of the method below.

2. The results of measurements of the velocity distribution function made at numbers $Kn_s < 10$ may be "purified" of the effect of skimmer interaction. In fact, we can plot a curve of correlations by combining the empirical data in Fig. 2 in the region of low Knudsen numbers into a general dependence on Kn_s, then using the corrected curve to account for the effect of skimmer interaction on the gasdynamic parameters of the flow.

The simplest method of obtaining a corrected curve involves the use of the fact that forward relaxation is accelerated with an increase in stagnation pressure. Consequently, with an increase in p_0 we may achieve conditions under which the "true" temperature is equal to the theoretical isentropic temperature, $T_{tr} = T_{isen}$. It was found in the present study that no freezing of forward temperature occurs throughout the entire measurement range with pressures $p_0 \geq 500$ mm Hg. Thus, the dependence of the ratio $T_\perp/T_{tr}$ on Kn_s at p_0 = 550 mm Hg may serve as the curve of corrections for skimmer interaction. This dependence is shown in Fig. 3 by a solid line.

There is one other method that can be used to obtain a corrected curve. As shown by the results in Figs. 1 and 2, skimmer interaction decreases with a decrease in skimmer diameter. Thus, skimmer interaction will be negligibly slight at some value d_s, and as the latter approaches zero the perpendicular temperature should approach the true value. This fact can be used to plot corrected curves. Most of the empirical results obtained with a skimmer having d_s = 0.18 mm lie within the range $Kn > 10$, i.e., in a range free from distortions associated with skimmer interactions. In such a case, these results may be taken as "true" values. With a fixed distance from the nozzle, the difference between empirical data for other skimmers and the "true" values can be attributed to skimmer interaction. Then all the empirical results can be replotted in the form of a Knudsen number dependence of the ratio of the perpendicular temperature for a given skimmer $T_\perp$ to the corresponding temperature for

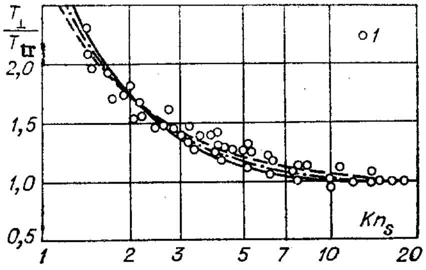

Fig. 3

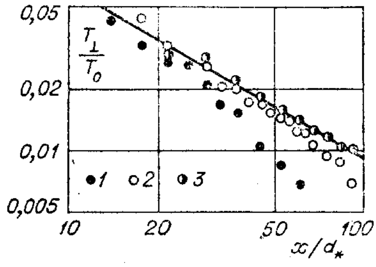

Fig. 4

a skimmer of minimum diameter T_{min} ($T_{min} = T_{tr}$). This dependence should also characterize the correlation for skimmer interaction.

The results of plotting such a dependence are shown in Fig. 3 (points 1); the dashed line shows the correlation curve plotted from averaged empirical data. It is apparent that the corrected dependences obtained by the two methods agree well with one another. The slight difference may be due to the fact that at a stagnation pressure $p_0 = 550$ mm Hg the isentropic temperature only approximately corresponds to the true temperature, as well as to the fact that the results of measurements with a skimmer of minimal diameter do not completely coincide with the true values. The general (averaged for the two methods) curve is shown in Fig. 3 by the dot-and-dash line.

An example of measurements of perpendicular temperature $T_\perp/T_0$, replotted with allowance for the correction factors, is shown in Fig. 4 for three stagnation pressures: $p_0 = 50$, 250, and 550 mm Hg (points 1-3, respectively). The data for small distances from the nozzle lie on the isentropic curve (solid line). With an increase in x/d_*, the perpendicular temperature deviates from the isentropic and declines more abruptly, particularly at lower stagnation pressures. Such a path for the curves in Fig. 4 corresponds to the occurrence of forward relaxation.

