Preliminary experimental assessment of supersonic airflow behavior over ExoMars and X–43 inlet models using multiple flow regime shock tube

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Abstract. Models of the ExoMars spacecraft [1-3] and variants of the X-43 air intake [4-9] were first tested in the hypersonic aerodynamic shock tube (HAST) [10-13] facility. The shock-wave structures of the gas flow under Mach numbers M=7…4.5 around the model surfaces were filmed by high-speed video camera. The obtained data were analyzed using image recognition software systems. Preliminary estimates of the flow behavior over the investigated models in the test section of the installation during the whole test are given.

1. Introduction
The interaction of shock waves with the surface of a spacecraft and a high-speed aircraft at supersonic and hypersonic flight speeds is one of the fundamental problems of modern aerodynamics. The relevance of this issue is related to the practical needs that arise when developing high-speed aircraft of complex shape. Of particular importance are aspects of this type of flow around the elements of thermal protection of the spacecraft, aerodynamic controls, elements of the feathering of a high-speed aircraft, wings, elements of the scramjet air intake. The experimental data obtained are the basis for further computer aerothermodynamic studies.

"ExoMars" — a joint program of the European space Agency (ESA) and the Russian state corporation Roscosmos [1–3]. The launch of interplanetary probe "ExoMars-2016" implemented in 2016 was unsuccessful. "Schiaparelli" module has not carried out a soft landing. New launch "ExoMars-2020" it is planned in 2020. In the framework of this paper experiments on the “ExoMars” spacecraft model were conducted with the aim of obtaining general patterns governing the formation of shock-wave interactions near the apparatus surface arising from the incoming high-speed air flow with different Mach numbers during one experimental run in the facility.

If one distinguish the characteristic features that can be inherent in perspective aerospace systems, then such aspects as the possibility of repeated use of the aerospace apparatus and close aerodynamic integration of the glider with control elements, propulsion system and launch vehicle are very important. A considerable amount of data in open sources of literature contains the hypersonic aircraft models (in particular, such as X-43) in terms of the geometry characteristics of the scramjet air intake [10-13]. This paper presents the results of preliminary experimental modeling of some air intake configurations of hypersonic aircraft.

Experimental studies were conducted in the hypersonic aerodynamic shock tube (HAST, figure 1). Detailed description of the HAST installation and its technical capabilities are presented in [12, 13].
2. ExoMars model experiments. Multiple flow regimes

ExoMars model was mounted in front of the hypersonic nozzle in the HAST test section (figure 2). The PCB sensors registered pressures at different distances from the nozzle exhaust. Schlieren photos of experiments with the structure detached shock wave over the model are shown in figure 3.

When considering the entire period of one test in shock-tube type installations with an aerodynamic section working under reflected shock wave regime, special attention is paid to the so-called periods of the quasi-stationary flow process around the model under study [11]. When using the same gases as a
driver and driven, during these periods the gas dynamic parameters of the flow at the nozzle block inlet undergo small changes. This is directly related to the character of the shock-wave interactions occurring in the combined volume of the driver and driven tubes during the experiment [11].

In the framework of the paper, a preliminary analysis of the model's motion during the experiment was carried out using software image recognition systems [14]. The files of high-speed video material of shadow images of shock-wave interaction near the model surface were analyzed. These data were recorded during the course of one experiment, i.e. the so-called periods of the quasistationary flow process were taken into account. Figure 4 shows the location of the coordinate axis on the video frames for recording the motion of the model. Two-dimensional graphs of the dependence of the spatial displacement on time are shown in figure 5. The center of the coordinate axis was specified at the deflection of the model’s rear surface.

![Figure 4. Registration the model movement. Coordinate axes.](image1)

![Figure 5. x-t and y-t diagrams of model movement during the experiment.](image2)

In the graphs of figure 5, one can select several phases of the experiment. The start of the test is determined by the static position of the model (0-30 ms). Then comes the period of a supersonic flow of the gas under investigation with stationary parameters. The first drop in the x-t graph in figure 5...
identifies the onset of the impact of the incoming flow from the nozzle on the model (backward motion). This period (30-55 ms on figure 5) shows rather small movements of the model in comparison with the general nature of displacements. For this consideration it can be neglected because of their fairly clear time comparison with the processes occurring at the entrance to the nozzle block (reflected shock tube test time, figure 3A).

