LABORATORY
TECHNIQUE

MEASUREMENT OF CROSS-CROSS INTENSITY PROFILES OF A MOLECULAR BEAM

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Abstract. A method for recording the intensity in the cross section of a molecular beam is described and verified. A scheme for accounting for the influence of background gas is proposed and tested. The obtained measurement results in argon and nitrogen flows demonstrated a direct dependence of the shape and width of the transverse profiles of the molecular beam on the Mach number at the skimmer inlet, as well as the average size of clusters under conditions of condensing supersonic jets.

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1. INTRODUCTION

Molecular beams formed from supersonic gas jets flowing into a rarefied space have long been the object of interest of researchers in various fields of science and technology [1–8]. One of the most modern areas is the use of clustered molecular beams. As a rule, experimenters strive to achieve maximum intensity in the axial region of the molecular beam. However, the gas dynamics, as well as the reliable detection of such objects, have not yet been sufficiently studied. In addition to the features of skimming clustered flows, which differs from the thoroughly studied formation of supersonic jets using a skimmer in the absence of condensation [9], many questions arise about the reliability of measurements parameters of a molecular beam by closed (measuring intensity) and open (measuring density) type sensors. For example, mass spectrometry of axial density profiles of a molecular beam under conditions of developed condensation gives completely unexpected results [10]. Measuring the density with a simple open-type ionization sensor in the presence of clusters in a molecular beam gives underestimated density data, including due to the fact that a cluster is, as a rule, a single ion, despite the large number of atoms or molecules that formed it. The most popular methods of mass spectrometry (quadrupole and time-of-flight) with a sufficiently long time interval between the ionization of the analyzed flow and its registration on the detector, due to the disintegration of clusters during ionization, on the contrary, demonstrate an unusually high concentration of monomers. At the same time, in a closed-type detector (usually an ionization-type sensor with a narrow input aperture), the data on the intensity of the molecular beam provide quite reliable information on the total number of particles that have reached the detector due to the effective evaporation of clusters inside the detector, but leave the question of the flow rate at the entrance to the detector uncertain.

The distribution of the intensity or density of the molecular beam across the axis allows not only to study the features of the expansion of the clustered beam and estimate the velocity ratio at the skimmer inlet, but also to consider the gas dynamics of supersonic flows before skimming. Previously, work was carried out on diagnosing the local density across the axis of the molecular beam in flows without clusters [11, 12]. In this paper, a system for diagnosing the intensity under conditions of the formation of molecular beams from supersonic clustered flows is proposed, and the results and problems of such measurements are presented.

2. EXPERIMENTAL EQUIPMENT

The experiments were performed on the LEMPUS-2 experimental gas-dynamic facility of the Applied Physics Department at Novosibirsk State University. Description of the facility, its vacuum and diagnostic capabilities are provided in papers [13-16].

Figure 1 shows a schematic diagram of the measurements. The source of the supersonic jet was a stagnation chamber with interchangeable sonic or supersonic nozzle *1* on a coordinate device *2* placed in the expansion chamber *3*, providing movement in three mutually orthogonal directions *X*, *Y*, *Z*, as well as rotation in the *XY* plane with an accuracy of 10 μm and 0.1 ° respectively. The movement is carried out according to a programmed sequence using stepper motors, also located inside the vacuum chamber *1*. The molecular beam is formed using a conical skimmer *4* with internal and external opening angles of 45 °, 55 °, inlet diameter $d_S = 0.49$ mm and a sharp inlet edge. The coaxiality of the molecular beam system is achieved through careful alignment using a laser beam passing through the nozzle, skimmer, and detector inlet opening at different coordinates along the *X* axis.

Fig. 1. Schematic representation of the measuring section of the LEMPUS-2 facility.

The work used a sonic nozzle and a supersonic nozzle with a conical diffuser section. The nozzle parameters are given in Table 1.

Table 1. Parameters of the nozzles used

Nozzle	d_*, mm	L, mm	d_a, mm	M_a	
				N_2	Ar
1	0.51	–	–	1.0	1.0
2	0.26	3.6	1.5	5.5	8.1

Note: d_* – diameter of the nozzle throat, L – length, d_a – exit diameter of the supersonic nozzle, M_a – Mach number value at the nozzle exit.

