Aerodynamic and Heating Problems of New-Generation Multi-Stage Launch Vehicles

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Abstract

In the work a three layouts of new launch vehicles are investigated on the subject of flow field structure, pressure and heat flux distribution at hypersonic speeds M_{∞}=[6, 7.5 , 8 , 10.5]. Experiments are performed at TsAGI wind tunnels T-117 and UT-1M. Experimental methods used: flow field visualization, surface streamline visualization, heat flux measurements, pressure fluctuations on the model surface and the temperature in the external part of the boundary layer. It was fined the complicated interaction pattern of shock waves between each other and with the model surface. Such flow pattern is reflected on heat flux distribution on the model surface producing an essential heat flux picks.

1. Introduction

At the present time an active investigations aimed at new generation of launch vehicles (LV) designing are made in Russia. These rockets named as "Angara" and "Russia-M" are intended for crew and payload space transportation. New LV layouts are developed using multistage scheme with parallel connection of stages (modules) having comparable sizes (batch scheme). It produces the serious problems of aerodynamic interference between modules when the peak loads appear on the launch vehicle layout and frequently have unsteady behavior. At hypersonic velocities an aerodynamic problems of such launch vehicle layout aggravated by heat loads that also have peak distribution.

The main purposes of this work is to investigate the flow field structure, pressure and heat flux distribution on the three layouts of multi-stage launch vehicle, to determine regions and elements of vehicle layouts subjected by increased aerodynamic and heat loads, to develop methods and means for vehicle layouts protection from the loads obtained.

2 Experimental techniques and facilities

Experiments performed in the two facilities: TsAGI's T-117 hypersonic WT at M=7.5 ; M=10.5 and TsAGI shock tunnel UT-1M. Hypersonic WT T-117 is a continuous flow wind tunnel. Basic parameters of flow regimes in T-117 are given in Table 2.1. T-117 has a flow heating system including 3 replaceable arc heaters, two of them (EDP-1A/B) having the power rate of 25 MWt and one (EDP-2) – 2.5 MWt. T-117 is accomplished by lengthy (L=5 m) contoured nozzles with exit section diameter of 1 m, which supplies large-scale flow core in the test section, as well as makes it quite uniform and steady. Run in T-117 has sufficient duration (40÷180 sec.), which provides for secure and highly informative performance of all types of ground-based testing. A wide range of angle of attack (α = -5°÷50°, α = 25°÷80°,) and sideslip (β=-30°÷30°) makes it possible to study almost all options of the model location with regard to the flow direction.

In addition to mentioned above it was carried out a number of experiments in TsAGI's shock tunnel UT-1M at Mach numbers M_{∞}=6 and 8.

Table 2.1

Parameter	Nozzles							
	1	2	**3**	4	5	6	7	8
M	**7.5**	8.3	**10.5**	11.6-12.0	13.7-14.0	15.4-15.5	15.6-17.0	17.6-18.6
$Re_{1\,m}\times10^6$	**1.7-8.3**	2.4-8.5	**1.6-4.3**	0.51-1.24	0.37-0.85	0.4-0.5	0.11-0.41	0.1-0.21
$P_0\times10^{-5}$, Pa	**8-26**	13-45	**38-100**	46-103	45-100	100-106	57-200	72-154
T_0, K	**640-800**	770-900	**1100-1800**	1700-2000	1740-1950	2290-2920	2180-2900	2290-3430
Core, m	0.68-0.7	0.68-0.7	**0.6-0.66**	0.38-0.42	0.5-0.55	0.5	0.45-0.5	0.4-0.45
$(\Delta M/M)_R$	**±0.9%**	±1%	**±1%**	±1%	±1.5%	±1.2%	±1.1%	±1.5%
$(\Delta M/M)_{L=1m}$	**+1.5%**	-1%	**+1%**	+1%	+1%	-1.5%	-1%	-1.9%

At these experiments the following investigations are performed:

