HEAT EXCHANGE IN THE FLOW OF A HYPERSONIC RAREFIED GAS STREAM OVER A BLUNT WEDGE

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The cooling of the leading edge of a blunt wedge over which a hypersonic rarefied gas stream flows is studied.

When a hypersonic rarefied gas stream flows over a blunt body aerodynamic heating develops, with the liberation and removal of the heat by thermal conduction, convection, and radiation occurring in the boundary layer. The temperature of the gas in the vicinity of the leading edge, which is the section of the highest thermal stress, reaches the stagnation temperature. Various methods of cooling are used to prevent the local overheating which develops. Among the cooling systems a special place is occupied by those which use the temperature difference between parts of a body to cool the leading hottest part of the body which is subject to aerodynamic heating [1]. Closed-cycle systems, in which the heat obtained in the bow section is drawn off through the circulation of the coolant to the coldest stern section where it is dumped into the surrounding medium, are usually used for this purpose. Such systems require the installation of special equipment which complicates and burdens the structure. The use of heat pipes to cool the leading edge of a blunt body in the flow of a supersonic gas stream represents an interesting and promising method. This means of cooling has a number of advantages over the other known methods. The required effect is provided without losses in frontal resistance, since the entire structure of the heat pipes is placed within the aerodynamic contour and is distinguished by comparative simplicity. The essence of the cooling of the leading edge of a blunt body with heat pipes consists in the removal of heat from the hottest section adjacent to the leading edge, the transfer of this heat to a colder section, and its dumping into the surrounding space by convection and radiation. In the present work an experimental study was made of the aerodynamic heating of a blunt wedge in a hypersonic rarefied gas stream and the cooling of the leading edge with heat pipes. The experiments were performed in the supersonic low-density wind tunnel [2, 3]. The test model was placed in a rarefied gas jet with a Mach number $M=8$ and a static pressure $p=5.5\cdot10^{-3}$–$7.7\cdot10^{-3}$ torr. The stagnation temperature t_0, measured in the forechamber with a Chromel – Alumel thermocouple, was varied from 100 to 500°C. A conical nozzle, which was designed by the method presented in [3, 4], was used to obtain the jet. The model (Fig. 1) consisted of a blunt wedge with an aperture angle of 20° and a blunting radius of 8 mm, made of polished stainless steel 0.2 mm thick. The width of the wedge was 50 mm and the length of the generatrix 110 mm. Heat pipes 150 mm long (Fig. 2) were soldered

TABLE 1. Experimental Results for Wedge without Coolant Flow

t_0, °C	t_{1max}, °C	t_{2max}, °C	t_{1min}, °C	t_{2min}, °C	Δt_1, °C	Δt_2, °C	$q_{T1}\cdot10^{-4}$, W/cm²	$q_{T2}\cdot10^{-4}$, W/cm²
100	35	33	26	29	9	4	1,82	2
150	49	46	35	41	14	5	8,6	10,5
200	67	61	46	55	21	6	11,4	17,76
250	84	77	60	71	24	7	28,8	29,2
300	96	90	68	81	28	9	35,1	38,6
350	107	100	77	91	30	9	43,8	48,2
400	118	110	85	100	33	10	52,5	56,1
450	129	120	93	108	36	12	61,6	66,7
500	139	130	99	114	40	16	71,5	74,3

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to the inner surface of the wedge with a thin layer of silver solder in the bow section of the model. The pipes were filled in with tin to increase the thermal contact. The heat pipes were made of stainless steel 6 mm in diameter with a wall thickness of 0.2 mm. The wick was made of two layers of brass mesh 0.2 mm thick having a porosity of 30% and designed so that the cross section of the vapor channel was 2/3 of the cross section of the pipe.

In order to evaluate the effect of cooling of the leading edge with heat pipes, experiments were performed on blowing over different models: a wedge with heat pipes not charged with a working liquid and a wedge with heat pipes charged with acetone. The variation in the temperature of the surface of the wedge along the axial generatrix was measured with thermocouples in the course of the experiments. The characteristic temperature distributions on wedges with working and nonworking heat pipes during the blowing by a hypersonic rarefied gas stream are shown in Fig. 3 (curves 1 and 2). The main result, of the experiments for the model of a wedge with heat pipes cooled only through radiation from the surface are presented in Table 1. The results presented (see curve 2 in Fig. 3) clearly show that the heat pipes equalize the temperature distribution over the surface of the wedge. In thse experiments the reduction of the temperature of the leading edge of the model is not great (see Table 1) since the dumping of heat is extremely small, in the given case being due essentially to radiation to the surrounding space. The radiant heat flux (Table 1) was determined from the equation

$$q_r = \varepsilon c_0 \left[\left(\frac{T_{av}}{100} \right)^4 - \left(\frac{T_c}{100} \right)^4 \right], \tag{1}$$

where $T_c = 300$°K is the temperature of the chamber walls; $T_{av} = [(t_{min} + t_{max})/2] + 273$ is the average temperature of the wedge surface in °K; $c_0 = 4.9$ kcal/m$^2 \cdot$ h $\cdot$ °K^4; ε is the emittance, taken as equal to 0.08 [5].

