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HEAT EXCHANGE MODELING ON THE AIRCRAFT SURFACE UNDER HYPERSONIC SPEED OF THE APPROACH FLOW

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ABSTRACT

The paper discusses the principles of modeling thermal interaction between aircraft protective coatings and approach flow. This work has developed software with relation to the flight of aircraft moving at high supersonic speeds combined functional setting for boundary conditions of various types particularly parameters of the atmosphere and hypersonic aircraft (HA) prototype material, reference flight conditions, parameters of the approach flow, etc. In this study, the hypersonic gas flow is considered as chemically nonequilibrium medium, which is an intermediate state of equilibrium and stagnated flows. The results from the numerical simulation of heat exchange on the winged vehicle surface at hypersonic flow rate are given.

1. INTRODUCTION

The purpose of the work is to demonstrate the developed software effectiveness in relation to the flight of aircraft moving at high supersonic speeds. The purpose was achieved with the help of the developed complex of programs which allowed setting boundary conditions of various types: parameters of the atmosphere and hypersonic aircraft (HA) prototype material, reference flight conditions, parameters of the approach flow, etc. The main task of hypersonic flow aerodynamics is to develop such materials that could withstand adequate stress from the approach flow. On the aircraft surface, temperatures can range from several hundred to several thousand degrees, depending on the flight height [1]. It makes the unmanned aircraft control difficult, since at sufficiently large Mach numbers (M> 10) an intense ablation of the protective metal layers (sublimation) occurs, which is caused by the plasma formation effect. For such high temperatures, hydrodynamic equations for gases and plasma are derived in two ways: phenomenological and statistical. The first takes into account all known equations of energy, mass, momentum. The second takes into account the molecular-kinetic concepts of matter for media to which the corresponding kinetic equations can be applied. The intense dissociation of subliming substance molecules makes control of such vehicles quite difficult due to the plasma electromagnetic effect, which can disrupt the aircraft flight path. This imposes

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certain difficulties in further structuring and study of such tasks. There is a small number of works where the problem of modeling heat transfer on the aircraft surface under supersonic and hypersonic flows is touched upon, [1, 2]. The basic principles of modeling heat transfer on the HA surface in a hypersonic flow and the results were given in the paper [3, 4]. Conducting flight tests is costly, so now the role of numerical modeling is greatly increasing. When designing advanced aircraft, as a rule, numerical studies of the flow around the proposed airframe configurations are carried out, which significantly reduce the cost of testing in wind tunnels. In the process of calculation it is possible to determine the main parameters of the flow: pressure on the aircraft surface, base pressure, temperature changes of the fuselage hull, formation of areas of streamlined gas flow recirculation, etc. This becomes especially relevant when modeling hypersonic flight conditions. The main condition that is applicable to such streams is that the path length of the sound wave is comparable or does not exceed aircraft characteristic size l ~ d. Since the flow is chemically non-equilibrium during the motion, we should consider the motion for the two extreme states: equilibrium and stagnated. In hypersonic flows, chemical nonequilibrium is decisive in describing such flows. An equilibrium flow increases the flow base pressure behind the fuselage cut, which provokes the formation of vortex zones. The shock waves arising on the surface, large temperature drops, ablation of the fuselage protective coating are among the most important in the compilation of flight description models of such vehicles in aerodynamics. Also, the determining factor in solving problems of hypersonic aerodynamics is consideration of a two-phase boundary layer [5], which consists of dispersed water droplets adjacent to the HA surface.

2. CALCULATION METHOD

In order to determine the flow structure and parameters of the flow, it is necessary to transform the system of differential equations of Navier-Stokes to a form that would take into account the geometry of changes in the heating surface. These equations for hypersonic flow have formed [2]:

$$\rho\left(u\frac{\partial u}{\partial s}+v\frac{\partial u}{\partial n}-\frac{\sin\theta}{r}\omega^2\right)=-\frac{k-1}{2k}\frac{\partial p}{\partial s}+\frac{\partial}{\partial n}\left(\frac{2k\mu}{Re(k-1)}\frac{\partial u}{\partial n}\right) \quad (1),$$

$$\rho\left(u\frac{\partial \omega}{\partial s}+v\frac{\partial \omega}{\partial n}+\frac{\sin\theta}{r}u\omega\right)=\frac{\partial}{\partial n}\left(\frac{2k\mu}{Re(k-1)}\frac{\partial u}{\partial n}\right) \quad (2),$$