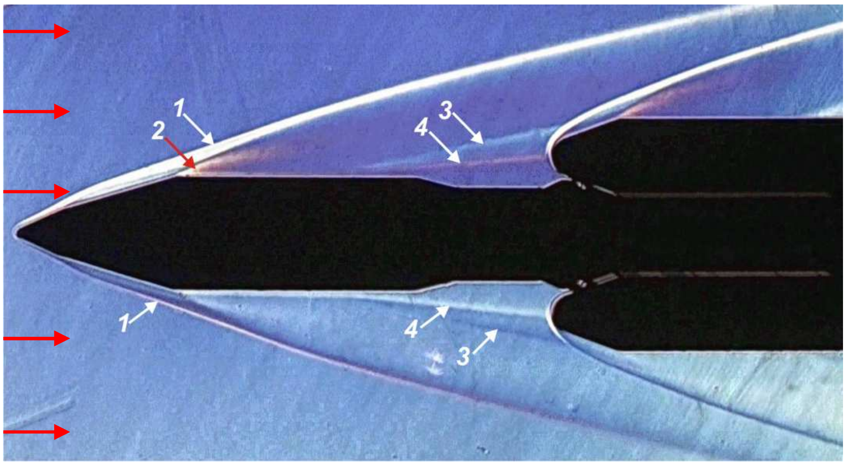
- investigations of pressure distribution on the model surface;
- investigations of pressure pulsations at the 6 points of model surface;
- investigations of surface heat flux by means of thermo sensitive coatings (melting paints) and various gauges (at T-117);
- investigations of surface heat flux by TSP-method (temperature sensitive paint - luminophor) at UT-1M;
- surface streamline visualization;
- schlieren and interferometry flow visualization.

Estimated pressure measurement accuracy after gage individual calibration is $\delta P\approx7$Pa. Three methods are used to measure the model surface heat flux: melting paints and TSP (evaluated accuracy is ±10%) and the calorimetric gages (evaluated accuracy is ±4%). All methods are included in the check-list of typical tests and always used in TsAGI.

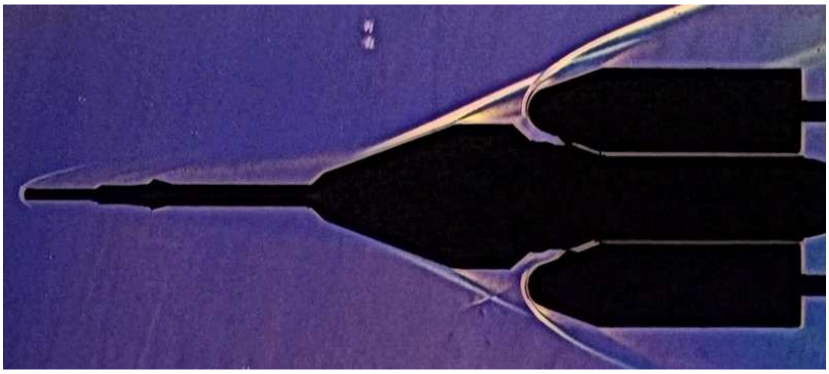
3 Experimental results and discussion

As the research objects the three LV multi-module layouts were chosen which correspond schematically to perspective carrier space rocket “Angara-5” (model designation MLV-A5) and two manned LV variants “Angara-5P” (model designation MLV-A5P) and “Russia-M” (model designation MLV-R). For aerodynamic experiments in TsAGI’s wind tunnels a three models were made: one of them is similar to carrier LV and the other two are similar to manned LV variants.

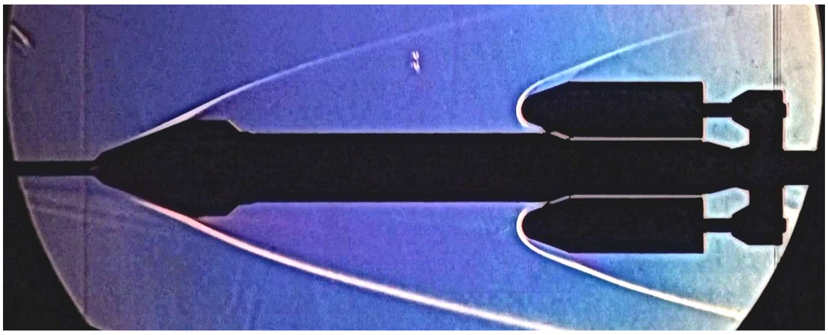
In the fig.1 the shadow pattern of flow field past MLV-A5P model is shown. It was obtained in the T-117 wind tunnel at Mach numbers M_∞=7.5 and $Re_{\infty,L}\approx6\times10^6$. The most complicated interaction pattern of shock waves between each other and with the surface is seen in the case of the model MLV-A5P. The presence of lateral modules causes the unfavourable pressure gradient and the boundary layer separation on the central module surface.



