AN EXPERIMENTAL AND NUMERICAL STUDY OF A SUPERSONIC-JET SHOCK-WAVE STRUCTURE

V.I. Zapryagaev[1], A.N. Kudryavtsev[1], A.V. Lokotko[1], A.V. Solotchin[1], A.A. Pavlov[1], and A. Hadjadj[2]

[1]Institute of Theoretical and Applied Mechanics, Siberian Branch, 630090 Novosibirsk, Russia
[2]LMFN-CORIA, UMR CNRS 6614, INSA de Rouen, St. Etienne du Rouvray, France

The investigation of the shock-wave structure and numerical characteristics of supersonic-jet shear layer is of great importance due to numerous applications of supersonic jets in aerospace engineering. In the present work, a detailed study of a supersonic non-isobaric jet aimed at validation and further development of numerical algorithms for jet flow prediction has been carried out. The difficulties in numerical simulation of supersonic non-isobaric jets stem from the necessity of accurate resolution of various flow scales and from the occurrence of multiple shock waves and subsonic pockets interacting with each other.

Although the literature [1, 2] contains many data on the structure of supersonic under-expanded jet flows, accurate verification of numerical predictions requires detailed measurements of the jet structure to be performed at a precise control over supersonic nozzle geometry and jet flow parameters.

The experiments were performed in the jet facility of the Institute of Theoretical and Applied Mechanics (Novosibirsk) operating on cold air (specific heat ratio γ=1.4, stagnation temperature To=287 K). The jet was exhausted into quiescent air with the ambient pressure Ph=1.008 bar and ambient temperature Th=294 K.

The setup (Fig. 1) was a vertically installed plenum chamber with a nozzle fixture assembly provided at center of its head. The inner diameter of the compression chamber, which housed a honeycomb and settling grids, was 330 mm. The inlet diameter of the air pipeline

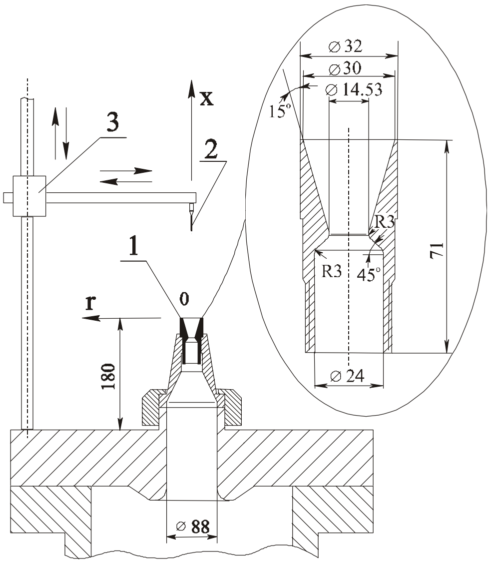

Fig. 1. Scheme of the jet facility used, 1 – nozzle, 2 – Pitot probe, 3 – traversing gear.

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through which the air was supplied to the nozle was 88 mm. The setup was equipped with a traversing gear that allowed us to scan the flow with a Pitot probe both in streamwise and radial directions (in the interval of respective cylindrical coordinates $0< x < 720$ mm and $0< r <50$ mm, respectively.

As a test case, a supersonic jet was selected issuing from a conical nozzle with a 15^o- half-angle at a design Mach number 3.005. The nozzle exit radius was R_a=15 mm, critical diameter Dcr=14.53 mm, and outer nozzle diameter 32 mm.

For the over expanded flow regime, the pressure ratios were $n = P_a/P_h = 0.6$ and $N_{pr} = P_o/P_h = 21.8$ (here P_a is the pressure at the nozzle exit and P_o is the stagnation pressure). The distributions of the Pitot pressure along the jet axis $P_t(x)$ and the radial directions $P_t(r)$ in various jet cross-sections were measured. The Pitot pressure was measured by Siemens pressure sensors KPY45A intended to measure pressure in the pressure range 0 to10 bars, whereas the pressure in the plenum chamber was measured with the Siemens pressure sensors KPY68AK (0 to 160 bars). The experiments were conducted using an automated data acquisition system built around a personal computer and a 12-bit ADC.

Optical visualization of the flow structure in the initial region of the jet at various plenum-chamber pressures was performed with the help of a CV-M10 CCD camera and a TV-signal input system which allowed us to feed the information into the computer with long (1/30 s) and short (~1 microsecond) exposure times.

