MIXING INVESTIGATION IN A CHANNEL BEHIND STAR-SHAPED SURFACE OF EXTERNAL COMPRESSION

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Abstract

Configuration and geometrical features of external compression surface of hypersonic inlet are influential on inlet parameters and wave drag particularly. Bodies of revolution not always have lowest drag. On computational investigations base [1, 2], star-shaped forebody consisting of pyramidal wedges (petals) has been suggested, as one of possible configuration. Actually, this design is a modification of the axisymmetric inlet [2] in which a conical forebody is replaced by a star-shaped body with n similar petals. The external edge of each petal stretches out to a cowl. An array of injectors is set in the rear part of the petals in order for the whole airflow between the neighboring petals to be percolated through the cloud of the fuel formed by the injectors. By giving various sweepback and yaw angles to each injector, one can increase the penetration height of the injectant between the petals. The petal cross section profile is fitted so that the bow shock wave is attached to the petal edges. The Mach shock wave system, accompanied by numerous weak internal shocks, should form in a cross-flow section.

It is also well known [3-11] that a star-shaped body at hypersonic speed has a lesser total drag compared to the equivalent cone. In addition to decrease of wave drag this form of compression surface promotes to mixing in the presence of complex three-dimensional structure of crossing shocks and rarefaction waves. Length decrease, that is necessary for a full components mixing, is a one of basic problems of supersonic speed in a channel investigations. The performance of the star-shaped inlet would be improved if a series of swept ramp injectors, which could add injectant inside the external part of the flow, were set along the intersection line of the bow shock with the cowlung surface. On the one hand, they would speed up the mixing process and on the other hand, these ramp injectors could generate additional thrust. As a matter of fact, the front part of the cowlung is usually inclined relative to the free flow [12] and the windward ramp injector surface is set at an angle where thrust effect of the injector [13] is manifest.

The experimental tests were conducted in the ITAM hot-shot wind tunnel IT-302M at the free stream Mach number, $M_{\infty} = 6$, and the results of these tests are also presented in this paper.

Setup for experimental tests

The forebody of experimental model consists of 2 petals. The whole inlet design also includes a cone-cylinder central body which is the continuation of the inner cone of the star forebody. The frustum of the cone starts smoothly from the petal back sides and extends along the inlet channel to reach mean flow Mach number, $M \sim 3$. 

An array of injectors is also set in the rear part of the petal surfaces and on their back sides, in order for the cloud of the fuel formed by injectors to be away from the boundary layer, and this contributes to the prevention of early fuel combustion. As well as additional fuel injectors are located on the cowl front edge.

General view of this model is shown in Fig. 1 and the scheme of the model is shown in Fig. 2. The model represents ? of the full model, due to the symmetry. Helium is injected from the lateral sides of petals (close to the back edge), from the back of petals, and using injectors on the cowl (near the cowl front edge).

Tests of the model have been carried out in the aerodynamic wind tunnel IT-302M at the nominal Mach number of 6. The wind tunnel was used in the mode with a double pre-chamber, which allowed for choosing the parameters of the flow with a necessary accuracy to maintain required test conditions (total pressure and temperature, Reynolds number) [14].

The helium supply system included:
- cylindrical (sonic) injectors on the back and lateral surfaces of petals, and on the internal cowl surface;
- channels to supply helium to the injectors on petals and cowl;
- the fast-acting valve to supply helium;
- a tank for gaseous helium with the volume of 500 cm³;
- pressure gages for measuring supply pressure and the mass flow of helium.

Two types of experiments have been conducted during these tests: a) measurement of the static pressure and Pitot pressure distributions in two longitudinal sections of the model at the same cross-sections at the channel exit between the petals on the central line and behind the petal; b) determination of the helium concentration in the flow by means of a sampling device and subsequent chemical analysis separately for each cross-section.

Measurements of volumetric helium concentrations (here and below the term “concentration” is the same as “mass fraction”) were done under the same conditions at which the pressure distribution measurements in the channel were conducted and at the various pressures of helium supply. Measurements of helium concentrations were conducted using the gas chromatograph ЛХМ-80 МД. The inaccuracy of these measurements was less than 1%.
Experiments of determination of the helium concentration were carried out separately during different runs, but determination of the helium concentration samplers were installed in the same sections as determination of the helium concentration and test conditions were the same.

In each run the following measurements were conducted:
- total pressure in the first and second pre-chamber;
- Pitot pressure at the exit of wind tunnel nozzle;
- static pressure distribution along the model;
- Pitot pressure distribution across the channel in two cross-sections at the exit of channel;
- pressure in helium tank.