a) model MLV-A5,
1 –head shock, 2 –expansion sector, 3 –oblique shock induced by flow separation,
4, 5 – separation region boundary.



b) model MLV-A5P,



a) model MLV-R

Fig. 1. Schlirein visualisation in the wind tunnel T-117 at $\alpha=0$, $M_\infty=7.5$, $Re_{\infty,\,L}=6\times10^6$.

The surface streamlines visualization will enable identifying the flow peculiarities - the separation lines, the flow reattachment lines and the total stagnation point (fig.2) .

a) model MLV-A5 at α=10, M_∞=7.5 , $Re_{\infty,\,L}=5.5\times10^6$.

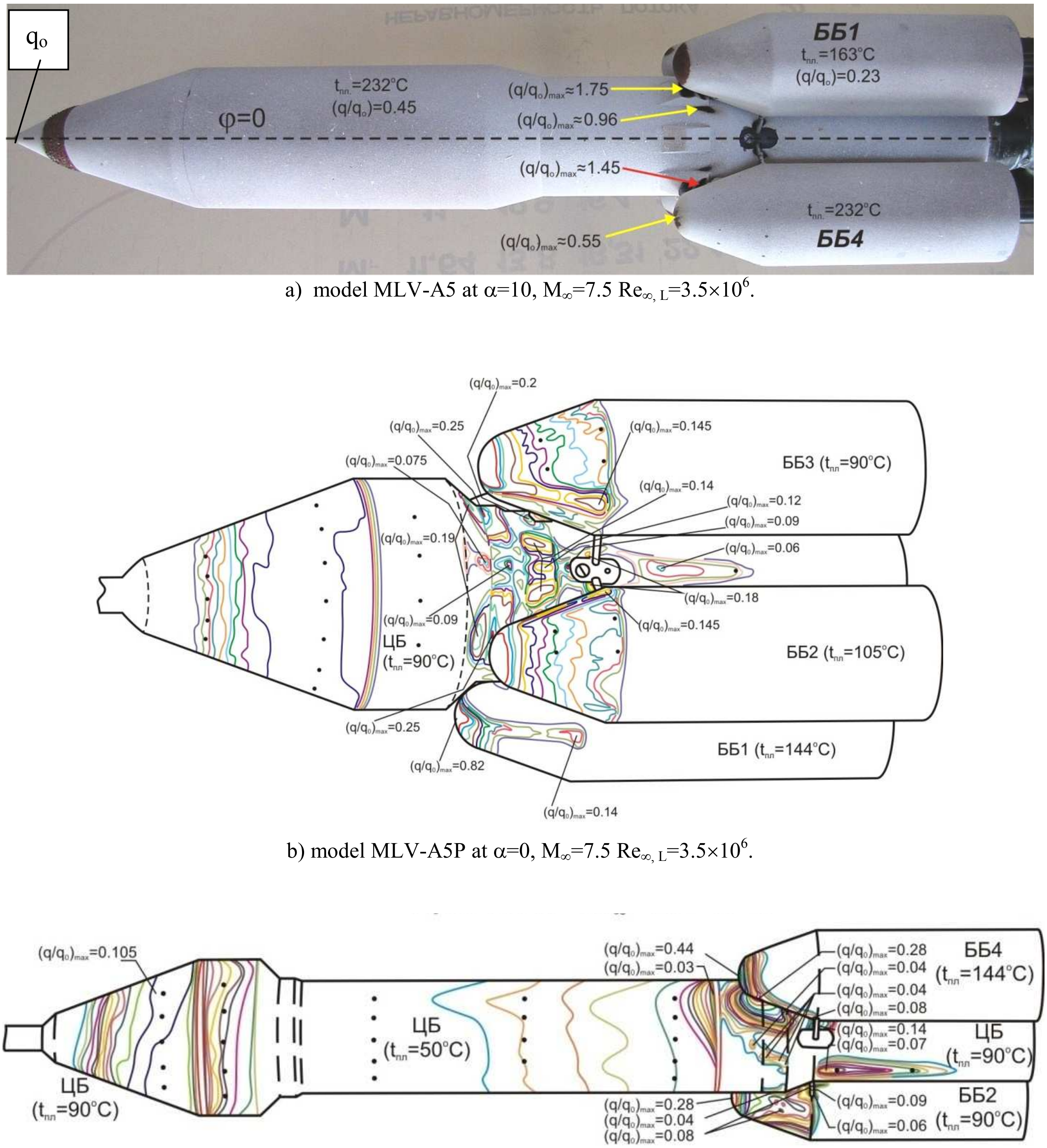

b) model MLV-A5P at α=0, M_∞=7.5 , $Re_{\infty,\,L}=5\times10^6$.


c) model MLV-R at α=0, M_∞=7.5 , $Re_{\infty,\,L}=6\times10^6$.

Fig. 2. Surface flow lines visualisation in the wind tunnel T-117

Complicated flow pattern is reflected on the surface heat flux distribution. Heat flux picks appearance is inevitable at mixing layer reattachment regions. In fig. 3 it is shown the models with thermo sensor after the experiment. The white zones on fig.2a are the regions of unfused sensor but the dark zones correspond to the areas of high heat flux where the sensor have been melt. In this figure the values of relative heat flux q/q_0 at the most heated