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Experimental investigation of aero-thermodynamic characteristics of "ExoMars" project descent module at hypersonic velocities.

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Abstract

Results of experimental investigation of stationary aerodynamic characteristics and heat flux distribution on the surface of DM-18 descent module of "ExoMars" project at hypersonic flow regimes are presented. The studies were initiated by a contract with FSUE "НПО им. С.А. Лавочкина" in framework of a collaboration program with the European Space Agency. To fulfill scientific goals of "ExoMars" project, delivery of DM-18 descent module with a payload on the surface of planet Mars is planned. The aim of this study was to determine aerodynamic characteristics and heat flux distribution on the surface of DM-18 descent module at hypersonic Mach numbers for calculating the module's descent trajectory in the Martian atmosphere. To carry out the assigned tasks, a model of DM-18 module for balance tests and a model for heat transfer tests were manufactured at TsAGI and tested in T-117 wind tunnel at Mach numbers of M=[7.5, 10.5, 14]. Aerodynamic force and moment coefficients were determined at a range of angles of attack α=[0÷25°]. Interferometric visualization of the flow past the model was obtained. Simultaneously with balance tests, surface streamlines visualization on the model was performed. Distribution of heat flux was obtained by melting paint method and by surface thermocouples at angles of attack α=[0, 10°]. Comparative analysis of calculated and experimental data was also carried out, and aerodynamic characteristics of DM-18 module in full-scale flight conditions in the Martian atmosphere were estimated.

Keywords: hypersonic flow, aerodynamic characteristics, heat flux, descent module.

Nomenclature

M – Mach number,

T – temperature,

T_0 – total temperature,

Re - Reynolds number,

P – pressure,

Cx – longitudinal force coefficient,

Cy – normal force coefficient,

mz – pitching moment coefficient,

α – angle of attack,

q – heat flux density.

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The object of study in this work is DM-18 descent module, a part of "ExoMars" project. To fulfill scientific objectives of this project, delivery of DM-18 module with a payload on the surface of planet Mars is planned. The studies were initiated by a contract with FSUE "НПО им. С.А. Лавочкина" in framework of a collaboration program with the European Space Agency.

The aim of this study was to determine aerodynamic characteristics and heat flux distribution on the surface of DM-18 descent module at hypersonic Mach numbers for calculations of the module's descent trajectory in the Martian atmosphere.

To carry out the assigned tasks, a model of DM-18 module for balance tests and a model for heat transfer tests were manufactured at TsAGI at 1:20 scale and tested in T-117 wind tunnel at Mach numbers of M=[7.5, 10.5, 14]. Aerodynamic force and moment coefficients were determined in the range of angles of attack α=[0÷25°], and interferometric visualization of the flow past the model was obtained (Fig. 1). At Mach numbers of M=7.5 and M=10.5, the front shock wave, rarefaction and acceleration zones near the edge and shocks generated by the holder are clearly observed in flow visualization images. At M=14, due to smaller air density in the stream, only the front shock was distinctively visualized. In all cases, shock position was stable, the incident stream was uniform, and no noticeable perturbations from stream boundaries were present. The distance between the shock and the body decreased with the increase of Mach number M=[7.5, 10.5, 14] as a consequence of the decrease in specific heat ratio γ=[1.36, 1.32, 1.29].

