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WILL THERE OR WILL THERE NOT BE A HYPERSONIC AIRPLANE?

Yu. V. Polezhaev

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An analytical overview of the problems of heat transfer occurring in horizontal flight of a body in the earth's atmosphere at a hypersonic speed is given. It is shown that, despite the enormous experience accumulated in the design and development of shuttle systems (Space Shuttle, Buran), the creation of a hypersonic airplane still remains a serious scientific and technological problem, the solution of which will require fundamentally new methods of protecting the structure against aerodynamic heating.

Introduction. Hypersonic refers to the whole range of flying speeds, to which the Mach numbers, from 6 and up, correspond. In the context of the gasdynamics of flow about bodies of a simple geometric shape (a cone, a wedge, etc.), this range is even easier to analyze than the subsonic or supersonic range. The stabilization of the shape of the bow shock wave for $M_\infty > 6$ results in self-similarity of the pressure and heat-flux distributions along the generatrix of the body in flow. However, the heat transfer theory points to a number of new physical phenomena that occur in the air when it flows with high Mach numbers. First of all, this is the dissociation of the main molecular components of air–oxygen and nitrogen. The appearance of atoms, ions, and electrons behind the shock wave intensities to a great extent the thermal action of the incoming flow on the surface of the aircraft, which, in turn, requires of the designers of aeronautical engineering and rocketry the development of special methods of thermal protection [1]. The interaction of the bow shock wave with elements of the wing or the steering did not turn out to be a less difficult problem. The decrease in the shock can increase by an order of magnitude the pressure on the surface in flow and cause a similarly intense increase in the heat flux [2].

All these problems in full measure confronted, too, the designers of shuttle systems and were successfully solved by them. Although the shape of the recoverable aircraft can only be tentatively classified as a classical "airplane" shape, it is generally agreed that the first hypersonic flight in the atmosphere took place on April 12, 1981. It is also known that before the Space Shuttle recoverable module was commissioned, several experimental aircraft (X-15, Bor-4) had been manufactured and tested under flying conditions. Nonetheless, there was no hypersonic airplane among them.

An airplane, unlike recoverable modules of spacecraft, can fly horizontally, using its high aerodynamic quality and a continuously operating propulsion system. The first condition makes it possible to create the necessary level of the lift and to balance the gravity, while the second one ensures the overcoming of resistance forces both tangential (friction) and normal to the outer surface of the airplane (pressure forces).

Aeronautical engineering was getting ready to break through the hypersonic barrier as early as in the 1960s. Figure 1 borrowed from the Great Soviet Encyclopedia (Aviation) shows a diagram of the growth in the flying speeds of Soviet fighters and bombers. If the speed-growth trend had remained the same, the hypersonic barriers would have been broken through by the end of the 1960s. However, this did not happen. Even at the threshold of a new millennium one cannot claim that a passenger flight over the ocean in an hour or an hour and a half can be realized in the near future.

Distinctive Features of a Hypersonic Airplane. As a first approximation, the hypersonic airplane differs from other types of airplanes only by the flying speed V_∞. However, even with Mach numbers M_∞ higher

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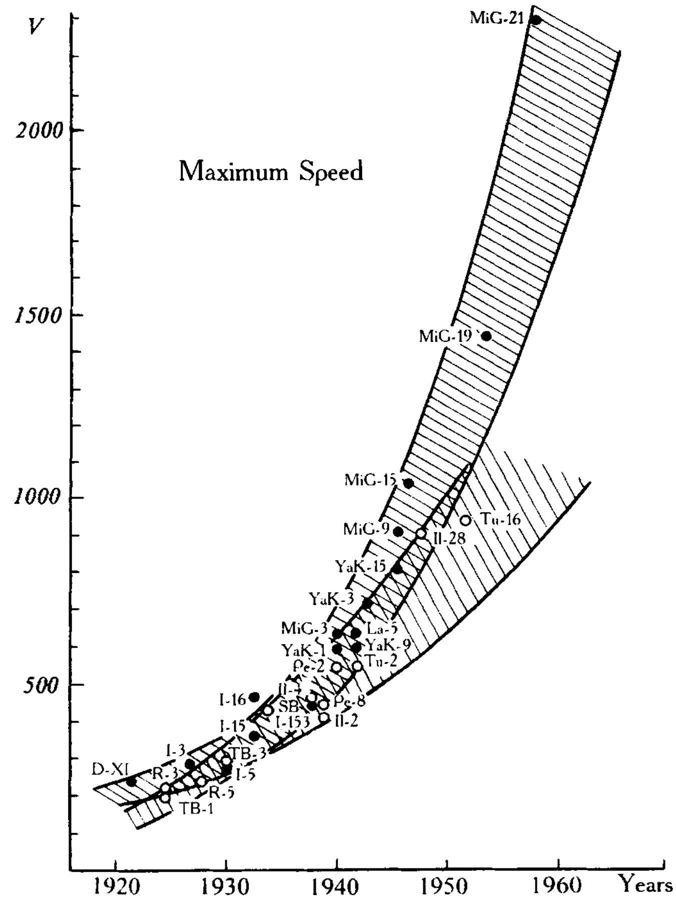


