The influence of dual stream jet nozzle internal parts on the three-dimensional flow structure in a supersonic jet

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Abstract. The work is devoted to the experimental study of a high-speed jet exhausting from a model dual stream jet nozzle, performed using non-contact (shadow visualization) and probe (total-pressure pneumatic receiver) methods for measuring gasdynamic quantities. Azimuthal non-uniformity of the pressure distribution, whose value in the external duct is much higher than that in the internal duct, is revealed. The cause for the formation of the spatial flow structure is related to the supporting pylons inside the nozzle contour and to the occurrence of a transonic flow regime in the external duct.

1. Introduction

The study of the structure of high-speed gas jets exhausting from the nozzles of jet engines is an important problem connected with the problems of reducing the level of the jet emitted acoustic noise and minimizing their impact on aircraft elements. Gasdynamic parameters of the jet substantially depend on the design of the nozzles used for forming the jet flow. Currently, the number of numerical studies of the structure of high-speed jets discharged from single and dual stream jet nozzles has substantially increased. In these studies, in-house numerical codes (such as Zeus in TsAGI) or commercial software packages (such as ANSYS, FlowVision, etc.) are used [1]. In [2], calculations and experiments for a dual stream jet nozzle with blades disposed inside the ducts at various angles to the incident flow were performed. The flows of cold and hot jets exhausted from the nozzle were studied both numerically, using numerical methods for solving the Navier-Stokes equations with the use of Reynolds-averaged equations, and experimentally, by measuring the velocity fields and acoustic characteristics.

In the present study, we carried out an experimental study of the spatial structure of the steady flow of a supersonic jet exhausting from an axisymmetric dual stream jet nozzle, taking into account the real features of the internal structure of the nozzle. The experiments were carried out for supersonic mode of the jet flow. The experimental data include results of shadow visualization of the flow and results of probing the jet flow with a total-pressure pneumatic receiver in radial and azimuthal directions. The purpose of the work was an experimental study of the 3D structure of the flow of a high-speed jet ejected out of a model dual stream jet nozzle and identification of reasons causing the formation of a substantial azimuthal non-uniformity of the flow in the dual-stream jet.

2. Experimental instrumentation

The experiments on studying the 3D flow structure were carried out using the jet module of the T-326 blowdown wind tunnel of ITAM SB RAS, whose description is given in [3]. In the experiment, a total-
pressure probe (Pitot tube with an internal diameter of 0.4 mm) was used for probing the flow. The probe was moved along the three coordinates, X, Y, and Z, using a three-component traversing gear installed in the Eiffel chamber over the nozzle. The range of movement was 0.2 meters along each coordinate.

The flow of the supersonic jets exhausted from the convergent dual stream jet nozzle was visualized using the schlieren method (shadow visualization). In the experiments, a shaped axisymmetric convergent dual stream jet nozzle with a central body was used. The nozzle attached to the settling chamber of the wind tunnel and a diagram of the nozzle with the adopted coordinate system are shown in figures 1a and 1b, respectively.

![Figure 1](image1.png)

**Figure 1.** Photo of the model nozzle installed in the test section of the T-326 wind tunnel (a), the nozzle contours and the adopted coordinate system (b), 1 – external contour, 2 – internal contour, 3 – central body, 4 – supporting pylons, 5 – Pitot tubes.

The nozzle was prepared for collecting the experimental data intended for testing results of numerical studies [1]. The geometric shape of the internal contours of the nozzle was chosen using numerical simulation data.

![Figure 2](image2.png)

**Figure 2.** Dual stream jet nozzle, rear view, 1, 2 - external and internal contours, 3 - pylons, 4 – Pitot tubes, A - probing direction along the pylon, B - between pylons.
The design feature of the nozzle was that at the nozzle exit there were structural elements obstructing the inlet channels of the contours, namely, supporting pylons 3 (3 items) and Pitot tubes 4 for measuring the wall pressure and the pressure at the inlet to the external and internal contours (see items 1 and 2 in figure 2b). The obstruction of the internal channels with pylons and Pitot tubes for both nozzle contours reduces the internal passage area by 17%, both in the internal and external circuits of the nozzle.

The cold air jet exhausted from the convergent dual stream jet nozzle into ambient space. The experiment was carried out in steady gasdynamic regime of the jet flow with pressure ratio NPR = P₀/Pc = 2.25 (P₀ and Pc are the pressures in the pre-chamber and in the test section of the experimental facility). The jet Mach number calculated by the formula for isentropic flow was Mj = 1.14. The stagnation temperature in the settling and the working chamber of the facility varied within the range T₀ = Tc = 282-300 K.

3. Results
Visualization of the jet flow exhausting from the dual stream jet nozzle was performed over the initial length of the flow using a shadow device and a digital camera. Visualization data taken from a supersonic jet at two exposures corresponding to the mean and instantaneous patterns of the flow are shown in figure 3.