The following jumps in the x-t and y-t graphs (figure 5, 55 ms) show the attenuation of the oncoming flow, the termination of the stationary flow process. This is followed by the onset of shock wave perturbations, which is due to the variable parameters of the gas-dynamic characteristics at the nozzle entrance.

The next significant change shows y-t graph of 100 ms. The change in the position of the model by 0.5 mm is due to the quasistationary flow process beginning (figure 3B). Diagnostics of gas-dynamic parameters of this period is of particular interest, since under the conditions of one test it is possible to investigate the influence of oncoming flows with different gas dynamic characteristics onto the model (under certain assumptions). The flow pattern shown in figure 3B lasts several tens of milliseconds on a high-speed video file. A more detailed picture of these periods can be obtained, in particular, by comparing the experimental data with the results of numerical simulation [10,13]. The further minor fluctuations in the x-t and y-t graphs are evidence of the static position of the model and are not of interest for consideration in the framework of this preliminary assessment.

With a more detailed study of the vibration nature of the investigated models during the entire time of the experiment, it is necessary to take into account not only the shock-wave interaction before entering the nozzle and changes in the parameters of the incoming flow at the outlet from it. In particular, additional factors attract attention, such as: the design features of the model holder, its attachment, its own resonant frequencies, acoustic oscillations of the facility sections during the experiment.

3. Variations of hypersonic air inlet model

The shock wave profile of the flow in the nose part of the hypersonic aircraft and directly near the air intake of the propulsion system plays an important role, since it directly affects the processes of the engine operation (such as local flow compaction, supersonic combustion, thrust, heat loads of the scramjet and etc.). Of particular importance is the adherence to these aspects in all phases of aircraft flight with a scramjet working (at various points of flight trajectory, at the accelerator separation period, etc.).

The procedure for aerothermodynamic modeling of hypersonic aircraft propulsion system contains several items (figure 6):

- Aerothermodynamic analysis of the air inlet configuration;
- Modelling of gas-dynamics and physico-chemical combustion aspects in the combustion chamber;
- Nozzle flow and system analysis.

Figure 6. Design of a scramjet propulsion system [5].

Figure 7 shows shock-wave interactions for ramp/double ramp configuration of hypersonic aircraft inlet. The separation of the boundary layer (figure 7A) is one of the critical moments in the design of the hypersonic air intake geometry as this can cause a local change in the flow pattern, pressure
parameters, heat transfer increment. This can lead to locking the engine path, causing unevenness and irregularity in its operation. According to Heiser-Pratt [6,15], there are certain values of the critical angles of inclination for laminar and turbulent flow cases to avoid the boundary layer separation and the appearance of flow recirculation zones. For example, the hypersonic aircraft 14-X B model has a second inclination angle of 14.5° and for some experiments with the Mach number M = 7, it was possible to observe these phenomena [6].

**Figure 7.** Configuration scheme with ramp (A) / double ramp (B) [5, 6].

Also one of the biggest problems in the design of the hypersonic air intake is to enable the engine to operate in a wide range of Mach numbers without using elements of variable geometry (rotating edge, moving lower cowl, etc.). With a fixed inlet geometry (ramp configuration angles), the angle of impact (the angle formed by the flow direction and the leader shock) becomes smaller for a larger Mach number $M$. This changes the structure of the flow field along the inlet (figure 8).

**Figure 8.** Schemes of shock-wave pictures for different Mach numbers with a fixed geometry of the air inlet [7].

When the engine is operating in the design mode all external inclined shock waves should be focused on the tip of the lower edge. The Mach number corresponding to this test case is called the design Mach number (figure 8A). When working at the Mach number below the calculated, the deviation angles increase and a leakage occurs (figure 8B). If the flight Mach number is higher than the design Mach number, the inclined shock waves deflect into the entrance throat (figure 8C). In this operating state, the interaction of the shock-boundary layer causes zones of detachment and reattachment of the flow, high-temperature spots inside the entrance throat. This creates huge heat loads on the intake structure [7].