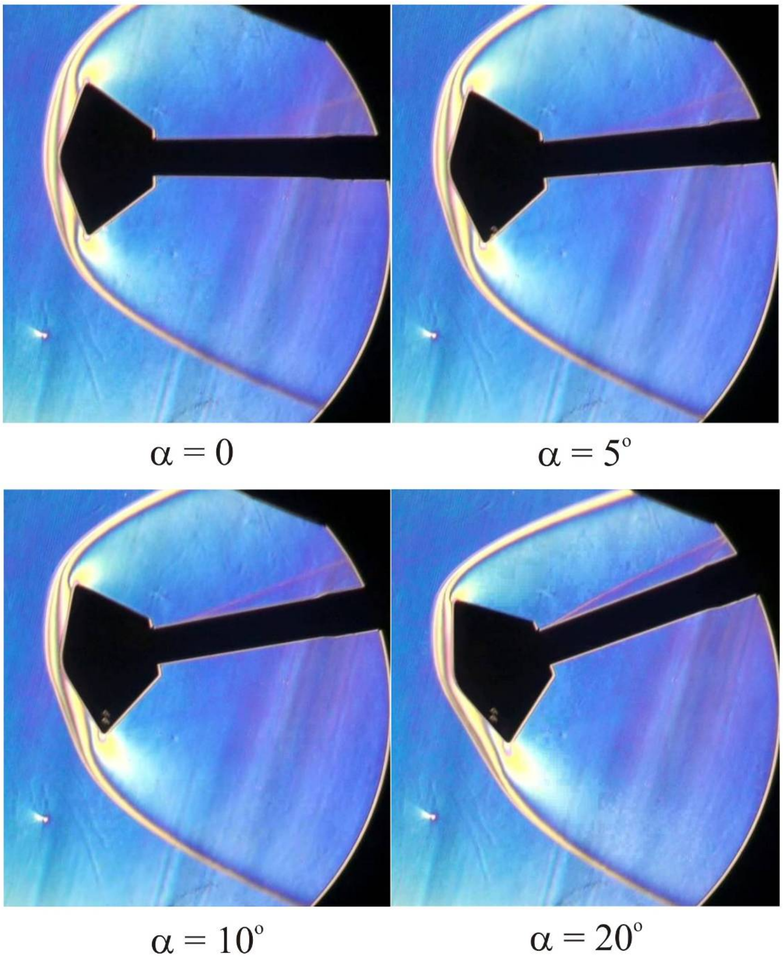


Figure 1. Visualization of flow past DM-18 model in T-117 at M=10.5.

Results of balance tests are presented in the standard form of dimensionless aerodynamic coefficients. Characteristic length and area were defined as D=2R=0.19 m and $S=\pi R^2=0.028353\ m^2$. All moments were determined relative to the nominal center of mass located at a distance of R/2 from the nose of the model or at X=-0.0685 m from the model's bottom cross-section plane. Aerodynamic characteristics of DM-18 model as functions of angle of attack are plotted in Figure 2.

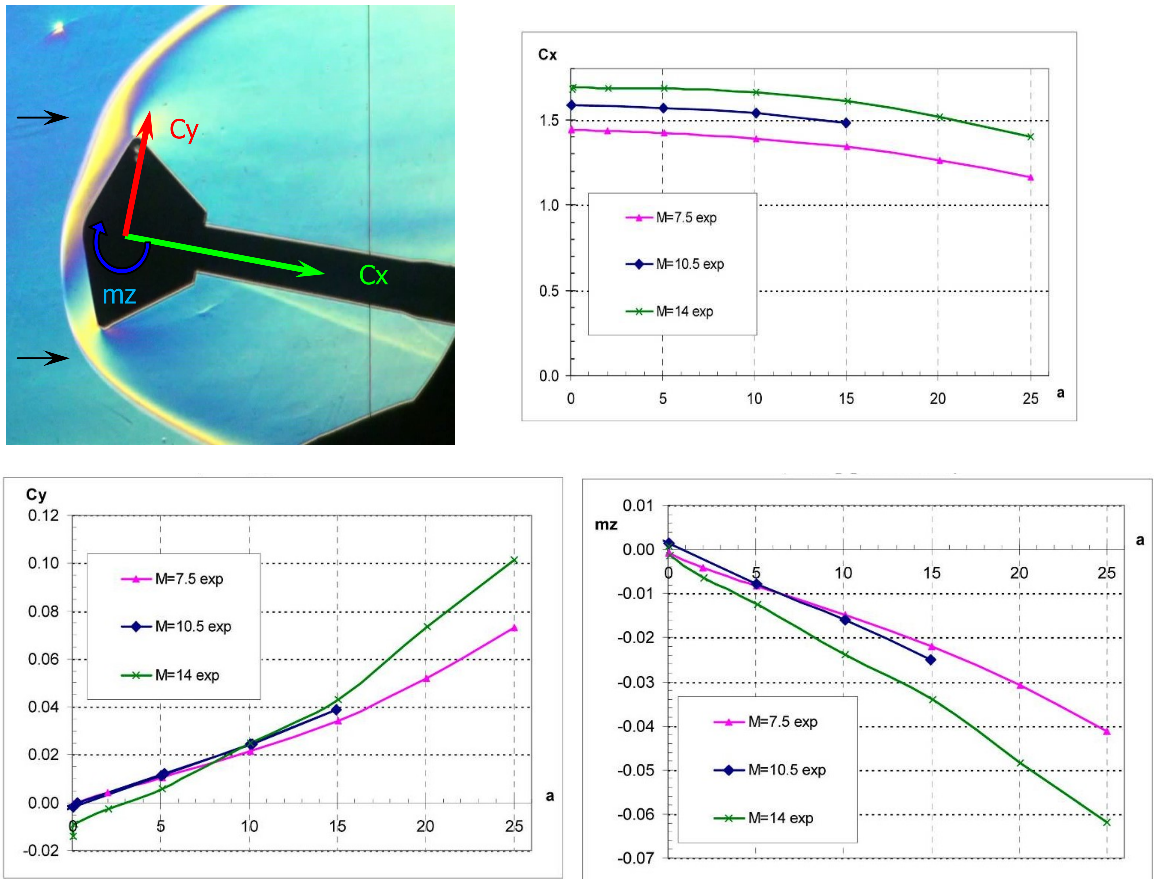
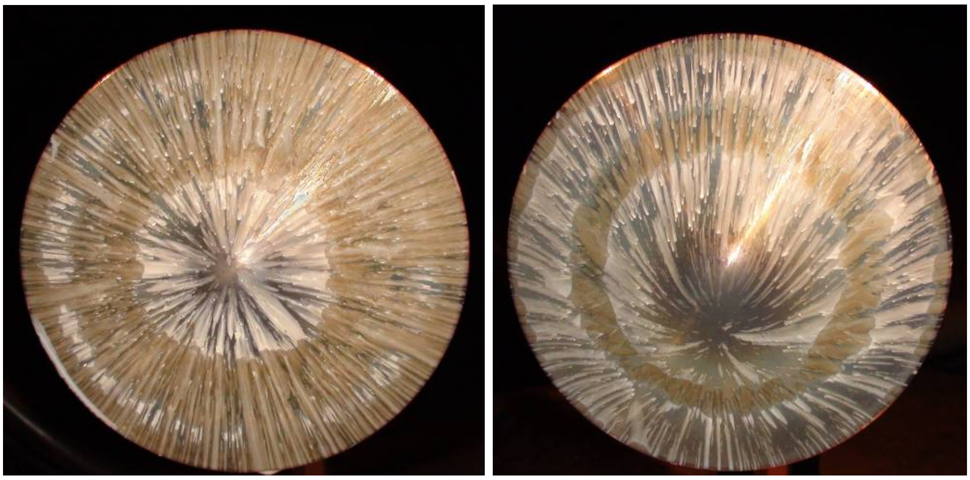