The schlieren images of the shock-wave structure of the supersonic non-isobaric jet taken with long (1/30 s) and short (10^{-6} s) exposure times are shown in Fig. 2. These images correspond to the following flow regimes: an overexpanded jet with an internal nozzle flow separation; with flow attachment into the nozzle in a supersonic overexpanded jet and a supersonic underexpanded jet. In the obtained pictures, individual elements of the shock wave structure of the supersonic jet are clearly seen. The schlieren photograph taken with the short exposure times also reveals the acoustic waves emitted into the outside surrounding space. Streamwise strips observed in the photographs are worth noting. These strips are due to stationary vortices in the shear layers of both under- and overexpanded supersonic jets. More details about the characteristics of the streamwise vortices can be found in [3, 4].

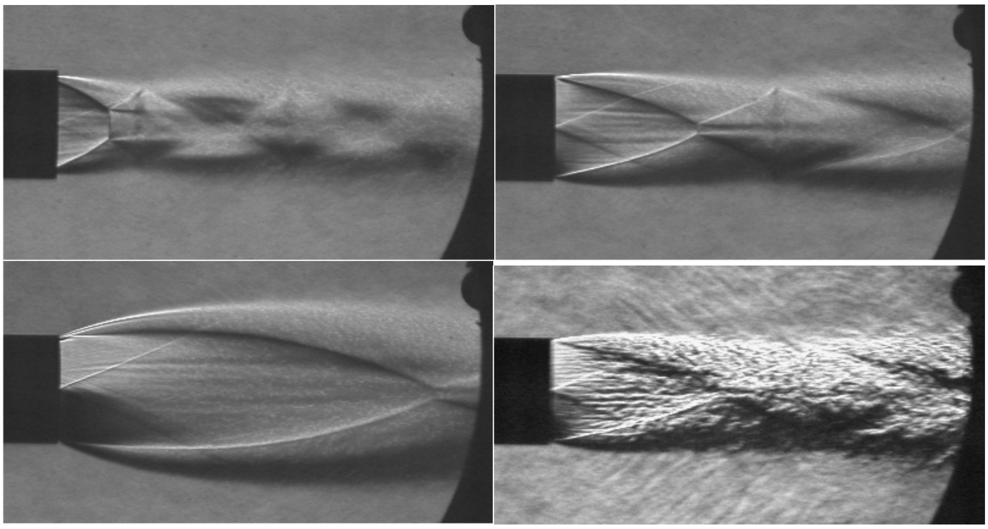


Fig. 2. Schlieren pictures of the supersonic non-isobaric jet taken with a long exposure time (1/30 s) for the pressure ratios n=0.303 (left top), n=0.748 (right top), and n=2.314 (left bottom) and with the short exposure time for n = 0.785 (right bottom).

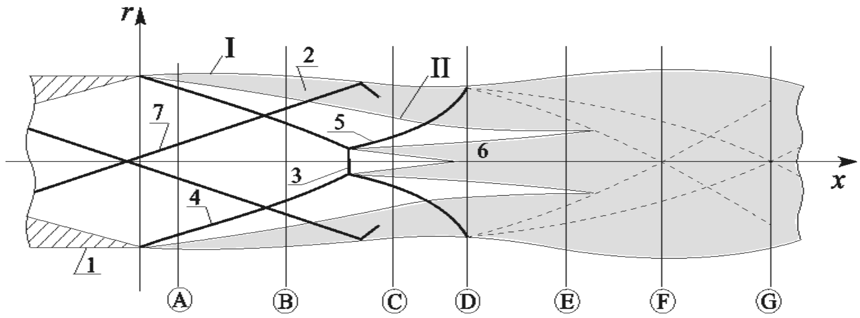


Fig. 3. Scheme of the supersonic over-expanded jet.
1 – nozzle, 2 – jet shear layer, 3 – Mach disk, 4 – compression shock, 5 – reflected shock, 6 – shear layer behind the triple point, 7 – nozzle shock, I, II – outer and inner boundaries of the jet shear layer. A, B…G – cross-sections where the radial Pitot pressure distributions have been measured.

The scheme of the supersonic overexpanded jet exhausting from an axisymmetric conical nozzle is shown in Fig.3. Instead of the barrel shock observed in the underexpanded jet (see, for instance, [2]), a compression shock is registered in the overexpanded jet, which raises the pressure in the outer part of the jet. Another structural feature is a nozzle shock induced by the absence of any profiling in the supersonic part of the nozzle. In the cross-section F the outer shear layer (2, see Fig.3) joins the inner shear layer (6) emanating from the triple point. Thus, already in the second cell of the flow, a fully turbulent jet flow develops.

