RESULTS OF INTERFEROMETER STUDY OF LAVAL NOZZLE

K. K. Kim and D. D. Tomilin

Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 10, No. 4, pp. 105–107, 1969

Interferometric measurement of the air density in a supersonic nozzle of rectangular cross section is described. The flow structure is studied in a real Laval nozzle. It is shown that the core flow follows the laws of motion of an ideal gas and has a wave nature. The relation $\delta_z = (3-4)\delta_y$ is obtained for the boundary layer thickness on the nozzle walls for nozzle width-height ratio $L/h = 3.75-7.5$.

The flow structure in a real supersonic nozzle may differ significantly from the theoretical structure, both because of defects in nozzle fabrication and because of boundary layer growth on the nozzle walls. In many cases it is important to know the parameters of the supersonic flow in the actual nozzle. The determination of these parameters (density ρ, pressure p, temperature T, velocity u, Mach number M) at any section of the nozzle in question is the objective of the present investigation.

1. Specific difficulties arise in Laval nozzle studies, associated with the large air density gradients along the nozzle and the appearance of a diffuse zone of the interference pattern downstream of the throat with approach to the design regime. The diffuse zone appears for small pressure differentials, which are, however, sufficient to establish the sonic velocity at the nozzle throat, and shifts downstream as the pressure ahead of the nozzle increases. A similar pattern is observed in transsonic flow past isolated profiles and cascades [1].

The nozzle segment studied consisted of two steel blocks and two plane-parallel plates made from LK-5 optical glass, which form the other two channel walls. For the sake of simplicity the contour of the supersonic segment of the nozzle was made rectilinear, since the condition of uniformity of the stream at the exit from the nozzle was not crucial. The nozzle was located in the working arm of a Michelson interferometer. The light source was a helium–neon laser with radiation wavelength $\lambda = 0.6328$ micron. The fact that the laser is an ideal monochromatic source simplifies greatly the adjustment of the interferometer. The laser beam was passed through a rotating matte filter in order to obtain a uniform light field.

The setup provided for measuring the total pressure p_0 and the stagnation temperature T_0 of the air entering the nozzle. The pressure was measured by a reference spring manometer and the temperature by a chromel-kopel thermocouple. The atmospheric pressure p_a and temperature T_a were also measured. Taps were provided along the nozzle profile on the upper and lower walls for static pressure measurements. These pressures were measured by means of U-tube mercury manometers mounted on a common board. The pressure measurement method was used as a check in this study.

2. The density ρ at any point of a compressible medium is proportional to the displacement of the interferometric fringe at this point in comparison with its original position and is defined by the formula [2]

$$\rho = \rho_a + CS \quad \left(C = \frac{\lambda \rho'}{2L(n'-1)} = \text{const}\right) \tag{2.1}$$

Here ρ_a is the reference field density (undisturbed atmosphere); S is the fringe displacement; λ is the wavelength of the monochromatic light source; 2L is twice the nozzle width; ρ' and n' are the air density and refractive index at $t = 20°$ C and 760 mm Hg pressure.

The following technique for analysis of the interferograms was devised. The interference pattern, magnified fivefold, was projected on a white paper screen. The nozzle contour and the midpoints of the dark fringes were marked by pencil and the zero-order fringe was identified. The latter is taken to be one of the bands which does not fall in the diffuse interference pattern zone during the disturbance and does not move out of the limits of the field being studied. The reticle of the comparator, mounted on the screen and equipped with a micrometer screw, is set to the center of this fringe. After this the valve of the line through which high pressure air is admitted to the nozzle is opened smoothly. The comparator reticle is displaced to follow the zero-order fringe until the required operating condition is established. The interference pattern of the displaced fringes is observed on the screen during this time.

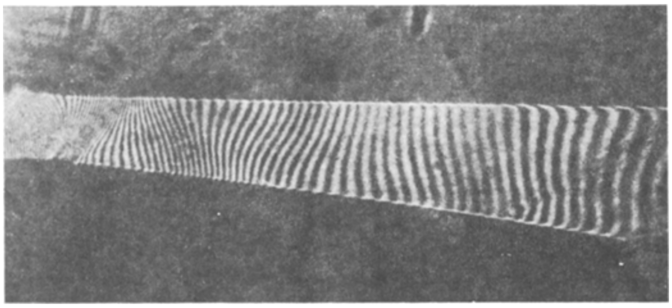

Fig. 1

The midpoints of the dark fringes and the final position of the zero-order fringe are again located. Then the valve is closed just as smoothly and the zero-order fringe is tracked continuously to verify its return to the original position. The interferogram of the displaced fringes is thus aligned with the interferogram of the unperturbed fringes and the correct correspondence is established between the fringe numbers. (Fig. 2).