$$\rho\left(u\frac{\partial T}{\partial s}+v\frac{\partial T}{\partial n}\right)=u\frac{k-1}{k}\frac{\partial p}{\partial s}+\frac{\mu k}{Re(k-1)}\left[\left(\frac{\partial u}{\partial n}\right)^2+\left(\frac{\partial \omega}{\partial n}\right)^2\right]+\frac{\partial}{\partial n}\left(\frac{2k\mu}{Re(k-1)}\frac{\partial T}{\partial n}\right) \quad (3),$$

$$\frac{\partial p}{\partial n}=\rho\left(\mathrm{k}u^2+\frac{\cos\theta}{r}\omega^2\right) \quad (4),$$

$$\frac{\partial}{\partial s}(\rho r u)+\frac{\partial}{\partial n}(\rho r v)=0 \quad (5),$$

where $V_\infty=\sqrt{u^2+v^2+\omega^2}$, n - normal to the body; s - straight line, measured from the front critical point along the generatrix of the body; u, v, ω - components of the velocity vector of the incident gas; k - curvature of the body surface, gas adiabat index; T - temperature of the flowing gas; Re - Reynolds number; ρ - gas density; r - distance from the body surface to its longitudinal axis.

The system of Equations (1)–(5) needs to be transformed to consider the more explicit twodimensional case. To do this, with a hypersonic flight speed of the aircraft take, $Re = \infty$ and longitudinal component of the flow velocity ω:

$$\rho\left(u\frac{\partial T}{\partial s}+v\frac{\partial T}{\partial n}\right)=u\frac{k-1}{k}\frac{\partial p}{\partial s} \qquad (6),$$

$$\rho\left(u\frac{\partial u}{\partial s}+v\frac{\partial u}{\partial n}\right)=-\frac{k-1}{2k}\frac{\partial p}{\partial s} \qquad (7),$$

$$\frac{\partial p}{\partial n}=\mathrm{k}u^2\rho \qquad (8),$$

$$\frac{\partial u}{\partial s}+\frac{\partial v}{\partial n}=0 \qquad (9).$$

The differential Equation (6) can be converted to form

$$\rho\left(u\frac{\partial T}{\partial s}+v\frac{\partial T}{\partial n}\right)=\lambda\frac{k-1}{k}\frac{d^2T}{dn^2} \qquad (10).$$

This differential equation allows us to relate the dynamic and thermal parameters when calculating heat transfer on the aircraft surface. The distribution of speed and temperature is presented in the form of polynomials: $u=a+b\left(\frac{n}{\delta}\right)+c\left(\frac{n}{\delta}\right)^2$, $T=A+B\left(\frac{n}{\delta}\right)+C\left(\frac{n}{\delta}\right)^2$. Then we get [3]:

$$T-T_{плав}=\lambda\delta\frac{k-1}{k}\left(1-\left(\frac{n}{\delta}\right)^2\right) \qquad (11).$$

To determine the temperature and heat flow fields, the results of which are given below, the three-dimensional heat conduction equation was used.

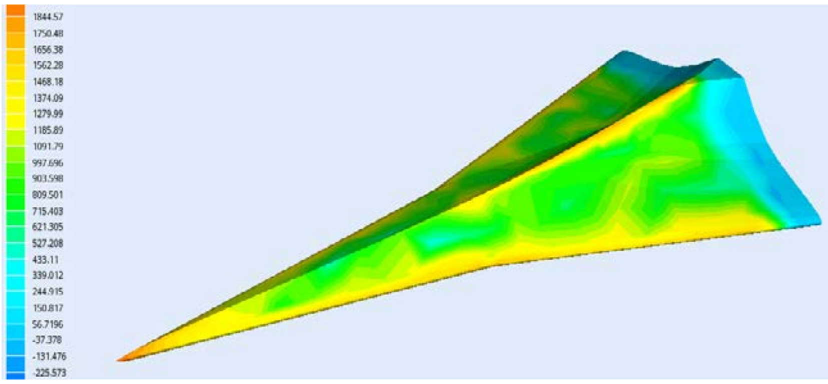

Figure 1: Distribution of heat flows on the surface of the winged vehicle at M_∞= 17. Non-catalytic surface. In a yellow - temperature of 1278 K.

3. RESULTS

After setting the parameters of the atmosphere (working gas - air with the temperature of 30 °C, being in statistical equilibrium), speed of the flow approaching the model, flow temperature, gas flow area, we will obtain patterns of heat flow distribution on the winged vehicle surface. Then we set the atmosphere parameters, heat transfer coefficient (~500-650), as well as the material, its thermal conductivity, the prototype initial parameters, the approach flow temperature, and number M_∞. Already after 500 seconds, the aircraft surface is heated to the temperature of 1100 degrees. In Figures 1 and 2, the vehicle is flowed around at M_∞ = 17. In all cases, the environmental parameters remained unchanged.   The mesh density was about 0.01.   Flow times in Figures 1 to 5 are 26, 158, 26, 72 and 217 sec. respectively.