The distribution of the Pitot pressure along the centerline of the overexpanded jet issuing from the conical nozzle is presented in Fig.4 (circles). The triangles in this figure show the radial distribution of the Pitot pressure. Nine maximums can be distinguished, in good correlation with the nine-cell structure of the jet.

Typical radial distributions of the Pitot pressure in eight characteristic cross-sections of the jet are shown in Fig.5. The same figure shows the dependence of the normalized Pitot pressure P_t/P_h on the radial coordinate r/R_a. A substantial modification of the profile – the sharp gradient of pressure in the first cell of the flow is observed. At x/R_a=0.53 (A) and 1.62 (B) the compression shock, denoted in the figure as BS, is clearly seen. The nozzle shock in the jet flow pattern is also detected by the Pitot probe; it is denoted in the $P_t(r)$ dependence as CR. The reflected shock RS emanating from the triple point is also clearly seen in the $P_t(r)$ plot for the cross-section x/R_a = 2.69 (C). The pressure distribution measured with the Pitot probe in the over expanded jet is characterized in the boundary of the first cell at x/R_a=4.02 (D) by two distinct shear layers, one coincident with the external boundary SL and the other stretching near the jet axis SLI behind the triple point.

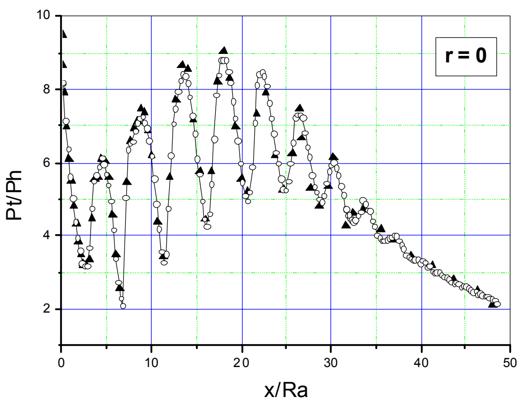


Fig. 4. Distribution of the Pitot pressure along the centerline (r = 0) of the supersonic over-expanded jet.

In the second and other cells, the flow displays smoother Pitot pressure profiles. Simultaneously, the shear-layer thickness increases and the flow exhibits no any sharp variation of measured flow parameters, see Fig. 5 (F, G, H).

The Pitot pressure measured in the jet core is reduces compared to the peripheral part of the jet in the upstream region of the seventh cell, the flow here exhibiting wavy variation of the Pitot pressure.