Extraction of the gas mixture in the channel of model, and the subsequent determination of its composition was carried out by means of special sampler (rake) and high-speed valve for preservation of samples.

Extraction of the mixture was carried out separately for each longitudinal section, i.e. for each rake separately. To determine helium concentration, a device with the selected sample was automatically closed within approximately 40 ms of the sample. The cylinder remained sealed during 24 hours. After each run, the chemical analysis of samples was carried out to determine mixture concentration. The analysis of sample was conducted immediately, but not later than in 2-3 hours after the run.

During all of time more than 50 full cycles of measurements were carried out.

**Experimental tests results**

Since during the tests the direct measurements of the air charge through the model channel were not conducted, the air mass flow was defined in the assumption that the factor of the flow rate coefficient was equal to 1, i.e. the channel has been started, and operated in the design mode. For confirmation of this assumption during each run the Schlieren visualization of the flow at the model entrance was carried out. The obtained data have shown (Fig. 3), that the design mode was achieved in both cases: without injection of helium and at its maximum supply pressure injection, which was equal to 16 bars.

In the cases of tests without helium injection, it has been obtained that the static pressure distribution in the model channel has essential non-uniformity both in longitudinal and in transversal directions. Comparison of pressure distribution along the model between the petals (central line) and behind the petal is presented in Fig. 4. These data show that the pressure can differ by more than 1.5-2 times. Non-uniformity of the pressure is especially significant in the front part of the channel (x < 500 mm). At the same time, the data are presented for various operating times of the wind tunnel, which confirm the reproducible character of the flow in the channel during of wind tunnel time operation.

![without helium injection](image1.png) ![with helium injection](image2.png)

Fig. 3 Schlieren visualization of the flow at the model entrance.
At the same time, it has been determined, that the decrease of Reynolds number during the wind tunnel operation weakly influences pressure distribution in the model channel, despite the 70% reduction of Reynolds number.

Distribution of the Pitot pressure across the channel also has essential non-uniformity (Fig. 5 and Fig. 6). Pitot pressure was measured in two cross-sections of the model: I – before the discontinuity of the contour of the central body (Fig. 5) and II – at the channel exit (Fig. 6).

First of all, it is necessary to note the essential two-layer character in the Pitot pressure distribution. This distinction was essentially changing depending on the transversal positions of the Pitot tubes rake. On the central line in section I, Pitot pressure nearby the central body exceeds pressure nearby the cowl by approximately 4 times (Fig 5a). Behind the petal in section II, Pitot pressure nearby the central body was approximately twice lower than the Pitot pressure close to the cowl (Fig. 5b).

At the channel exit (section II) the Pitot pressure distribution across the height of the channel changed, however the non-uniformity remained significant. The maximum pressure is achieved in the middle part of the channel. On the central line, the pressure near the central body was lower than pressure nearby the cowl by approximately 2 times (Fig. 6a). Behind a petal, qualitative character of distribution pressure remained the same as on central line. The maximum distinction in the pressure value in the core of the flow and nearby the central body amounted to only 60% (Fig. 6b).

As well as static pressure (Fig. 4), Pitot pressure remained constant during the operating regime of the wind tunnel up to 70 ms.

*Influence of helium injection on pressure distribution in the channel.* Injection of helium leads to the change of static pressure distribution along the channel of the model, but, at the same time, the distinction in static pressure distribution on the central line and behind the petal remains. For compari-
son, pressure distribution without and with helium injection is shown in Fig. 7. It can be seen that the change of pressure occurs in the rear part of the channel, and this change is different on the central line and behind a petal. Evidently, the greater change of pressure occurred behind the petal as the great bulk of helium was injected from the petal back side.

Comparison of pressure distribution on the central line and behind a petal at the helium supply pressure of 4.8 bar is presented in Fig. 8. It is possible to see that the pressure distributions remained constant during 20 ms.

The tests have been conducted with various ratios of helium and air mass flow. This allows for determination of the influence of dynamic pressure on mixing efficiency.

The increase in supply pressure up to 15.4 bar has not led to essential change of pressure distribution in the channel. It is simultaneously possible to see that in this case, the influence of injection pressure change with time becomes more apparent, which can achieve 15% at channel exit.