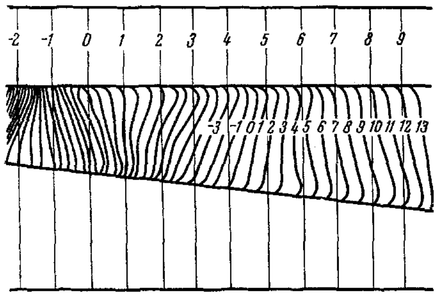

Fig. 2

Analysis of the interferograms reduces to measurement of the displacements S of the interference fringes in the field being studied relative to their original position.

If the flow is isentropic and the stagnation pressure p_0 and temperature T_0 are known, then the remaining flow parameters are determined from the resulting density using the known gasdynamic relations.

We must bear in mind that the interferometric method sums the disturbances along the beam length and does not permit identifying local field nonuniformities. This constitutes the primary error source, since the measurement itself of the fringe shifts can be made with high precision.

The boundary layer growing on the glass side walls causes deviation of the visible pattern from the two-dimensional pattern. Owing to the lower density in the boundary layer the core flow density as determined by the fringe displacement will be lower than its actual value. In fact, the density ρ_e outside the boundary layer is connected with the apparent density ρ, defined by (2.1), as follows [2]:

$$\rho_e = \rho + \frac{2}{L}\int_0^\delta \Delta\rho(z)\,dz \qquad (2.2)$$

Here δ is the boundary layer thickness on the wall; $\Delta\rho(z)$ is the difference of the densities ρ_e in the core flow and $\rho(z)$ in the boundary layer at the distance z from the glass wall.

3. The results of analysis of the interferograms in the ρ/ρ_0 (relative density) and x (distance along the nozzle from the throat section) coordinates are shown in Fig. 3 (points 1 and 2 correspond to the values $p_0 = 3.5$ and 4.1 kg/cm^2; points 3 are the data obtained as a result of analysis of the pneumometric measurements for the same values of the air pressure ahead of the nozzle). The open points correspond to the measurement points along the upper wall of the nozzle, the filled points are for the lower wall.

The nozzle was designed using one-dimensional theory and the method of characteristics without account for boundary layer thickness. The values calculated by the two methods were essentially the same. The difference between the experimental points and the calculated curve does not exceed 5–7%.

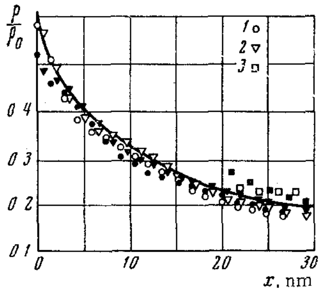

Fig. 3

From visual observations and analysis of the density distribution obtained as a result of reduction of the interferograms, we see that along the nozzle there propagates a weak expansion-wave characteristic for supersonic flow in a two-dimensional channel with a corner point. The expansion-wave movement along the nozzle coincides with the flow pattern obtained by the method of characteristics.

The boundary layer on the metal nozzle walls is clearly defined thanks to the sharp curvature of the interference fringes, and its thickness δ_y amounts to 0.6–0.85 mm at the nozzle exit section for Reynolds number $R_x = 1.35 \cdot 10^6$ and Mach number $M \approx 2$. The boundary layer thickness is negligibly small in the vicinity of the nozzle throat, and it cannot be measured on the interferograms.

These results are in good agreement with the data of [3], where for $R_x = (2.8–3.5) \cdot 10^6$ and $M = 2.3$ the boundary layer thicknesses lie in the range from 0.6 to 1.4 mm. In this case the pressure ahead of the nozzle did not exceed 2–5 kg/cm^2.

An estimate of the boundary layer thickness δ_z on the glass wall, made using (2.2), yields $\delta_z = (3–4)\delta_y$ for $L/h = 3.75–7.5$, where L is the nozzle width and h is its height.

The authors wish to thank V. P. Koronkevich for his assistance in this study.

REFERENCES

1. L. M. Zysina-Molozhen and I. G. Shapiro, "Interferometric study of flow past a compressor profile cascade," Aérodinamika, vol. 27, Mashgiz, Moscow, 1954.

2. R. Ladenburg et al., eds., Physical Measurements in Gasdynamics and Combustion [Russian translation], Izd-vo inostr. lit., Moscow, 1957.

3. R. Ladenburg and D. Bershader, "The laminar and turbulent boundary layers in supersonic flow," collection: Mekhanika [Russian translation], no. 1, 1950.

15 April 1969

Novosibirsk