MATHEMATICAL MODEL OF FLIGHT DYNAMICS, INTERNAL AND EXTERNAL AERODYNAMICS, HEATING AND RADIATION OF HYPERSONIC VEHICLES

1. Introduction

A mathematical model is presented. It takes into account flight dynamics, internal and external aerodynamics, heating and radiation of hypersonic vehicles. This model is to be used for analysis of interaction of those processes during multiple-factor optimization of concept and different aspects of applications of hypersonic vehicles. For example, a range of first sighting of a vehicle on base of its infrared radiation with regard to different factors in flight is analyzed.

2. Model of hypersonic vehicle flight and registration with infrared detectors

The model of a hypersonic vehicle is described. The flight dynamics was computed on base of the system of equations of three-dimensional rigid body movement. Semi-empirical relations were used for modeling of the hypersonic flow over the vehicle and for calculation of local heat transfer rates. Both laminar and turbulent boundary layers and the laminar-turbulent transition with account for compressibility were considered. Flow characteristics behind shock waves and in Prandtl-Meyer flow were calculated with the help of analytical relations. Unsteady heating of structures inside the vehicle was considered, for instance, with the "outer layer" of machinery and devices which absorb radiation from the wall, and the "inner parts" which are shielded by this layer. Thermal conduction and heat emission were taken into account in calculation of the internal heat transfer. A possibility of account of active cooling of the engine walls was provided.

The channel approximation was used to describe gas dynamics in the engine, with taking into account that the transverse gradients of flow core parameters were small, with boundary layers corresponding to the initial and main parts of the flow in a ring channel of alternate diameters, with fuel income and energy release being distributed in a preselected volume of the burner section. Mass and energy income was determined from the fuel-flow rate. The program offers an opportunity to specify different laws of control of fuel injection, including real-time manual control. In this work the fuel-flow rate was in a direct proportion to the air flow rate in order to keep constant the excess air ratio.

In our calculations we used the law of control which was keeping a constant angle of attack during all the flight. In case of variable height, but constant velocity of flight it corresponds to conservation of the shock wave structure in front of the engine, which makes it possible to optimize ramjet operation without any additional adjusting of this structure.

The heat radiation power was calculated in flight for a selected spectral band of infrared detectors disposed on the ground. Integration of the heat radiation from elements of the surface of the vehicle was carried out with account to its detailed geometry, heating rate distribution, changing position of the vehicle relatively the detectors, the Earth surface curvature, etc. The moment of registration of the vehicle by a detector was determined with comparison of the calculated radiation flux with the typical threshold parameters of the 3rd generation night-vision devices with the coefficient of light amplification from 60 000 to 100 000.

3. Results of modeling

An example of five detectors was considered: the position of the 1st detector is on the distance X = 250 km from the point of start of the vehicle (in the direction of flight), and Y=0 shift from its course; 2nd – X= 500 km and Y=150 km (shift to the left), 3rd – X = 750 km and Y = −100 km (shift to the right), 4th – X = 1000 km, Y = 450 km (shift to the left), 5th – X = 1250 km, Y = 0.

The considered version of design supposed engine cooling via endothermic reaction of fuel decomposition. A screen was placed between the upper engine wall and the devices above the engine, in order to block the heat flow from the engine to the fuel tank and the devices above the engine. Fuel was used for cooling of the engine.

Three cases were considered: A – without additional means of chilling and insulation, B – with heat insulation of the surface below the engine via installation of an additional screen, C – with heat insulation of the version B and with active chilling (down to 400 K) of the air intake and aerodynamic control surfaces (winglets).

The trajectory of flight was periodical, with oscillations of height and other kinematic parameters. The horizontal velocity increased a bit at the beginning and then remained almost constant.

Area mean temperatures of some parts of the vehicle were calculated. The most heated place was on the surface below the engine. Heat insulation of the engine (case B) brought down the area mean temperature of the lower surface, and then the most intensive radiation came from the last stage of the air intake and from the aerodynamic control surfaces. Their active chilling (case C) brought to further lowering of the radiation.

The vehicle detection was determined as the moment of exceeding of the threshold radiation power received by the detector within its frequency band.