The molecular beam detector *5* is installed in the post-skimmer section of the molecular beam system *6* on a single-component coordinate device *7*, which provides movement of the detector across the molecular beam within 150 mm with positioning accuracy of 0.1 mm. A 356 Micro-Ion Plus vacuum pressure sensor was used as a detector in this work, with information from it recorded to a PC via an adapter. To measure the molecular beam intensity, the sensor input is equipped with a diaphragm with a 2 mm diameter hole. Intensity measurements are carried out by sequentially localizing the position of the sensor (input hole of the ionization lamp) at specified distances relative to the molecular beam axis. Simultaneously, the background gas pressure in the post-skimmer section is recorded using a second identical sensor located on the branch pipe of the post-skimmer section away from the molecular beam axis *8*. Prior to measurements, the readings of both sensors in the absence of a molecular beam are verified and reconciled within the measurement range. The difference between the pressure sensor readings on a selected streamline in the molecular beam and in the background space (guaranteed to be outside the influence of the directed particle movement in the molecular beam) is taken as the value of the molecular beam intensity in relative units, provided that the speed of the directed movement in the molecular beam is constant (in hypersonic flows corresponds to the terminal flow velocity).

The gas temperature in the nozzle prechamber, in the expansion chamber, and in the post-skimmer chamber is recorded by a multi-channel Ketotek STC-3008 sensor *9* with an error of less than 0.2%. The gas pressure before expansion is set by the RRG-12 gas flow controller *10* and recorded by a Siemens Sitrans P7MF1564 sensor *11* with an error of 0.25% of the maximum measurable value. The vacuum in the expansion chamber and post-skimmer chamber is provided by a pumping system consisting of turbomolecular and helium cryogenic pumps connected in a parallel configuration. Varying the working gas supplied to the nozzle prechamber, the stagnation pressure and temperature, as well as the angle of rotation of the jet relative to the axis of the molecular beam system, provides the ability to determine the transverse intensity profiles of the molecular beam under different flow conditions (in regimes with Mach numbers $M > 3$). It should be noted that this measurement scheme made it possible to determine the intensity in the cross-section of the molecular beam not only at a fixed nozzle-skimmer distance (and, accordingly, constant background gas pressure in the post-skimmer section), but also when varying this distance, which changes the gas flow through the skimmer and the background pressure value in the post-skimmer section. Thus, it was possible to record the intensity dependence on any streamline in the molecular beam when changing the nozzle-skimmer distance.

3. MEASUREMENT RESULTS

An example of recorded intensity values depending on the distance between the detector's inlet aperture and the molecular beam axis, y_b (in mm), at three distances between the nozzle and skimmer ($x = 25, 45, 60$ mm) is shown in Fig. 2 *a* . The data were obtained during the outflow of nitrogen from sonic nozzle No. 1 (Table 1), at fixed values of temperature ($T_0 = 300$ K) and stagnation pressure ($P_0 = 50$ kPa), as well as the pressure in the expansion chamber ($P_\infty = 0.59$ Pa). The intensity values are given in units corresponding to the readings of the sensor that registers the total signal determined by the molecular beam and background gas in the post-skimmer section. It is worth noting that the range of sensor movement across the molecular beam axis is 150 mm, which allows recording the complete transverse profile and background signal value only on one side of the molecular beam axis. When background signals are subtracted, the dependencies take the form shown in Fig. 2 *b*. Comparable values of useful and background signal intensities increase the measurement error, estimated to be at least 20%; however, as can be seen from the presented graphs, the data scatter due to random noise does not significantly affect the recorded values.

Fig. 2. Experimental values of signal intensity ...