3. In accordance with current concepts, skimmer interaction may be conditionally classed as internal or external. External skimmer interaction is caused by the appearance of a gas cloud in front of the leading edge of the skimmer formed by molecules reflected from the outer surface of the skimmer and by particles dispersed earlier. Internal skimmer interaction is caused by dispersion of the molecular beam into particles that collide with the inside walls of the skimmer.

The parameters of the gas cloud in front of the skimmer depend on conditions in the flowing stream, the shape and dimensions of the skimmer, and the quality of its outside surface. Thus, the number of collisions occurring between molecules of the flowing stream and gas-cloud particles in nearly independent of the diameter of the skimmer inlet hole, which is small compared to the diameter of the base and other overall dimensions of the skimmer. On the other hand, the shape of the molecular beam cut by the skimmer and the number of collisions between beam particles and the inside surface of the skimmer depend heavily on the Knudsen number, calculated from the diameter of the skimmer inlet hole. Consequently, generalization of the empirical data for different skimmer diameters in relation to Kn_s shows that internal skimmer interaction plays the main role in distortion of the parameters of the distribution function. However, direct proof of this cannot be obtained from the above-described experiments.

To study the processes being discussed here in more detail, we conducted an experimental investigation of the effect of perturbation of the flow in front of the skimmer on the parameters of the molecular beam. To this end, the gas cloud in front of the skimmer was simulated by a shock wave formed by an impact support. The density of the dispersing particles in front of the skimmer tip was varied by shifting the support with the aid of a coordinate mechanism relative to the stationary skimmer. Here we recorded the density of the gas in front of the leading edge of the skimmer and the velocity distribution function for the molecular beam. A detailed description of the equipment used in the experiment and the raw data obtained are presented in [13]. It was found that with an increase in the size of the dispersing gas cloud in front of the skimmer, i.e., with increasing penetration of the skimmer into the shock wave formed by the impact support, the density on the axis of the molecular beam decreased sharply. However, the form of the velocity distribution function, normalized to unity at the maximum, and, thus, the normalized moments of the function remained the same throughout the entire investigated range of parameters of the flowing stream.

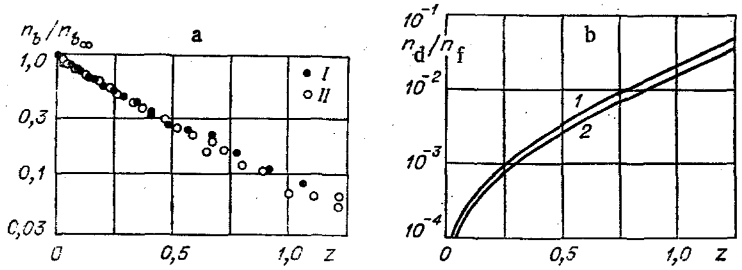

Fig. 5

The above-described effect is explained as follows. The geometry of the molecular-beam system [7] was chosen in such a way that the beam detector could be reached only by those molecules moving within a low solid angle close to the beam axis. Thus, nearly every collision between a particle of the flowing stream and a particle of the gas cloud in front of the skimmer knocked the collided molecules outside the limits of this solid angle. The dependence of the density of the molecular beam recorded by the detector n_b on the number of such collisions Z is shown in Fig. 5a for two experiment modes differing in the distance between the nozzle and skimmer: points I — data for $x/d_* = 75$, II — for $x/d_* = 55$ (stagnation pressure $p_0 = 350$ mm Hg, diameter of inlet section of skimmer $d_s = 0.81$ mm). The number Z was computed from the formula shown in [13]. Index ∞ denotes conditions in the unperturbed flow. It is easy to see that an increase in the density and length of the gas cloud in front of the skimmer and a corresponding increase in the number of collisions, leading to dispersion of the flowing stream, are accompanied by a sharp drop (by more than an order with a change in Z from 0 to 1) in the particle density recorded by the detector. Unfortunately, the sensitivity of the equipment used in this experiment was such that it was not possible to make measurements with a further drop in n_b, i.e., at numbers $Z > 1.25$.

