Investigation of jets mixing in the channel of the hypersonic rocket-ramjet engine model

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Abstract. A technique of investigating jet mixing in the channel of a rocket-ramjet engine model in the conditions of an external supersonic airflow is proposed. Rocket exhaust jets are modeled with heated high-pressure air. Numerical computation of the mixing ratio (V. I. Kopchenov, Central Institute of Aviation Motors (CIAM)) yielded satisfactory qualitative agreement with the experimental results.

1. Introduction
There has been a number of recent studies on constructing a conceptual design of a transatmospheric vehicle propulsion system. One of the promising schemes considered in this research is the hypersonic ram-rocket engine [1]. It is a compound propulsion system that has a number of significant advantages due to combining elements of both a rocket engine and a jet engine. The main advantage is the possibility of obtaining a high specific impulse without increasing the mass while the design remains relatively simple. As the Mach number and the altitude increase, the engine operates first as a regular rocket-ramjet, then as a ramjet with subsonic channel speed (supersonic combustion ramjet, or scramjet), and finally as a ramjet with supersonic speed (hypersonic combustion ramjet, or scramjet). In the last two modes, the rocket nozzles operate as fuel injectors, without implementing the impulse. In vacuum, the propulsion system operates purely as a rocket engine. One of the main objectives in the development of a propulsion system is to achieve a high combustion efficiency at an air-fuel ratio close to stoichiometric, with minimal losses of total pressure in the airflow duct [2]. This requires a high air-fuel mixing efficiency. At the same time, it is known [3,4] that at high Mach numbers turbulent exchange processes slow down and traditional fuel supply schemes (for example, jet feed in the combustion chamber) are rendered inefficient. Two ways of increasing the mixing intensity can be outlined in a most general formulation: by generating long-lived three-dimensional vortex structures, or by increasing the initial turbulence level (through the choice of the nozzle shape, wedges, shock wave inducers, etc.).

The possibility of generating streamwise vorticity in rocket nozzles by distorting the axisymmetric nozzle shape is additionally considered [5, 6]. All of that leads to the concept of an integral air inlet with spatial flow compression.

This paper presents the results of the so called cold blowdowns of the combustion chamber [7, 8] with the air inlet in the external airflow, during which the most significant gasdynamic flow features in the channel are determined. The applicability of the results of such studies to combustion chambers relies on the fact that the structure of a microdiffusion flame follows the structure of the turbulent airflow in which the combustion occurs [9].
The process of jet mixing in rocket engines in a cocurrent air flow has been studied by heating the jets. It is known that the diffusion processes of impurities and heat (the so called transportable substances) are very close qualitatively and follow the same patterns [9]. Characteristics of turbulent transfer can be determined through the intensity of impurity diffusion.

The main purpose of in-depth study of the gasdynamic structure of the channel flow and of the mixing process is to verify numerical flow solution models.

2. Description of the model and experimental procedure

The experiments were conducted in the T-313 supersonic wind tunnel of the Institute of Theoretical and Applied Mechanics, Siberian Branch of the Russian Academy of Sciences with the test section size of 0.6 x 0.6 x 2 m. The flow parameters were fixed: $M_{\infty} = 4.03$, $Re = 54 \text{ mln m}^{-1}$, $T_{0p} = 270 - 280 \text{ K}$, stagnation pressure = 1.046 MPa, static pressure = 6.655 kPa. The tests were carried out in two modes: passive flow (no jet discharge) mode and jet injection mode.

The model (figure 1) is a rectangular channel equipped with a supersonic air inlet. The air inlet consists of side walls 1, a lower compression wedge 2 with a 6° angle, an upper cowl 3, and a wedge-shaped pylon 5 located on the longitudinal symmetry axis. The incoming air flow is compressed on the edges of the pylon, so the air inlet serves as a spatial compression device. Nozzles that mimic rocket engines nozzles with an exhaust Mach number of 2.94 are placed at the rear end of the pylon. The test medium of rocket engine jets – cold or heated (up to $\approx 200 \text{ °C}$) high-pressure air – was fed into the pylon. The air is heated in a high pressure gas generator that operates on the basis of burning hydrogen [10].

**Figure 1.** Model outline

**Figure 2.** Relative excess temperature
At the channel entrance, after the air inlet, there are steps that receive the impulse that occurs at the diffusion and heating of the incoming airflow by the rocket engine jets.