Fig. 2. Visualization of flow past DM-18 model in T-117 at M=7.5, the coordinate system and aerodynamic characteristics of the model.

Analysis of balance test results shows that the longitudinal component of full aerodynamic force vector is absolutely dominant over other components. This is a characteristic feature of all vehicles of this type, which have a primary purpose of efficiently decelerating before parachute systems are engaged. DM-18 vehicle's lifting capacity is quite small and of little importance, since the nominal angle of attack at the descent trajectory is $\alpha \approx 0$ at which the lifting capacity is not being used. As far as aerodynamic quality is concerned, at studied angles of $\alpha \leq 25°$ it has a small negative value, which linearly depends on α and is practically independent of the Mach number.

Simultaneously with balance measurements, surface streamlines visualization was performed on the balance model by discrete drops of white visualizing compound applied preliminarily on the model surface. Images of visualized streamlines on DM-18 model in T-117 at M=14 are shown in Fig. 3.



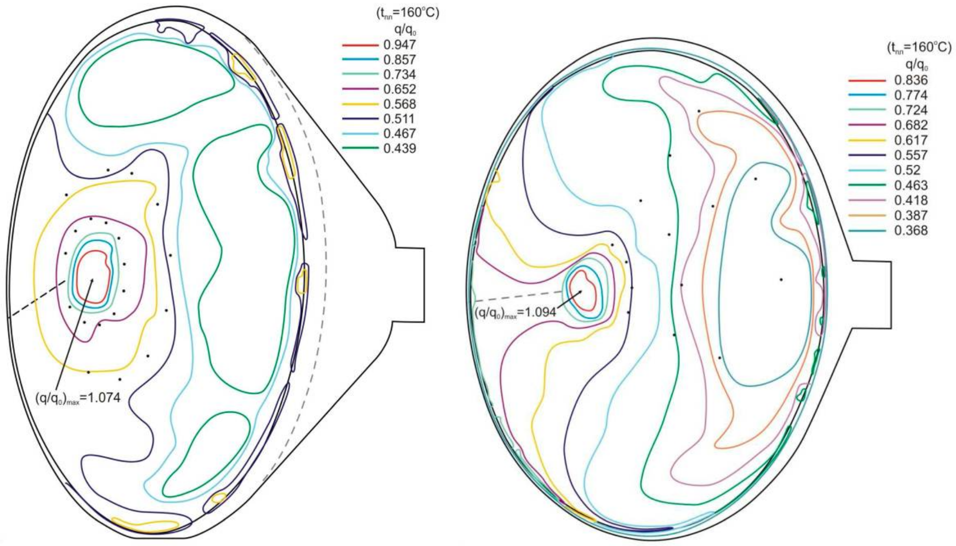
α=0. α=10°.