Since relative intensity values of the molecular beam transverse profiles are required for subsequent data analysis, Fig. 3 shows data normalized to unity at the maximum, $I_{norm} = (I - I_b) / (I - I_b)_{max}$. According to the estimate [17], the distance to the Mach disk in these measurements was about 100 mm. The Knudsen number, calculated from the isentropic density value in the jet and the diameter of the skimmer inlet cross-section, at distances of 25, 45, and 60 mm was $Kn_S = 2.6, 8.5, 15$. Therefore, at the distance closest to the nozzle, the influence of internal skimmer interaction [9] on the measurements of transverse density profiles could be expected. As assumed, at a distance of $x = 25$ mm, the transverse profile (dependence on y_b) is significantly wider, which corresponds to a wider dispersion of molecules in the molecular beam and, accordingly, a smaller Mach number. At the same time, as the skimmer moves away from the nozzle and the Knudsen number increases, the influence of skimmer interaction weakens, and the Mach number increases.

Fig. 3. Transverse profiles of molecular beam intensity ...

When argon flows out of a small-diameter supersonic nozzle (nozzle No. 2, table 1) at a stagnation pressure of 100 kPa, cluster formation has practically no effect on flow gas dynamics (the average cluster size, estimated according to [18], is $\langle N \rangle = 4$), therefore the dependence of the transverse intensity profiles in the molecular beam on the distance x differs little from that obtained in nitrogen (Fig. 4). The size of the primary barrel for these flow regimes was over 100 mm, the Knudsen number $Kn_S = 10$ already at the minimum of the considered distances x . A slight broadening of the profile at a distance $x = 40$ mm indicates, apparently, an incomplete process of Mach number growth.

Fig. 4. Transverse intensity profiles of molecular ...

The dependence of the broadening of the transverse profile of the molecular beam not only on the geometric position of the skimmer relative to the nozzle and the isentropic Mach number in the jet, but also on the efficiency of cluster formation is illustrated in Fig. 5, which compares the results for two gases under comparable outflow conditions. In all modes, supersonic nozzle No. 2 (Table 1) was used. Modes with the same distance between the critical section of the nozzle and the skimmer, $x = 60$ mm, were selected. For argon outflow, modes with stagnation pressures differing by a factor of three while maintaining a fixed stagnation temperature were compared. According to the estimate [18], the average cluster size at $P_0 = 100$ kPa is $\langle N \rangle = 60$, at 300 kPa – $\langle N \rangle = 840$. At the same pressure in the nitrogen jet $\langle N \rangle = 15$. Accordingly, the width of the transverse intensity profile of the molecular beam in the nitrogen jet is the largest, and in argon at high stagnation pressure – the smallest.

Fig. 5. Comparison of results with different average cluster sizes.

The obtained experimental data clearly illustrate the possibility to relate the shape and width of the recorded transverse density profiles of the molecular beam with the Mach number at the inlet edge of the skimmer.

4. CONCLUSION

An experimental methodology for measuring intensity in the cross section of a molecular beam in the post-skimmer section of the installation has been developed. A vacuum manometric sensor was used as an intensity detector. A scheme for accounting for the influence of background gas was proposed and tested. Parallel recording of background pressure values in the post-skimmer section provided controlled accounting of the background component's contribution to the useful signal and high reliability of the obtained results. The powerful pumping system of the installation made it possible to conduct research in a wide range of stagnation pressures with nozzles of different shapes and geometric dimensions. The presented measurement results demonstrated a direct dependence of the shape and width of the transverse profiles of the molecular beam on the Mach number at the skimmer entrance, as well as the average cluster size under conditions of condensing supersonic jets. The established reliability of the obtained results allows for further determination of the Mach number, and with knowledge of the directed flow velocity – the translational temperature in the jets under study.

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FIGURE CAPTIONS

Fig. 1. Schematic representation of the measuring section of the LEMPUS-2 test bench: *1* – expansion chamber, *2* – stagnation chamber with nozzle, *3* – 4-component coordinate mechanism, *4* – skimmer, *5* – molecular beam detector, *6* – post-skimmer chamber, *7* – manual coordinate mechanism, *8* – ionization vacuum gauge, *9* – temperature sensor, *10* – flow controller, *11* – absolute pressure sensor.