The model was installed in the test section of the wind tunnel on a high prop, which ensured its position in the core of the unperturbed flow.

The following model parameters were variable:
- the dispersal degree of the high-pressure flow, varied by injecting either twelve or six jets while the other parameters (the relative rate, the Mach number, and the exhaust pressure ratio) remained approximately the same – pylons 1 and 2, respectively;
- the structure of the flow in the model channel, varied by increasing its turbulence in the deep indentations during the installation of pylons 2 and 3;
- the structure of the injector flow, varied by using nozzles with an elliptical exhaust area (pylon 3). Pylon 2 had six round conical nozzles, and pylon 3 reproduced its geometric and rate characteristics as closely as possible, changing only one parameter – jet configuration.

The study of the gasdynamic parameter fields was performed using rake probes of total pressure $P_0$, static pressure $P_{st}$, and temperatures $T_0$ that scanned the flow field across the channel using a traversing probe. The traversing probe was adjusted in the longitudinal direction on installation. The rakes contained: ten $P_0$ and $T_0$ probes set in 7 mm increments; six $P_{st}$ probes set in 12.6 mm increments. Chromel-alumel (ChA) thermocouples were used. As a primary analog-to-digital converter for temperature measurement, the digital voltmeter Shch-1516 was used. The accuracy of the rakes’ movement along the height of the airflow duct is 0.1 mm. The flow parameters in each cross-section were calculated based on the measurement results for 160 points.

The total pressure in the gas generator at the exhaust of cold jets was about 3.0 MPa, for hot jets $1.6$ MPa, the pressure ratio of the exhaust $n = p_c/p_g$ (where $p_c$ is the pressure at the nozzle section, $p_g$ is the pressure at the air inlet throat section) varied from ~ 1.2 at the top of the channel up to ~ 6.4 at the bottom for cold jets, and, accordingly, from 0.3 to 1.6 for hot jets. The uneven nature of the pressure ratio was determined by the change in pressure along the height of the air inlet throat.

3. Measurement validation

The validity of the results depends on the following factors: maintaining the equity of the measured rate in three cross sections along channel length $G$; adherence to the impulse balance as measured in cross sections of the mixing chamber and calculated from the parameters of high-pressure and low-pressure flows within the mixing chamber $I$; stability of the averaged temperature $T_0\bar{\cdot}$, (table 1), calculated as an example for pylon 2 during the hot jet tests. Evidently, the maximum deviation of rate $\delta$ from the average value is 0.91%. Rates are absolute values measured in different tests, so they indirectly characterize the reproducibility of maintaining the parameters both in the pre-chamber of the wind tunnel and in the gas generator.

| Cross section | $G$, kg/s | $I$, N | $T_0$, K |
|---------------|-----------|-------|---------|
| I             | 2.201 (0.14) | 1569.0 | 334.8   |
| II            | 2.186 (0.82) | 1531.7 | 338.4   |
| III           | 2.224 (0.91) | 1524.9 | 337.3   |

Calculated values: impulse, disregarding losses in the air inlet, $I = 1603.2$ N; average flow temperature in the mixing channel after gas generator nozzles:

$$ T_{om} = r_{ai} T_{0p} + r_{gg} T_{gg} = 0.7896 \cdot 291.6 + 0.2115 \cdot 485 = 332.8 \text{ K,} $$

here $r_{ai}$ and $r_{gg}$ are proportions of gas rate respectively through the air inlet and through the nozzle of the gas generator, $T_{0p}$ and $T_{gg}$ are
proportions of temperature of the incoming flow diffusion (in the pre-chamber of the wind tunnel) and of the combustion products in the gas generator. Evidently, the received measurements are very valid.