In the case A the vehicle was detected in points 3, 4, 5 just after its rising above the horizon, in points 1, 2 it was detected later. The range of first sighting in point 1 was much less than that in point 5, though both points were placed on-course. One of the reasons of this fact is that the 1st and 2nd detectors received the radiation from relatively cold surfaces of the vehicle, because then it was subject to aerodynamic heating for a comparatively short time period.

In the cases B and C the heat flow rates were much less than in the case A. That is why the vehicle was detected much later in the points 1-3 and 5, and it was not detected at all in the 4th point (this detector was too far from the course).

The ranges of first sighting have proved to be dependent also on the phase of the periodic flight at the time when the vehicle approaches the average registration limit. The range of first sighting is minimal during the phase of ascend, because the vehicle is just heated in the lower layers of the atmosphere, and its hottest lower side is directed to the detector. During the phase of descent the vehicle is cooler, and its lower side is hidden from the detector, so the range of first sighting is maximal. Thus the moment of detection can be delayed considerably by optimizing the phase of flight.

The distance Y between the trajectory of the vehicle and the detector is important too. Besides the dependence due to the divergence of radiation, the radiation power is lower at higher Y due to the relative direction, because the lateral surfaces are relatively cold, and the observation angle for the most heated lower surfaces is smaller.

The presented data also show that the described means of radiation mitigation (the engine thermal insulation, active chilling of the air intake and the control surfaces) are effective.

4. Conclusion

The developed model makes it possible to calculate various aspects of in-flight operation of subsystems of a hypersonic vehicle. For instance, the power of infrared radiation of a hypersonic vehicle on positions of stationary infrared detectors with account to a number of factors can be calculated, which can be useful for some applications.

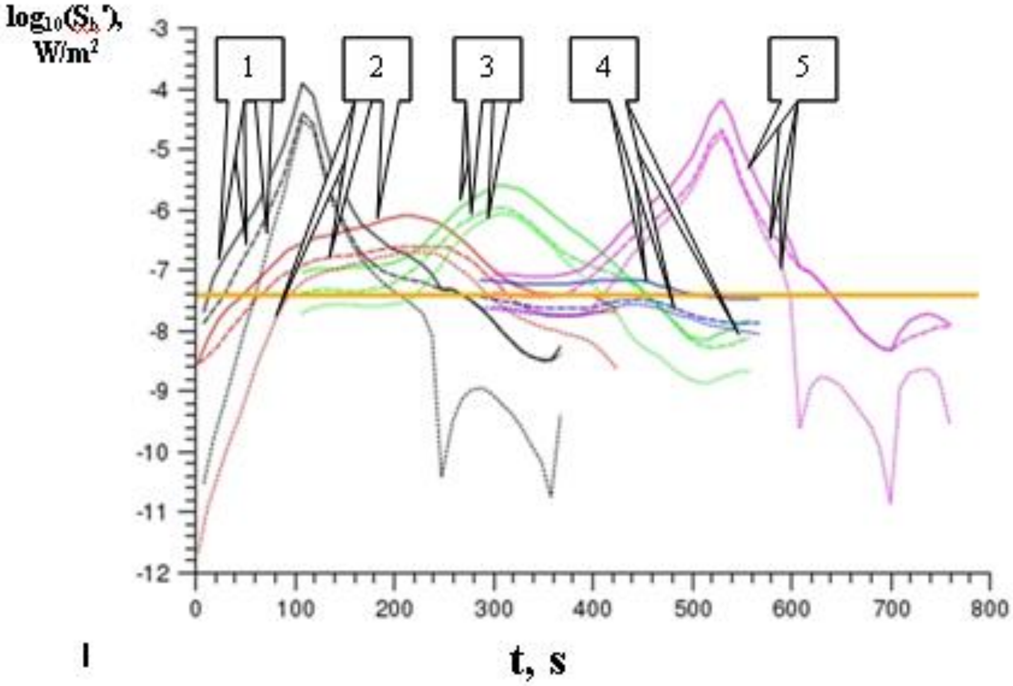

Figure. Radiation flux density (logarithmic scale) for different detectors (indicated by numbers).

Full lines – case A (without additional insulation or chilling), dashed lines – case B (with engine insulation), dotted line – case C (with engine insulation and active chilling of air intake and control surfaces). The horizontal line corresponds to the registration limit for a 3rd generation infrared detector