areas are placed (q_0 is the heat flux value on the head nose stagnation point.). In fig. 3b,c a schemes of isocalorific lines distribution on model surface are shown that was obtained as a result of tests analysis. The most high-heat part is on the central body under the lateral module fairing. In some places a values of heat flux are very big. On the future full-scale vehicle these areas should be protected obligatory.

In fig. 4 the heat flux distribution on the model MLV-A5 is shown. It was obtained as a result of TSP mesurements in TsAGI's shock tunnel UT-1M at α=10° , M_∞=6 , $Re_{\infty,\,L}=3.1\times10^6$.



a) model MLV-A5 at α=10, M_∞=7.5 $Re_{\infty, L}$=3.5×10^6.

b) model MLV-A5P at α=0, M_∞=7.5 $Re_{\infty, L}$=3.5×10^6.

c) model MLV-R at α=0, M_∞=7.5 $Re_{\infty, L}$=3.5×10^6.

Fig. 3. Heat flux measurements in T-117 by thermo sensitive coatings.

To understand time behaviour of the flow an investigation of pressure pulsations at the 6 points on model MLV-A5 surface is performed. The dimensionless pressure pulsation spectrums on the MLV-A5 model are shown in fig.5 atT-117 α=10, M_∞=7.5 $Re_{\infty, L}$=3.5×10^6. It is seen the high chaotic pressure pulsation in the region of strong aerodynamic interference.