A calculation of turbulent Prandtl numbers can also serve as indication of measurement validity. It is known [3,12] that for turbulent flows the transfer of momentum, heat, and matter is proportional to the gradients of the averaged values of velocity, temperature, and impurity concentration, i.e. \( \tau = \mu/\partial U/\partial y \), \( Q = c_p\mu/\partial T/\partial y \), \( G = \rho D_\mu/\partial c/\partial y \). The coefficients in these equations are proportional to the gradient of the averaged velocity: \( \mu = \rho u^2/\partial U/\partial y \), \( a_1 = u^2/\partial U/\partial y \), \( D_u = \rho\mu^2/\partial U/\partial y \), where \( lu \), \( lt \), \( lc \) are the mixing path lengths in terms of speed, temperature, and concentration. Suppose that the derivative of the velocity with respect to the coordinate can be replaced by the corresponding differences or, according to Prandtl, present these coefficients as analogues of the maximum gradients of corresponding parameters. Then the turbulent Prandtl and Schmidt numbers can be represented [3] in the form

\[
Pr = l_u/l_t, \quad Sc = l_u/l_c.
\]

Following [3, 11], the length of the mixing path can be expressed as the ratio of the maximum difference of a parameter (for example, the velocity in a given cross section \( \Delta U_m \)) to the maximum gradient of the parameter \( (\partial U/\partial y)_{\text{max}} \):

\[
l_u = \Delta U_m/(\partial U/\partial y)_{\text{max}}^{-1}
\]  

(1)

In our case the maximum difference for velocity will be characterized by the maximum difference in velocity coefficient \( \Delta \lambda_m = \lambda_{\text{max}} - \lambda_{\text{min}} \), for temperature – by the value:

\[
\Delta T_{\text{max}} = T_k - T_{\text{mix}}/T_k.
\]

Next, we make the following assumption: the values of standard deviations \( \sigma \) are taken as analogues of the maximum gradients of corresponding parameters. Then the formula (1) can be represented as \( l_u = \Delta U_{\text{max}}/\sigma U \). Following that assumption, we calculate the lengths of the mixing paths: \( l_u \approx l_{\text{max}}/\sigma \cdot l_{\text{t}} \approx \Delta T_{\max} / \sigma \cdot T_o \). The results of calculating the \( Pr \) numbers are presented in table 2. It is evident that the obtained \( Pr \) numbers are close, within some limits, to the known values for turbulent jet flows: \( Pr = 0.5 - 0.8 \). The patterns of \( Pr \) number changes with the development of the jet (a relative decrease in its value due to an increase of the mixing path by temperature) are also consistent with the data [3,13]. The values of the parameter differences were determined through the results of spline interpolation.

| Table 2. Turbulent Prandtl numbers |
|----------------------------------|
| **Pylon type** | **Cross sections** |
|                | I        | II       | III      |
| 1               | 1.15     | 0.52     | 0.32     |
| 2               | 0.69     | 0.60     | 0.48     |
| 3               | 1.14     | 0.49     | 0.56     |

4. Experimental results

Three-dimensional distributions of the relative excess temperature for pylons 1 and 2 are presented in figure 2, and contours of the temperature distribution in three cross-sections along the length of the channel are presented in figure 3. The figures demonstrate the process of jet ensemble expansion. Characteristic features are identified: jet axes, determined by Mach numbers maxima, (square markers) and temperature (round markers) are some cases not congruent. For pylon 3, with elliptical cross-section of the nozzle, a bifurcation of the jets and the appearance of two maxima is observed. That can contribute to improving the mixing process.

An analysis of flat distribution patterns of relative temperature (figure 3) allowed to construct jet trajectories in the channel (figure 4).

A significant confluence of the jets is observed for pylon No 1 in the second cross section. That feature obviously does not improve the mixing process.
Figure 3. Contours of relative excess temperature

Figure 4. Rocket trajectories in the model channel

Figure 5. Results of calculation and experimental determination of the displacement coefficient in the channel of the RPD model.

The dependence $\eta = 1 - \overline{\sigma_T}/T_{0m}$ where $\overline{\sigma_T}$ is the standard deviation of the temperature in the cross section, and $T_{0m}$ is the defined above temperature of the hot and cold flows mixture averaged over the relative areas, was taken as the mixing coefficient. As $\sigma_T$ tends to zero (ideal mixing), $\eta$ tends to 1, which
determines the physical essence of this coefficient. Figure 5 presents the values of $\eta$ for the three types of pylons, obtained in experiments and through numerical computation by a group of Central Institute of Aviation Motors (CIAM) employees under the leadership of V. I. Kopchenov.

5. Conclusions
A technique of studying jet mixing in the channel of a ram-rocket model has been developed. Numerical computation results (V. I. Kopchenov, CIAM) were shown to be in satisfactory qualitative agreement with the experimental results. The structure of the external and internal flows was demonstrated to have a significant influence on the mixing intensity.

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