Fig. 1. Diagrams of the growth in flying speeds of Soviet airplanes in 40 years. V, km/h.

than 3 the usual turbojet engines have to be abandoned in favor of compressorless ramjet engines. As the flying speed increases further, compressorless ramjet engines become inefficient, too, and they are being replaced by hypersonic ramjet engines. It is not difficult to understand that the entire arrangement of the hypersonic airplane must be governed by the task of providing the ramjet engine with the required flow rate of air. While solving this gasdynamic problem, an aircraft designer has to integrate the fuselage, the wing, and the engine into a unified system, rigidly limiting the permissible angle-of-attack range and the site of attachment of the bow shock.

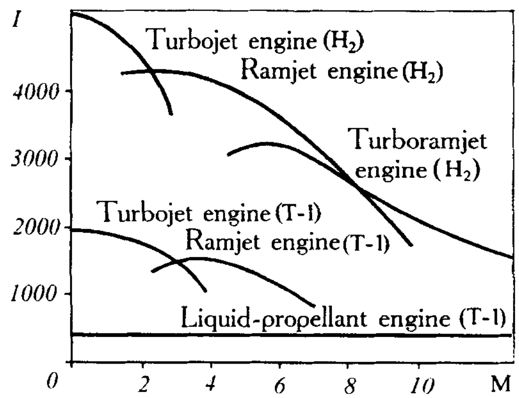
There are even more differences to be noted between a hypersonic airplane and a recoverable module of a Buran-type shuttle system. Here the priority parameters are the flight range L and the payload mass, or, to be more precise, the ratio of this mass to the starting mass of the entire aircraft m_0.

Unlike recoverable modules of shuttle systems, a hypersonic airplane has a long segment of horizontal flight in the earth's atmosphere with a constant speed V_∞. It is possible to ensure this regime of flight only if two conditions are fulfilled simultaneously:

a) the engine thrust power must balance the aerodynamic-resistance force usually determined as the product $C_x S \rho_\infty V_\infty^2/2$;

b) the lift of the wing+fuselage arrangement, which is equal to $C_y S \rho_\infty V_\infty^2/2$, must balance the force of gravity (mg).

Here C_x and C_y are the coefficient of aerodynamic resistance and the lift coefficient, whose ratio is called the airplane's aerodynamic quality: $K = C_y/C_x$; S is the characteristic cross-sectional area of the airplane; ρ_∞ is the atmospheric density at the flight altitude H determined as a first approximation as



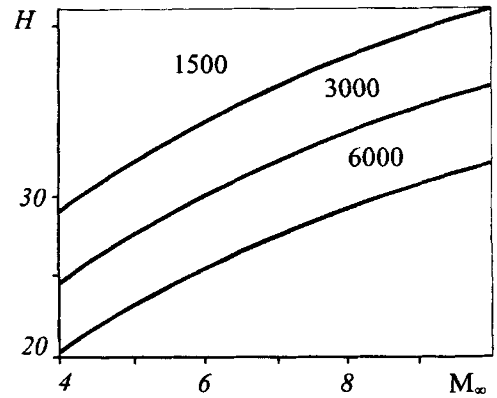


Fig. 2. Specific pulse of the fuel vs. flying speed (the Mach number) and type of propulsion system. I, sec.

Fig. 3. Horizontal-flight altitude vs. Mach number and load on the wing $mg/(C_y S)$ (kg/m^2). H, km.

$$\rho_\infty = \rho_0 \exp(-\beta H), \tag{1}$$

where ρ_0 is the atmospheric density at sea level and $\beta = 7100^{-1}$ m^{-1} for the lower layers of the Earth's atmosphere.

The engine thrust F_x depends on the flow rate of the fuel and the specific pulse I inherent in it. Figure 2 presents the data [3] on the specific pulse of hydrocarbon fuel (T-1) and hydrogen (H_2). It is shown that, unlike the liquid-propellant engine, the specific pulse in a turbojet or a ramjet engine varies within wide limits as the Mach number of the flight increases. The specific pulse I has a determining effect on the flight range L. This can easily be established by combining obligatory conditions a) and b) to ensure a horizontal flight. Using them we derive the relation for calculating L (the Breguet formula)

$$L = KIV_\infty \ln\left(\frac{m_0}{m_0 - m_f}\right), \tag{2}$$

where m_0 is the starting mass of the airplane and m_f is the mass of the fuel.