Comparison of pressure distribution at the supply pressure of 4.8 and 15.4 bars is presented in Fig. 9. On the central line, qualitative and quantitative conformity in distribution of static pressure remains (Fig. 9a). Pressure decrease in the front part of the channel is caused, apparently, by ejecting influence of high-pressure helium jets. More significant influence of helium supply pressure becomes apparent in pressure distribution behind the petal (Fig. 9b). By increasing supply pressure up to 16 bars, the pressure on the central body can increase by 50%.
Injection of helium leads to significant decrease in Pitot pressure and to the reduction in non-uniformity of its distribution across the height of the channel (Fig. 10). However the distinction in pressure value on the central line and in the section behind the petal remains large, which follows from the comparison of the data on Fig. 10a and Fig. 10b. Also, it is necessary to note that the two-layer flow remains as well as in flow without helium injection. Pressure nearby the central body and cowl became approximately identical in both cases.

The maximum Pitot pressure at the exit of the channel has been obtained in flow core, but in the section behind the petal it was less by approximately 25% than in the flow without helium injection (Fig. 6b and 10b). In the section between petals, Pitot pressure has changed insignificantly both in flow core, and close to walls.

The increase of pressure of injection up to 16 bars leads to minor change of the Pitot pressure and the reduction of pressure non-uniformity across the height of the channel (Fig. 11). However the general features of Pitot pressure distribution remained.

As it was already mentioned above, to estimate the influence of helium supply pressure, runs have been done with various helium injection pressures. The generalized comparison of static pressure distribution along the channel of the model on the central line and behind the petal is presented in Fig. 12. Results of the pressure distribution measurements without helium injection (dark blue markers) are shown in the same figure. It is possible to see that the saw-tooth distribution of pressure remains under all conditions. The character of pressure distribution on the central line (between petals) changed a little bit and weakly differs from pressure distribution without helium injection (Fig. 12). Behind a petal, the influence of helium injection was more appreciable and the change of pressure has begun at the distance of approximately 600mm. It can be simultaneously seen that the smoothing of pressure distribution occurs in comparison with pressure distribution without injection of helium.
This three-dimensional problem has been analyzed at the Hampton University Aeropropulsion Center (HU/APC) using the NASA CFD code VULCAN based on full algorithms for averaged Navier-Stokes Equations for steady and unsteady processes of turbulent mixing. The results of the three-dimensional numerical simulation of supersonic flow at Mach number $M=6$ in the inlet with star-shaped forebody (proceeded smoothly to the frustum of a cone) compared with experimental results have shown on Fig. 13.

Results of the concentration measurements are presented in Table.

<table>
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<th>$P_t$, bar</th>
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<th>33.1</th>
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<td>1710</td>
<td>1786</td>
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<tr>
<td>$P_h$, bar</td>
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<td>16.2</td>
<td>5.35</td>
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<td>Concentration of He between petal, %</td>
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<td>10.01</td>
<td>2.84</td>
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<tr>
<td>Concentration of He behind petal, %</td>
<td>10.76</td>
<td>33.2</td>
<td>10.6</td>
</tr>
</tbody>
</table>

Fig. 10. Pitot pressure distribution on Section II, $P_t=4.8$bar. a) on central line; b) behind petal.

Fig. 11. Pitot pressure distribution on Section II, $P_t=15.4$bar. a) on central line; b) behind petal.
Conclusions

The physical model to study the flow parameters and conditions of mixture in the channel behind the star-shaped central body for experimental tests in the hot shot wind tunnel with high total parameters was developed, manufactured, and tested. The following results were obtained.

- Static pressure distribution on the central body has essential nonuniformity on the length of the channel. Qualitatively and quantitatively this distribution was different on the central line (between petals) and behind the petal. Pitot pressure distribution at the exit cross-section of the channel has two-layer character with higher pressure in the flow core. Pressure in the flow core can exceed pressure close to walls by 2 times.
- The injection of helium leads to the decrease in non-uniformity of Pitot pressure distribution, however, the qualitative character of the distribution remains the same.
- It was determined that the average volumetric concentration of helium on the central line and behind the petal differs by approximately three times. To reduce the non-uniformity of pressure and concentration fields, first of all, additional efforts are necessary to reduce the non-uniformity of pressure field in the transversal direction and to significantly reduce helium injection from the back sides of petals.
- Good agreement of numerical simulations and experimental data has been received.

Fig. 12. Influence of injection pressure on pressure distribution.
   a) on central line; b) behind petal

Fig. 13. Static Pressure distribution along central body
   a) on center line; b) behind petal.
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REFERENCES