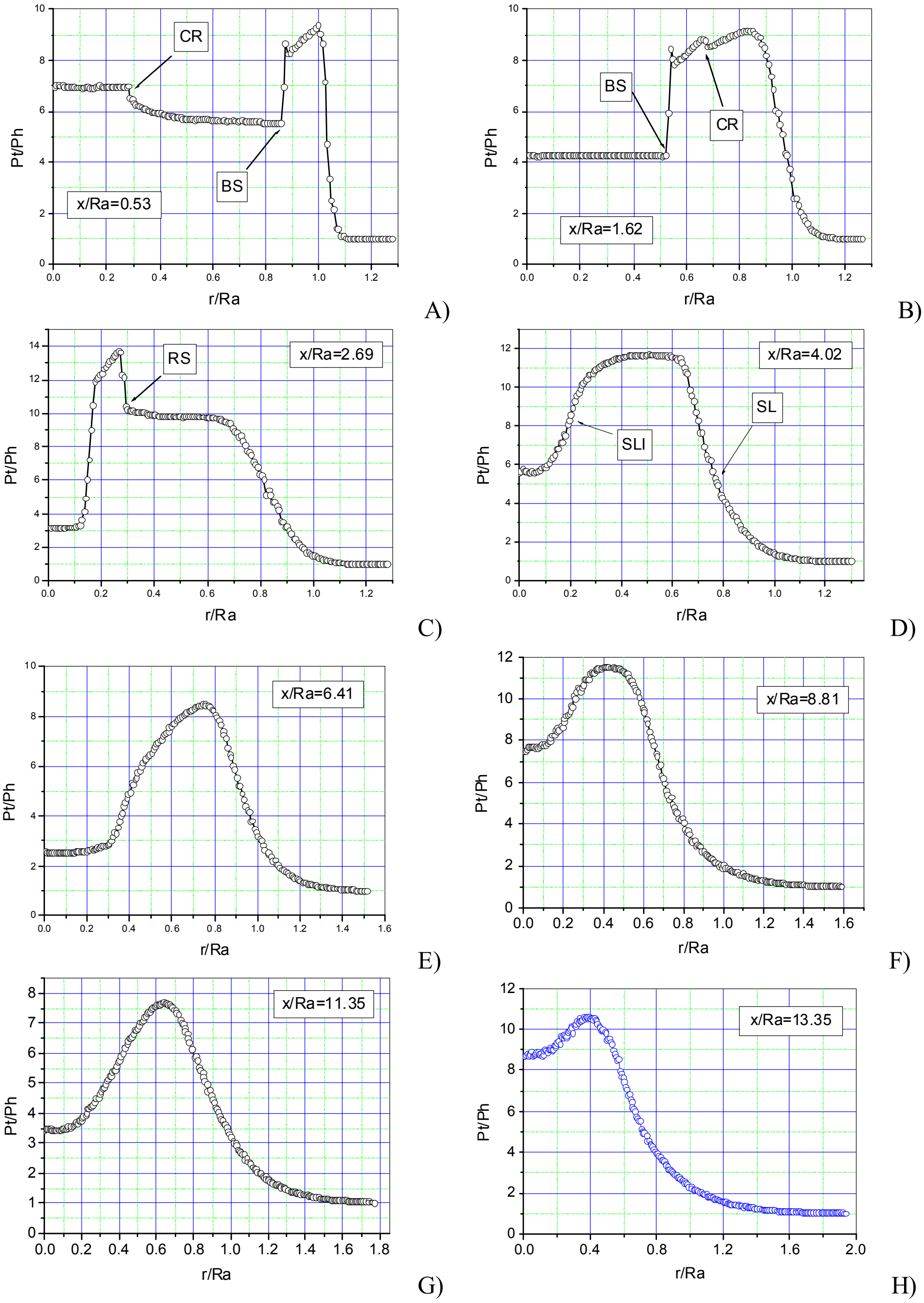
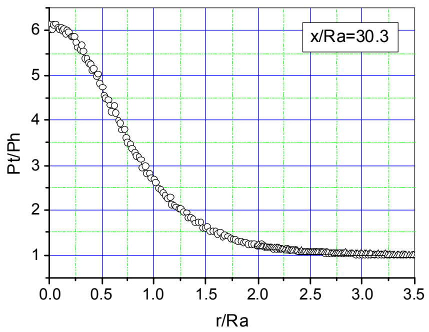
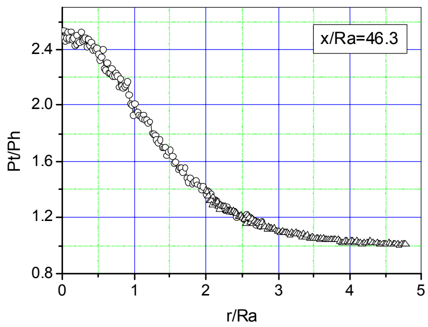


Fig. 5. Radial distribution of the Pitot pressure in the supersonic over-expanded jet measured in various jet cross-sections, M_a=3.005, n=P_a/P_t=0.6.



a)



b)

Fig. 6. Radial distribution of the Pitot pressure in the supersonic over-expanded jet measured at long distances from the nozzle exit x/Ra=30.3 and 46.3, M_a=3.005 n=P_a/P_t=0.6.

The last cells display no peripheral maximums in the radial distributions of the Pitot pressure (x/Ra>30). The radial pressure profile becomes self-similar (see Fig. 6). The peak pressure in the maximum at the axis exerts distinct oscillations. To measure the radial pressure profiles at x/Ra>30, we used two identical Pitot probes spaced apart by 30 mm. In Figure 6, the indications of the inner and outer pressure probes are shows with circles and triangles, respectively. In the region where the data measured by the both probes are available, these data are seen to be in a fairly good agreement.

Within the framework of the present study, numerical simulations of the nozzle and jet flows were carried out. Their first results will be discussed at the presentation.

Conclusions

Detailed experimental data of a complex study of the flow structure of air supersonic over-expanded jet exhausted from an axisymmetric conical nozzle into drowned space have been presented. These data may prove useful in verifying numerical algorithms for predicting the shock-wave structure of supersonic non-isobaric gas jets.

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