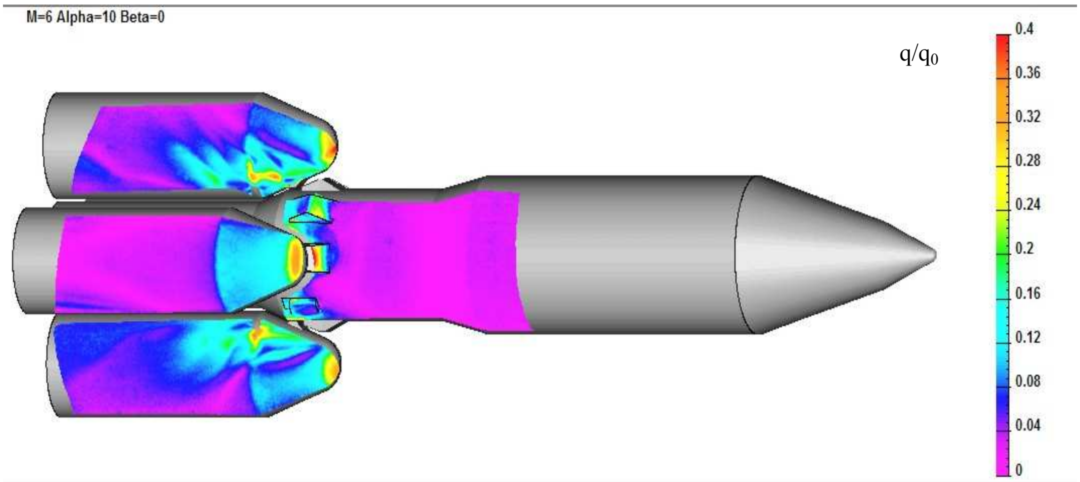


Fig.4. Heat flux measurements by TSP. UT-1M, model MLV-A5 at α=10, M_∞=6, $Re_{\infty, L}=3.1\times10^6$.

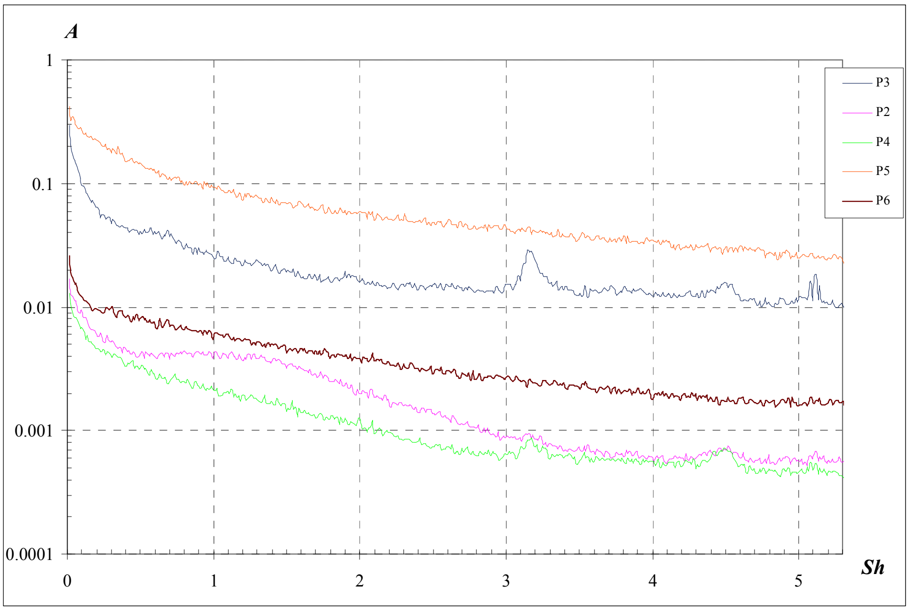


Fig.5 Pressure pulsation spectrums on the MLV-A5 model atT-117 α=10, M_∞=7.5 $Re_{\infty, L}=3.5\times10^6$.

Conclusion

Due to aerodynamic interference the hypersonic flow filed past multistage launch vehicle possesses the complicated character with separation zones and opposite flow in front of the lateral blocks. Complex 3D flow realized in the gap between blocks and in the regions of body superstructures and shock-shock interaction.

From the three LV layouts investigated the MLV-A5P is most problematic from the aerodynamic interference, flow filed structure and heat flux peculiarities points of view.

The main aerodynamic problem of LV cargo variant MLV-A5 is a strong interaction of separated flow past central head module and bow shock waves produced by lateral modules. At α=0 the flow filed past MLV-A5 is mainly laminar and steady in the range of investigated parameters. Pressure pulsations observed only on the lateral block fairing and in the gap between blocks. Maximum heat flux is moderate (q/q_0=0.55) and observed also on the lateral block fairing. At α=10° the pressure pulsations rise essentially (>10 times) on the lateral block fairing, in the gap between blocks and in the regions of launcher body superstructures. In the same places very high heat flux peaks (q/q_0=1.75) are obtained. Obviously it is dangerous for the launch vehicle design.

For the model MLV-R the aerodynamic and heating problems are comparatively less due to less aerodynamic interference of modules.

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