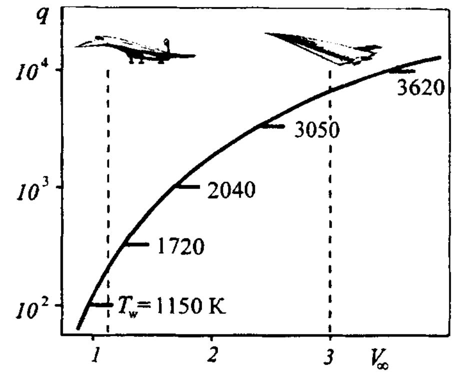
Finally, condition b) enables us to determine the altitude H of the horizontal flight as a function of the permissible load on the wing $mg/C_y S$

$$H = \frac{1}{\beta} \ln\left[\frac{\rho_0 C_y S V_\infty^2}{2mg}\right]. \tag{3}$$

A typical spread in the values of H as functions of the Mach number and the load on the wing is shown in Fig. 3.

Thermal Regime of a Hypersonic Airplane. Let us assume that the range of the horizontal flight L = 10,000 km is selected as the "reference" point. Using formula (2) we can show that a hydrogen (H_2) ramjet engine can ensure the flight of a hypersonic airplane within this range for Mach numbers of from 8 to 10. The aerodynamic quality of the airplane K must be no less than 3, which is twice as high as the aerodynamic quality of the recoverable module of the Buran system but is worse by a factor of 1.5–2 than in modern supersonic airplanes.

The difference in the parameters K causes us to abandon completely the variant of arrangement taken on Buran and to approach as close as possible supersonic aerodynamic shapes. This means that the leading edges of the wings and the fuselage dome must have radii of curvature of the order of 10 mm, unlike Buran where $R_{lead} \approx 1000$ mm.



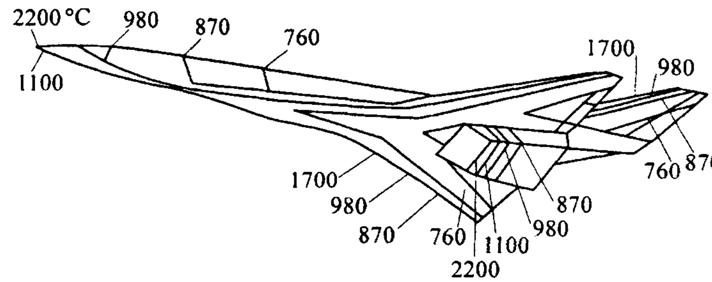
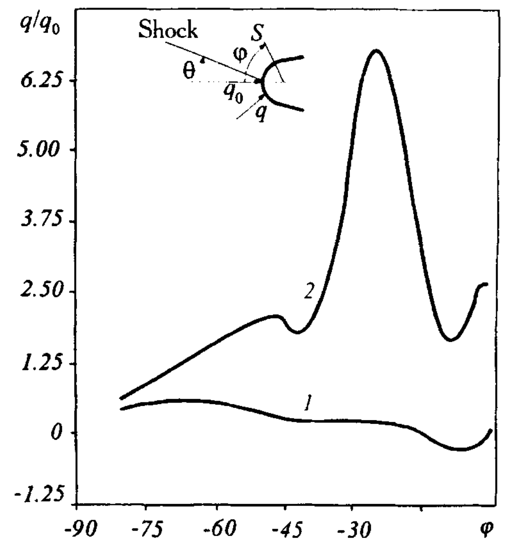


Fig. 4. Heat flux at the forward stagnation point vs. flying speed (the dashed lines are the levels of equilibrium temperatures for the emissivity factor $\varepsilon = 0.8$. q, kW/m^2; V_∞, km/sec.

Fig. 5. Distribution of the equilibrium temperatures on the airplane surface for M = 8 and H = 27 km.



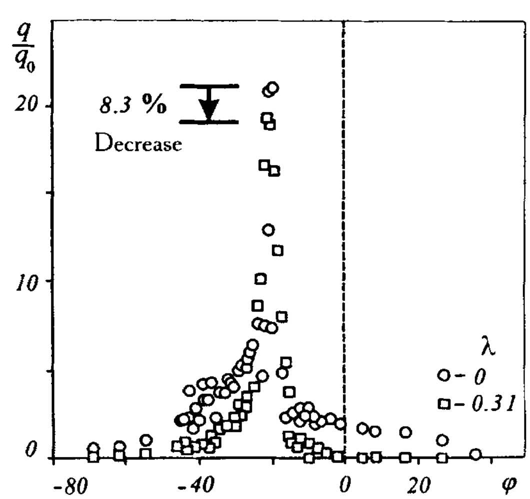


Fig. 6. Distribution of the heat fluxes at the sites of decrease in the bow compression shocks: 1) with a jet protection system; 2) without protection. φ, deg.