![Figure 3](attachment:figure3.png)

**Figure 3.** Schlieren photograph of a dual-stream jet at NPR = 2.25 and Mj = 1.14, time of exposure 10 ms (a) and 4 μs (b).

In this regime, a slightly underexpanded supersonic jet is formed. In addition to the boundaries of the jets exhausting from the shaped nozzle and apart from the wake produced by the central body, the photographs show the shock-wave structure of the flow at the nozzle exit, both in the inner and outer jet. Compression shocks formed at the nozzle exit and accompanying the ejection of the supersonic jet are distinctly seen (Fig. 3, a). Possible reason for the dissipation of compression shocks in the flow region behind the central body is the high turbulence level in the jet stream. At low exposures (figure 3, right), substantial fluctuations of flux density are registered.

Using the traversing gear of the data acquisition system, the radial and azimuthal distributions of total pressure, P(r, φ), measured by a Pitot tube in characteristic cross sections of the jet flow were obtained. The measurements were carried out in two directions from the flow centerline corresponding to the section in front of the pylon and in between adjacent pylons, as shown in figure 2b (lines A and B).

The radial distributions are shown for the cross-section x/Rc = 2.32 (figure 4). The profiles have a similar appearance involving features due to the gas-dynamic structure of the flow. At the centerline, r/Rc = 0, a pressure minimum due to the presence of the separated flow in the wake behind the cone of the central body is registered. Two regions can be distinguished in the graph, the flow regions for
$r/R_a = 0 – 0.38$ and $r/R_a = 0.38 – 1.2$, corresponding to the jet exhausting from the internal and external contour of the nozzle. The local pressure minimum in the region $r/R_a \approx 0.38$ corresponds to the flow in the mixing zone of the inner and outer jets.

One can see a difference between the profiles in the region $r/R_a > 0.4$ occupied by the outer jet. The pressure maximum observed at radius $r/R_a = 0.53$ in front of the pylon (curve 2) is shifted towards the periphery with respect to the maximum in the section between pylons, $r/R_a = 0.45$ (curve 1). The position of the maxima corresponds to the internal boundary of the mixing layer; therefore, it can be concluded that in the cross-section in front of the pylon the jet becomes narrower than in the region between pylons, since the external boundary of the jet observed at radius $r/R_a \approx 1.2$ remains roughly unchanged.

The characteristic measured azimuthal profiles of mean relative pressure measured by the Pitot tube are shown for the supersonic regime with NPR = 2.25 in the jet cross-section $x/R_a = 2.32$ in Fig. 5. The measurements were performed at values of radial coordinate corresponding to the jet streams discharged from the internal and external contours. Here, lines 1 and 2 refer respectively to the inner and outer jets. The graphs show a substantial azimuthal non-uniformity of both jet flows. The maximum amplitude of non-uniformities (from minimum to maximum) with a range of 11% is registered in the outer jet, and the minimum one, in the inner jet, with amplitude of 1%.

The spatial non-uniformity of the flow is caused by the presence of vortex structures formed as a result of disturbances generated by the internal design elements of the nozzle. A similar flow structure was observed for a supersonic jet exhausted from a nozzle with chevrons located at the nozzle exit [4].

The geometric Mach number calculated by the formulas for isentropic flow, without taking into account the blockage of flow passage area in the external and internal contour (“clean channel”) was $M \approx 0.6$ and 0.24, respectively. In the presence of supporting pylons and Pitot tubes, the flow in the external contour was accelerated to a transonic speed (Mach number $M \approx 0.9$), whereas the flow in the inner channel, with allowance for the blockage, was accelerated slightly, to $M \approx 0.3$.

4. Conclusion
An experimental study of the 3D structure of a high-speed jet exhausting from an axisymmetric dual stream jet nozzle with a central body was performed in supersonic regime of the gas-dynamic flow in both nozzle contours at NPR = 2.25 and $M_j = 1.14$. 

Figure 4. Radial distributions of measured total pressure in section $x/R_a = 2.32$ in between pylons and in front of one of the pylons (curves 1 and 2, respectively).

Figure 5. Azimuthal distributions of pressure in section $x/R_a = 2.32$, curve 1- $r/R_a = 0.17$, curve 2- $r/R_a = 0.43$. 

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Shadow visualization of the flow showed the presence of shock waves, wakes of the cone of the central body and the nozzle edge in the interface region of the external and internal jets. The results of probing the flow field of the jet have demonstrated the presence of a substantial azimuthal non-uniformity of the pressure distribution registered in the outer supersonic jet and related with the presence of intense disturbances formed as a result of the interaction of nozzle elements (pylons and Pitot tubes) with the transonic flow.

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