As the estimates show, simultaneous with a drop in the density of the undispersed particles there is an increase in the flow of "thermal" particles of the gas cloud flowing through the skimmer into the chamber behind the skimmer, i.e., there is an increase in the density of background molecules recorded by the detector. Figure 5b shows the results of calculation of the ratio of densities of background molecules n_d and molecules of the flowing stream n_f at the detector in relation to Z performed on the basis of measurement data using the formulas in [14]. Curve 1 is for $x/d_* = 55$, 2 — $x/d_* = 75$. At the maximum values of Z achieved in the experiments, the ratio n_d/n_f does not exceed ~ 0.05. It should be emphasized that simulation of the external skimmer interaction by a shock wave gives an upper limit of density for the dispersing gas cloud in front of the skimmer that is practically unobtainable in actual experiments.

Thus, primarily undispersed particles of the flowing stream are reaching the detector, with the velocity distribution function here not changing — at least within the limits of measurement error. A similar result should be expected for the distribution of velocities in the plane perpendicular to the axis of the flow, since the solid angle of the detector in the above electron-beam measurements was, as shown by the estimates, 1.6 times less than for time-of-flight measurements. Thus, the presence of the dispersed molecules on the axis of the molecular beam could have made only a slight contribution to the signal at the detector. Consequently, the experiments with the impact support confirm the above assumption that the distortions of the forward-moving temperature observed at Knudsen numbers $Kn_s < 10$ are caused by processes occurring inside the skimmer, i.e., by internal skimmer interaction.

4. There is now a satisfactory explanation for the effects causing deviation of the recorded intensity (or density) of the molecular beam from the expected value [2, 3]. As shown by the results obtained here, changes in the higher moments of the distribution functions of velocity and forward-moving temperatute with skimmer interaction cannot be described within the framework of existing concepts. This is connected with the lack of a perturbing effect by external skimmer interaction on the high moments of the distribution functions, and, thus, the predominance of the effect of internal skimmer interaction on the process of molecular beam formation. Evidently, the process of internal skimmer interaction is due to inefficient evacuation of beam molecules that have collided with the inside surface of the skimmer close to the inlet hole. The dispersed particles, i.e., the particles lost due to collision, may stay within the region of the inlet hole for a fairly long time, thereby further increasing the number of collisions with other particles of the molecular beam. Skinner [15] has called such a process the "avalanche suppression" of the molecular beam.

Thus, in conducting experiments connected with the recording of velocity distribution functions for a supersonic flow by the method of molecular-beam diagnosis, the requirements with respect to skimmer geometry should be somewhat different than those assumed earlier [2]. First of all, under such conditions it is best to use short skimmers with fairly large interior and, thus, exterior angles. This requirement issues from the need to maximize the rate of evacuation of the internal volume of the skimmer in order to prevent the formation of "plugs" inside the skimmer that will "seal off" the molecular beam. Obviously, such suppression of the beam should be less of a problem with a large interior angle for the skimmer. Secondly, there is no need for stringent requirements with respect to the quality of preparation of the leading edge and outer surface of the skimmer. Thus, the reduction in internal skimmer interaction may be achieved even at the expense of increasing the size of the gas cloud in front of the outer surface and inlet section of the skimmer. The main limitation on the magnitude of external skimmer interaction is imposed by the requirement of maintaining the intensity (density) of the molecular beam within limits permitting reliable recording of the velocity distribution function.

All of these requirements may be met by developing a skimmer that is qualitatively different from earlier designs and that takes the form of a conventional hollow conical skimmer, but with a truncated tip, the inlet hole of which is hermetically closed by a very fine, flat end-piece with a central aperture of small diameter. The use of such a skimmer will make it possible to expand the range of measurement of velocity distribution functions, using the molecular beam method, in the direction of higher densities of the flowing stream.

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