Fig. 3. Streamlines on front surface of DM-18 model at M=14.

A highly important goal of the investigation was to determine heat flux distribution over the surface of DM-18 module. Heat flux measurements were made at angles of attack α=[0, 10°] by melting paint method and by surface thermocouples (Figures 4, 5). Dimensionless heat flux was calculated relative to characteristic heat flux density q_0 at the front critical line of a cylinder with a radius of r=0.0475 m defined by the Fay-Riddell formula.

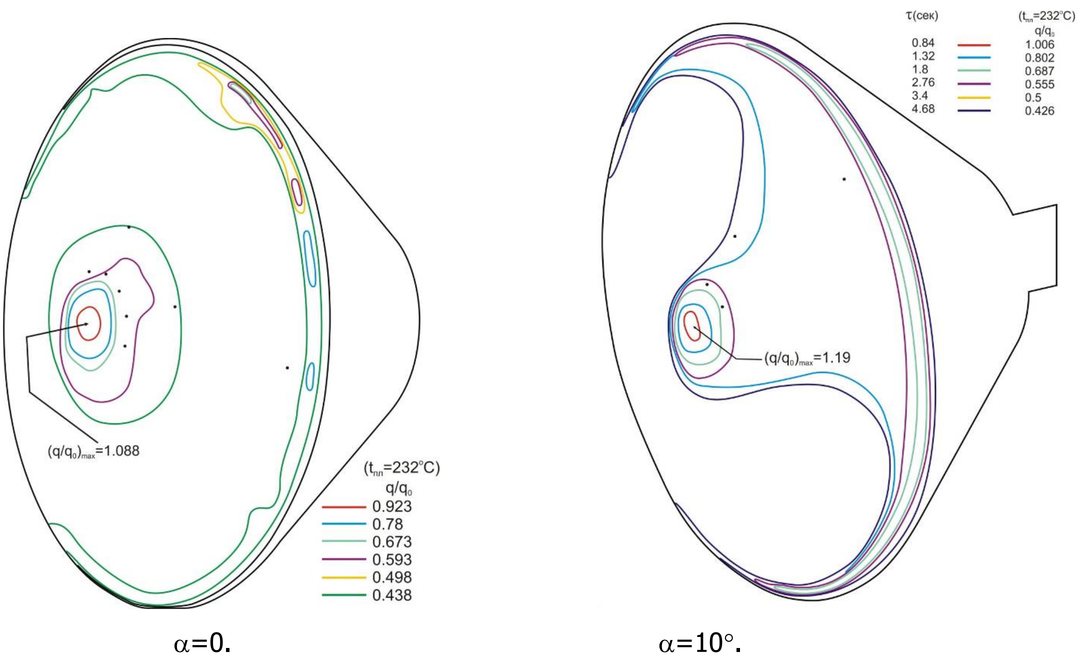
Analysis of heat flux distribution on the front surface of DM-18 model at zero angle of attack (Fig. 4) shows that at M=7.5 and M=10.5 the shape of isolines of Q is rather complicated and not as close to concentric circles as it should be in case of axisymmetric flow (such as obtained in calculations at α=0, for example). A possible reason for this distortion is the presence of a small angle of attack α=-0.15°. But it is unlikely for such a small attack angle to cause such considerable deformation of heat flux distribution. Therefore, the most probable factor to cause complication of heat flux distribution is the beginning of transition to a turbulent flow, which could have taken place at Reynolds numbers of Re=[700000…800000] attained in T-117. This explanation agrees with the results of heat flux measurements at M=14, where the Reynolds number is 5 times smaller (Re=139000), the flow is laminar, and isolines of Q at α=0 are close to concentric circles (Fig. 5).