Fig. 2. Experimental values of signal intensity across the nitrogen molecular beam at three distances x between sonic nozzle No. 1 (Table 1) and skimmer: 25 mm (*1*), 45 mm (*2*) and 60 mm (*3*); ***a*** – integral values, ***b*** – after background signal subtraction.

Fig. 3. Transverse intensity profiles of the molecular beam after normalization to unity at maximum. Conditions are the same as in Fig. 2.

Fig. 4. Transverse intensity profiles of the molecular beam at four distances x between the nozzle and skimmer: 40 mm (*1*), 60 mm (*2*), 80 mm (*3*) and 100 mm (*4*). Argon, supersonic nozzle No. 2 (Table 1).

Fig. 5. Comparison of results at different average cluster sizes: *1* – N_2, P_0 = 300 kPa, x = 60 mm; *2* – Ar, P_0 = 100 kPa, x = 60 mm; *3* – Ar, P_0 = 300 kPa, x = 60 mm.

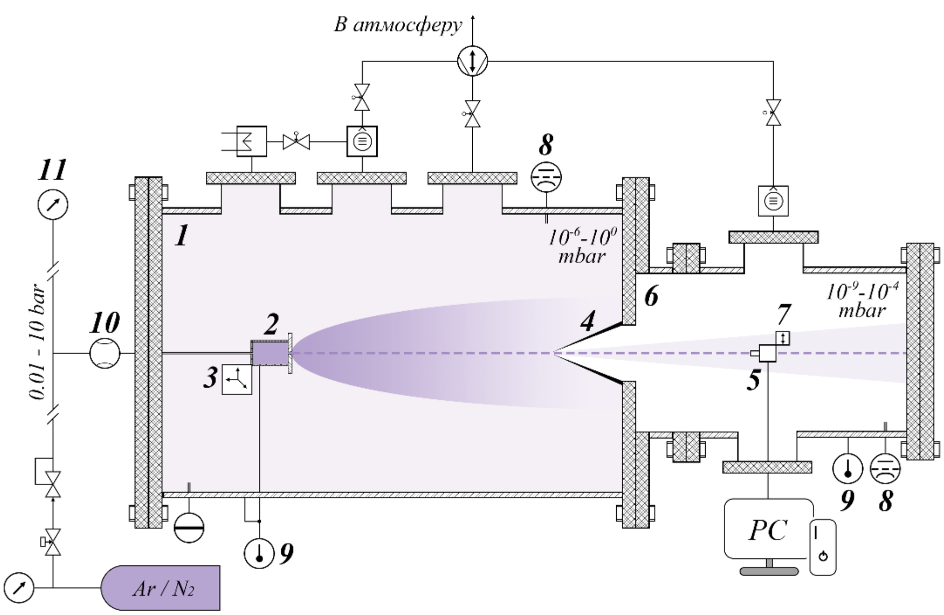


Fig.1

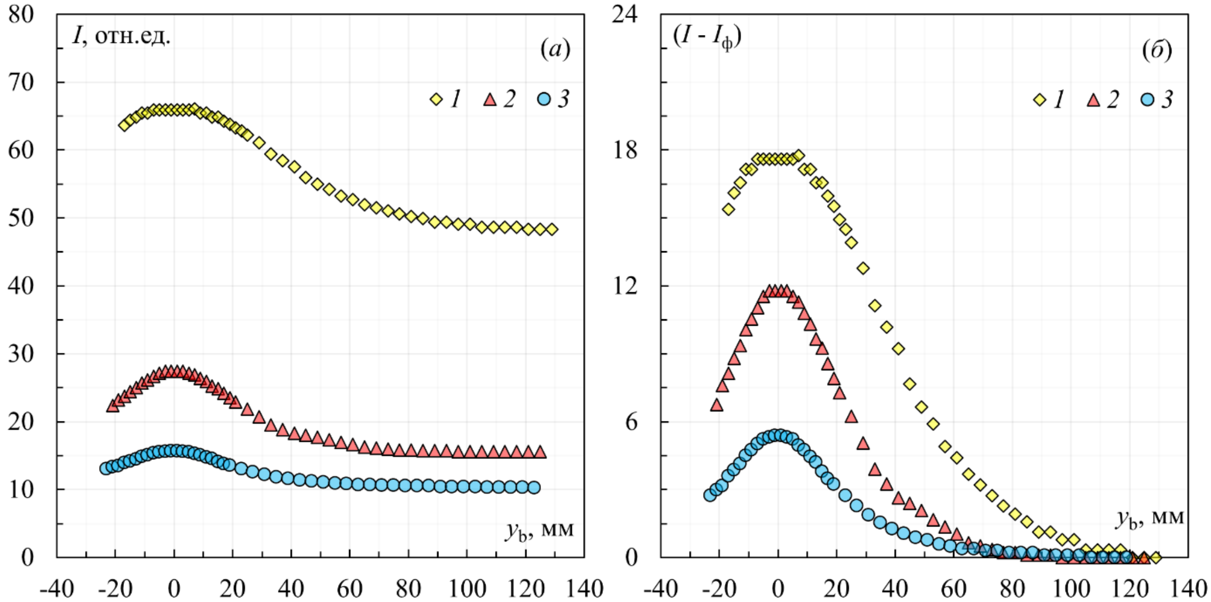


Fig. 2.

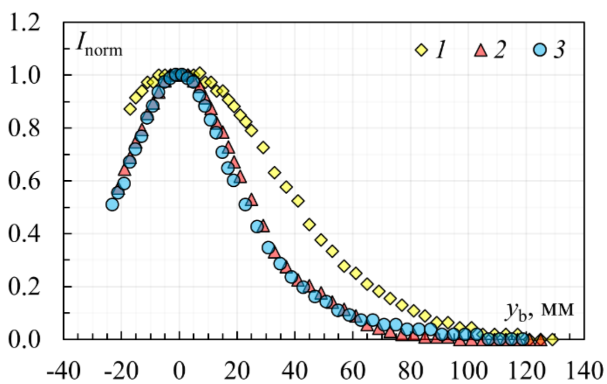
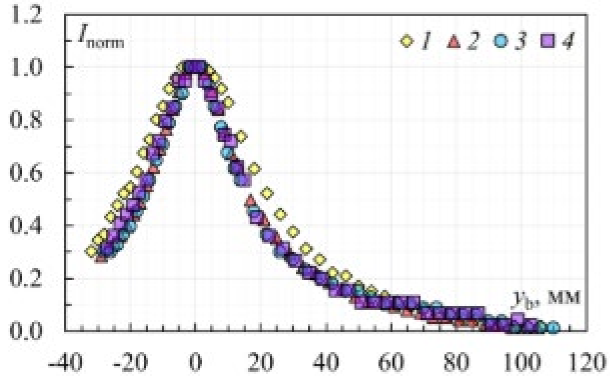


Fig. 3.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I_{norm}
1
2
3
4
1.0
0.8
0.6
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y_b, мм
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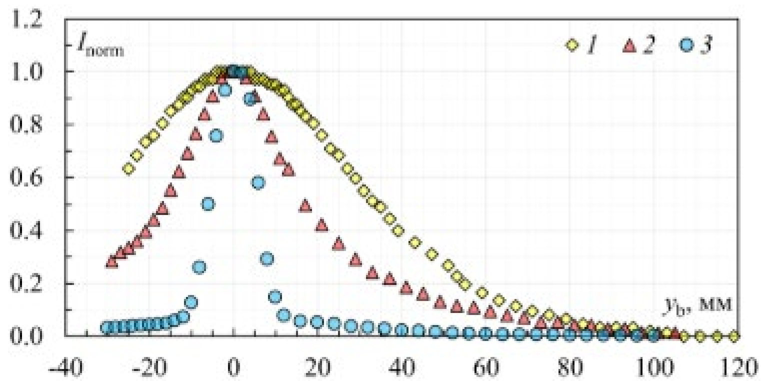
-20
0
20
40
60
80
100
120

Fig.4.


1.2
I_{norm}
1
2
3
1.0
0.8
0.6
0.4
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y_b, мм
-40
-20
0
20
40
60
80
100
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Fig.5