Fig. 7. Behavior of the heat flux in the interference zone of shock waves with uniform coolant supply (λ, dimensionless flow rate of coolant).

The optimum angle of attack in the flight of a hypersonic airplane must not exceed 5°, whereas in Buran it reaches 20° and more. A strongly extended, "sleeked down" shape is attained due to the small relative thicknesses of the wings and the fuselage. Finally, unlike classical airplanes, a hypersonic airplane will be produced in the integrated circuit, according to which the bottom of the body acts as the top of a two-dimensional nozzle, while the bow compression shock must be "tied" to the inlet edge of the air intake.

All these arrangement solutions make the thermal regime of a hypersonic airplane drastically more rigid both as compared to the Buran shuttle system and, apparently, in comparison with supersonic airplanes. Figure 4 presents the dynamics of the growth in the heat flux q and the equilibrium temperature T_w of the nose dome as a function of the flying speed of a hypersonic airplane.

It is seen that as compared to a modern supersonic airplane the heat load increases by nearly a factor of 50, while the equilibrium temperature T_w increases nearly threefold. Figure 5 shows the isotherms on the surface of one arrangement of a hypersonic airplane (the Mach number of the flight is $M_\infty = 8$ and the flight altitude is $H = 27$ km). Particular stress is produced by the regions in the vicinity of sharp edges of the fuselage, the wing, and the air intake of a ramjet engine. A strong temperature nonuniformity makes it problematic to employ sprayed coatings.

Experience in developing shuttle systems suggests that the optimum solution boils down to using different thermal-protective coatings on the aircraft surface: from dense heat-resistant carbon-carbon composite materials to superlight fiber mats of quartz glass. Nonetheless, the increase in the flight time τ to 5000 sec involves a substantial increase in the thickness of the heat-insulating coating

$$\delta_h \approx 3\sqrt{a\tau}\ ,$$

where a is the thermal diffusivity of material.

Allowance must also be made for a higher (than on Buran) level of tangential stresses (especially on the leeward surface), the problem of saturating a porous insulation with atmospheric moisture, large linear dimensions, etc. As far as the sharp edges are concerned the methods of their thermal protection must be totally different from all the known technical solutions. Consideration should, probably, be given to both passive and active methods of heat removal, including liquid-metal heat pipes, too.

Heat Transfer and Thermal Protection in the Interference Zones. Efficient operation of ramjet engines is possible when the regimes of atmospheric-air compression in the inlet diffuser are optimized. One solution of this problem requires the "closing" of the compressed layer, i.e., "tying" of the bow shock to the leading edge of the air intake. Figure 6 shows diagrammatically the pattern of interaction of the shocks in the vicinity of the leading edge and the heat-flux distribution along its surface in the presence and the absence of interference. As is seen, the intersection of the bow shock from the leading edge of the airplane's fuselage with the intrinsic shock wave ahead of the air intake creates a very complex interference scheme with the formation of a high-head jet directed toward the surface. The pressure and the heat flux can increase by an order of magnitude. Taking into account the small cross dimension of this jet, it is very difficult to find an adequate method of thermal protection. Figure 7 presents experimental data [4] on a heat-load reduction in the interference zone using the traditional method of penetrating cooling [1]. Even with a nondimensional injection intensity $G_w/(\rho_\infty V_\infty)$ that attains 30%, the effect of the reduction in the heat flux did not exceed 10%. It should be noted that at a distance from the site of the decrease in the shock the efficiency of penetrating cooling, conversely, is very high. But the presence of a high counterpressure, probably, produces the nonuniformity of coolant filtration and, as a consequence, a local zone with a decreased flow rate.

Conclusions. The prospects for developing a hypersonic airplane could be considered to be quite encouraging after the outstanding achievement of space-rocket technology: creation of the Space Shuttle and Buran shuttle systems. However, more detailed analysis shows that the aerodynamic arrangement, the conditions of trajectory flight, and hence the thermal regime of the hypersonic airplane differ radically from similar parameters of SSs. This necessitates a search for new technological ideas primarily among the methods of thermal protection and a joint consideration of the aerodynamics and heat transfer of different variants of arrangement with the aim of optimizing them.

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NOTATION

C_x, coefficient of aerodynamic resistance; C_y, lift coefficient; g, free-fall acceleration; H, flight altitude; I, specific pulse; m, mass; S, cross-sectional area; V_∞, flying speed; β, coefficient in the zone of density variation; ρ_∞, density of air; q, heat flux. Subscripts: 0, initial value; f, fuel; h, heat insulation, lead, leading.

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