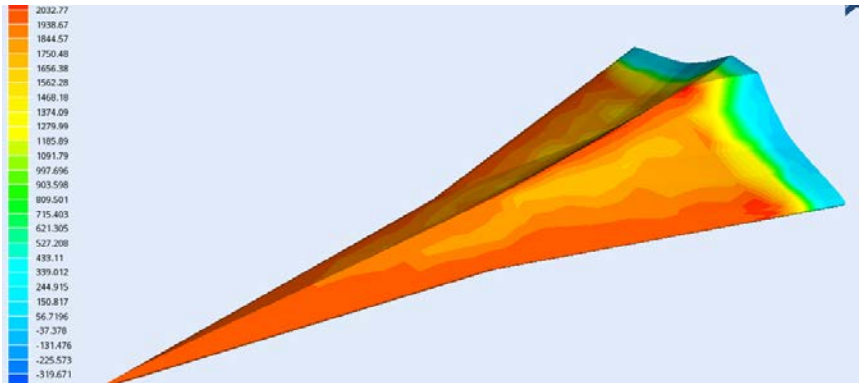

Figure 2: Distribution of heat flows on the surface of the winged vehicle at M_∞ = 17. In red - temperature of 1939 K

There are many thermal protection methods that use different materials, but they often do not meet the specified requirements or impose severe restrictions at extremely high heat flows in local areas of the HA surface. For example, the sharp edges of the air intake of a high-speed aircraft should be slightly blunt. But the decrease in the radius of blunting is usually hampered by an increase in the temperature of individual sections of the HA. This can be observed on the lower part of the model's fuselage (Figures 3-5), where there is a sharp temperature rise in the front part of the aircraft, which then begins to spread over the entire surface of the aircraft. The obtained results complete the picture of the distribution of heat flows on the HA fuselage surface, which makes the study of thermal loads more explicit. The main methods of aircraft thermal protection are divided into passive and active. In the latter case, it is composite thermal protection coatings [6] which use, for example, secondary gas injection into the boundary layer adjacent to the surface - the so-called transpiration cooling. This method allows for obtaining a high-efficiency level of the aircraft surface cooling. In the future, the main directions for dealing with high temperatures should take into account both passive and active methods.

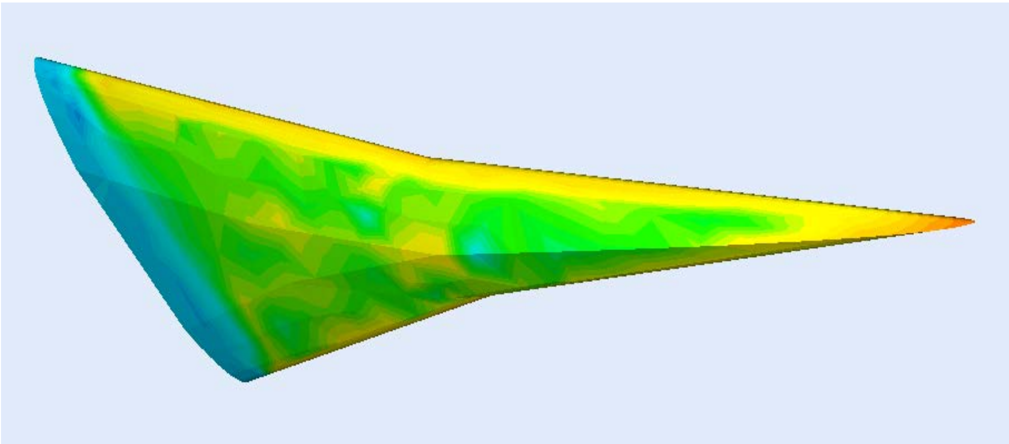

Figure 3: Distribution of heat flows on the surface of the winged vehicle at $M\infty$ = 17. Non-catalytic surface. In a yellow - temperature of 1278 K