Apart from the melting paint method, heat flux was measured in 8 points by surface thermocouples. Overall, measurements by thermocouples agree with melting paints' data. Especially valuable results were provided by thermocouples T4-T8 located on the rear cone of the model where the sensitivity of melting paints is not always sufficient. On the rear inverse cone surface, very small heat flux levels were registered, which are 50-100 times lower than maximum values on the windward surface. However, these levels must be known, since the inverse cone of the full-scale vehicle is practically devoid of heat protection.



α=0 α=10°

Fig. 4. Distribution of dimensionless heat flux Q at DM-18 model obtained in T-117 at M=10.5.



α=0. α=10°.

Fig. 5. Distribution of dimensionless heat flux Q at DM-18 model obtained in T-117 at M=14.

On the inverse cone of the model, the result most unexpected was a number of spots of increased heat flux obtained at α=10° for M=7.5 and M=10.5 on the leeward side of the model. On the windward side, at the same time, the heat flux was considerable lower. At a regime with α=10° at M=14, conversely, a spot of increased heat flux was realized on the windward side of the model. The discovered effects can be explained by reorganization of flow separation structure on the inverse cone. At comparatively small values of Re≈139000 which take place at M=14, local reattachment of the flow occurs on the windward side of the inverse cone of the model, while at large values of Re≈800000 (M=10.5, M=7.5) reattachment takes place on the leeward side.

Figure 6 gives a comparison between experimental values of Cx and Cy and the results of numerical simulation of flow and heat transfer of DM-18 module by solution of three-dimensional Navier-Stokes equations, performed by the TsAGI specialist Palchekovskaya N.V. It is evident that calculated and experimental values satisfactorily agree with each other. Figure 7 shows Mach number distribution and streamlines near DM-18 module in a stream with M=7.5 at an angle of attack α=10°.

Based on the data obtained in experiments and in numerical simulations, aerodynamic characteristics of DM-18 descent module in full-scale flight conditions in the Martian atmosphere were estimated.

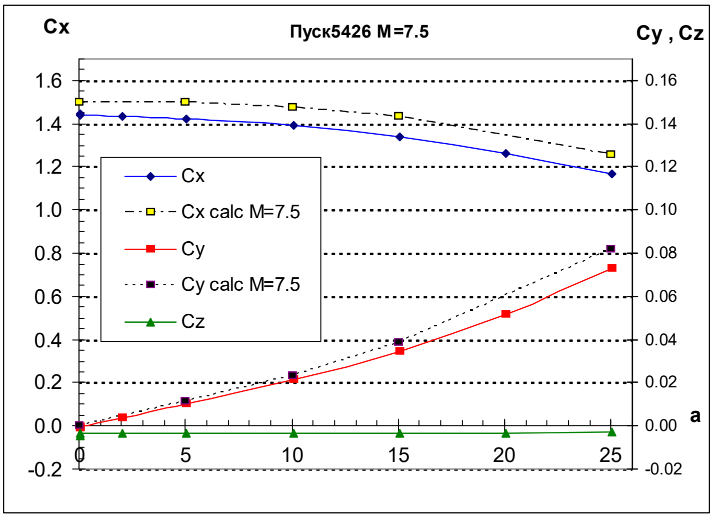


Fig. 6. Comparison of calculated (---calc) and experimental aerodynamic characteristics of DM-18 at M=7.5.

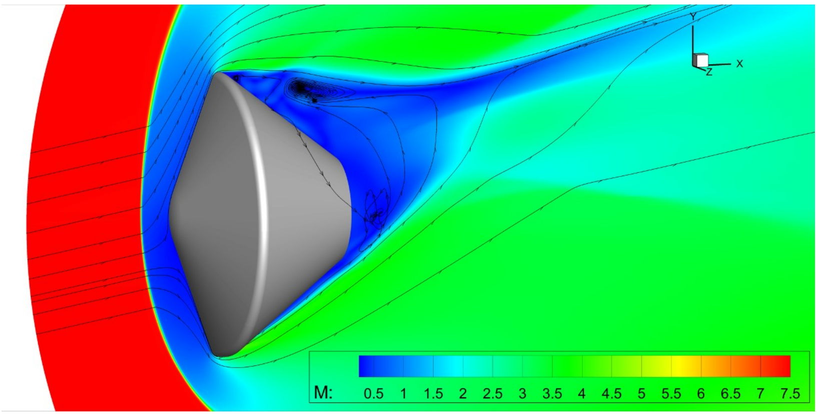


Fig. 7. Mach number distribution and streamlines near DM-18 module obtained in calculations at M=7.5 α=10°.