As a geometric source of compression wave concentration at the tip of the lower edge of the apparatus, the Prandtl Meyer compression fan can also be used [8]. Example of this geometry is shown in figure 9.
Figure 9. Inlet configuration with Prandtl Meyer compression fan [8].

By means of analyzing of literature open sources of literature [4-9] the three-dimensional CAD model of the X-43 (figure 10) was created at the Laboratory of Radiative Gas Dynamics at the Institute for Problems in Mechanics of the Russian Academy of Sciences. This model is used for numerical simulation of aerothermodynamic processes [16].

Figure 10. Hypersonic aircraft X-43 CAD model [16].

4. Models of X-43 air inlet configuration
Taking into account the above-mentioned aspects of the hypersonic aircraft inlet design, a variant of the model for carrying out the experiments was created (figures 11, 12).

Figure 11. The experimental X-43 air inlet model in the HAST test section.
In the case, the ramp angles were 6° and 7° so there was no boundary layer separation. Figure 13 shows shadow picture results combined from two experimental runs with M=7 incoming airflow. Features of flow motion are shown in figures 14, 15.

**Figure 12.** X-43 air inlet model scheme.

**Figure 13.** Shadow picture combination of M=7 incoming airflow onto X-43 air inlet model.

**Figure 14.** Formation of the second and third oblique shock waves.

The formation of the second and third oblique shock waves occurs immediately at the first ramp surface, which indicates that there is no boundary separation (figure 14). Figure 15 shows the enlarged flow picture in the flow path.

**Figure 15.** Shadow picture of flow in the entrance throat.
The lower edge in the experiment was located in such a way that the place of encounter of shock waves from the first and second deflections (figures 13, 14) of the upper edge occurred at its tip (figure 15, 1). This was done to enhance the picture of the shock-wave interaction in the flow path. An oblique shock wave from the second ramp (figure 14) occurs with the bottom edge slightly further downstream (figure 15, 2). Particular attention is drawn to the separation of shock waves at the point of reflection and their subsequent curvilinear structure (figure 15, 3). At the location of the shock waves (figure 15, 3), reflected from the head shocks of the leading edge (figure 15, 1 and 2), attention is drawn to the presence of a detached flow from the upper edge of the air intake. The places of encounter of shock wave re-reflections and separated flows are shown in figure 15, 4-6.

To assess the influence of the side walls on the flow structure in the throat section, experiments with lateral edges simulating the sidewalls of the propulsion system of the apparatus were performed (figures 16, 17). The edges were made of plexiglass 2 mm thick with a blunt radius of 1 mm.

Figure 16. Schematic of the model with side edges.

Figure 17. Comparison of experimentally obtained flow patterns for configurations with side edges and without. M = 7 airflow.
As can be seen from figure 17, the main features of the flow pattern are traced in both model configurations. However, aspects of the influence of the side edge characteristics on the shock-wave processes inside the flow path require additional experimental studies. In particular, for more complete and detailed implementation of these studies, it is expedient to use the so-called panoramic recording methods [17].

5. Conclusion
At the HAST facility, preliminary studies of the ExoMars model were carried out under multiregime flow conditions. Shock patterns are obtained near the model for Mach numbers \( M = 7...4.5 \). Using the pattern recognition system, the results of model oscillations were analyzed throughout the entire experiment. This allowed to distinguish several periods of shock-wave interactions in the shock tube sections and to compare them with the behavior of the high-speed flow oncoming to the model. A more detailed study of the model movement during the test is expedient to carry out taking into account the influence of additional factors on the process of carrying out the experiment.

Open sources of literature were analyzed for modeling the geometry of the hypersonic aircraft inlet. The main aspects of design and issues of ensuring the operation of the propulsion system under various conditions of high-speed flight are singled out. At the HAST installation experiments were conducted on several variants of the air intake model with the Mach number \( M = 7 \). The results of a preliminary analysis of the obtained shock-wave interaction pictures are presented. For a more detailed consideration of the proceeding physical processes, it makes sense to use the methods of panoramic diagnostics and carry out validation calculations using the methods of computational aerothermodynamics which is planned for implementation in the future.

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