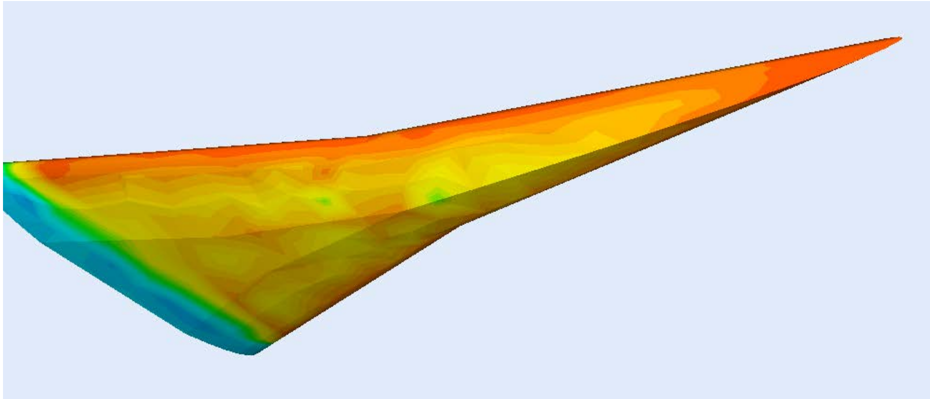

Figure 4: Distribution of heat flows on the surface of the winged vehicle at M_∞ = 17.

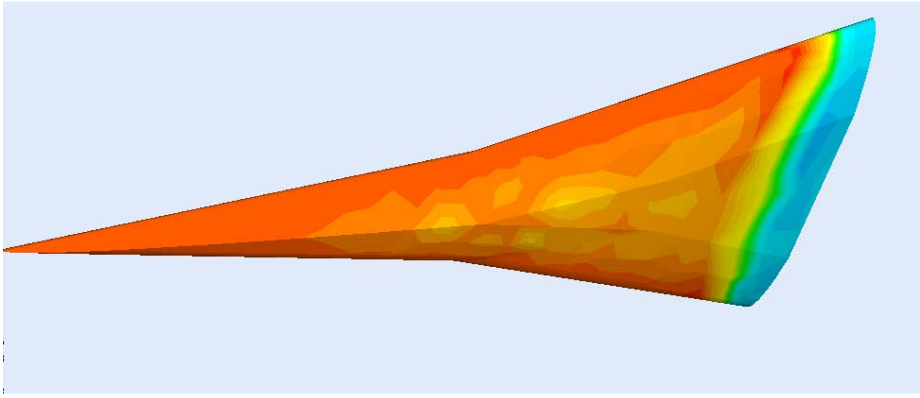

Figure 5: Distribution of heat flows on the surface of the winged vehicle at M_∞ = 17.

At hypersonic flight speeds, the aerodynamic characteristics of the entire aircraft and its individual elements will significantly influence the characteristics of the power plant, since the mechanical interaction between the HA of the complex geometry and the hypersonic flow leads to intense interacting shock waves occurrence. Therefore, the fundamental conceptual task of HA designing should be an integration of the fuselage, wings, and engine into a single system. In this case, it is necessary to limit the allowable range of attack angles and the area of attachment for head pressure jump.

4. CONCLUSION

Based on the developed software, which allows taking into account the atmosphere parameters, as well as the hypersonic flow characteristics, we obtained the thermal patterns of the heat flows distribution on the fuselage surface of the winged vehicle type HA. For a more balanced picture of heat flows, it is necessary to take into account catalytic reactions on the HA surface, since at high velocities of the approach flow, we have to take into account phenomena of the ablative and sublimation types. In this case, it is necessary to find a compromise in a sufficiently large area of equilibrium and non-equilibrium flow of the gas stream, since in case of chemical nonequilibrium, the spread of theoretically calculated data will oscillate between two types of the hypersonic flow. This becomes relevant when one has to consider different types of flows when calculating the flow in different nozzles or in a scramjet.

5. REFERENCES

[1] G.G. Cherniy Hypersonic flow around wings at high angles of attack. Working Papers Academy of Sciences of the USSR. 1964, 155(2): 302-305.

[2] Yu.P.Golovachev Numerical simulation of viscous gas flow in a shock layer. Nauka FIZMATLIT. M.: 1996.

[3] G.G. Cherniy Motion of a melting solid between two half-spaces. Working Papers Academy of Sciences of the USSR. 1985, 282(4): 813-818.

[4] A.A. Chernykh, A.I. Sharapov, A.V. Peshkova, and Y.V. Shatskikh. Comparison of heat exchange progress when conjugins bodies by hypersonic flow. The Turkish Online Journal of Design, Art, and Communication. 2018, Special Edition, 465-474.

[5] A.A. Chernykh, V.Ya Gubarev / Propagation of sound waves in two-phase environments / Energy saving and efficiency in technical systems Proceedings of the V^{th} International Scientific and Technical Conference of students, young scientists and specialists. TSTU – 2018: 272-273.

[6] A.A. Chernykh Approach to the determination of thermal conductivity of composite materials with filler/ Energy saving and efficiency in technical systems Proceedings of the Vth International Scientific and Technical Conference of students, young scientists and specialists. TSTU – 2018.

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