As seen from the results (see Table 1), the radiant heat flux calculated for the average surface temperature on a wedge with heat pipes charged with acetone and cooled by radiation from the surface is higher than for a wedge under the same conditions but with uncharged heat pipes. This is explained by the increase in the average wall temperature due to the operation of the heat pipes. The effect of cooling of the leading edge increases considerably with an increase in the heat dumping which is due either to an increase in the radiation surface and its special organization or to convective heat removal. For example, according to predictions made in [6] the temperature of the leading edge of the body undergoing the blowing can be reduced from 1300 to 1000°K using heat pipes operating on calcium, due only to the effect of equalization of the heat load. In our experiments additional heat removal was accomplished by the pumping of coolant through the condensers of the heat pipes. The flow rate of the coolant and its temperature at the inlet to and outlet from the condenser were recorded during the experiment. The heat removal at the condenser was determined from the equation

$$q_{cool} = G_{cool} \rho_{cool} c_{p\,cool} \Delta t_{cool} / F. \tag{2}$$

The results of these experiments are summarized in Table 2.

The characteristic temperature variation of the surface of the wedge in this case is shown in Fig. 3 (see curve 3). We can see that the additional heat removal, exceeding the radiant flux by more than an order of magnitude, leads to a considerable reduction in the bow temperature of the model, with the temperature differential $\Delta t_3 = t_{3max} - t_{3min}$ between the extreme points of the profile (Table 2) remaining almost the same as in the case of the absence of coolant flow (Δt_2 in Table 1), which is explained by the specific nature of the operation of heat pipes of providing a small temperature gradient over the length of the heat pipes within the limits of the admissible heat fluxes.

Thus, on the basis of the experimental data obtained one can conclude that the use of heat pipes to prevent the local overheating of bodies over which supersonic gas streams blow is very effective.

NOTATION

M, Mach number; p, static pressure in gas jet; p_0, stagnation pressure; ε, emissivity of total normal radiation; c_0, absolute black-body radiation coefficient; q_r, radiant heat flux removed from condenser; T_c, temperature of chamber walls; t_0, stagnation temperature of stream; t_{1max}, bow temperature of wedge with heat pipes not charged with working fluid; t_{1min}, temperature of outermost section of wedge surface with uncharged heat pipes; t_{2max}, temperature of leading edge of wedge with charged heat pipes; t_{2min}, temperature of outermost section of wedge surface with charged heat pipes; t_{3max}, temperature of

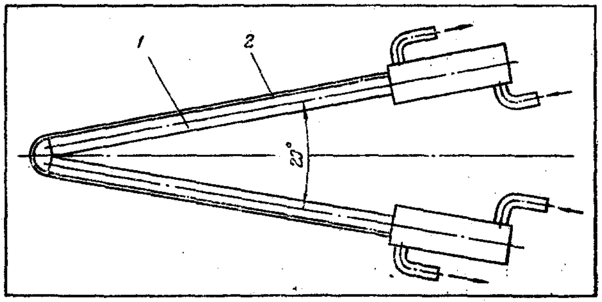

Fig. 1. Model of blunt wedge with heat pipes: 1) heat pipe; 2) surface of wedge of stainless steel.

TABLE 2. Experimental Results for a Wedge with Additional Heat Removal by a Liquid Coolant

t_0, °C	$t_{s\,max}$, °C	$t_{s\,min}$, °C	Δt_s, °C	Δt_{cool}, °C	G_{cool}, ml/sec	$q_{cool} \cdot 10^2$, W/cm²	$q_r \cdot 10^{-2}$, W/cm²
195	49,2	46,5	2,7	2,75	0,45	2,9	11,4
255	60,9	57	3,9	5,1	0,45	4,6	18,2
290	64,5	59,2	5,3	5,4	0,45	6,7	20,5
400	73,2	65,2	8	7	0,45	9,96	25,1

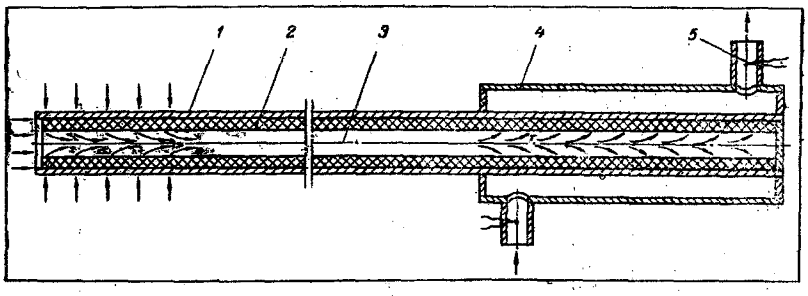

Fig. 2. Diagram of heat pipe: 1) body of pipe; 2) wick; 3) vapor channel; 4) condenser; 5) thermocouple for measurement of coolant temperature.

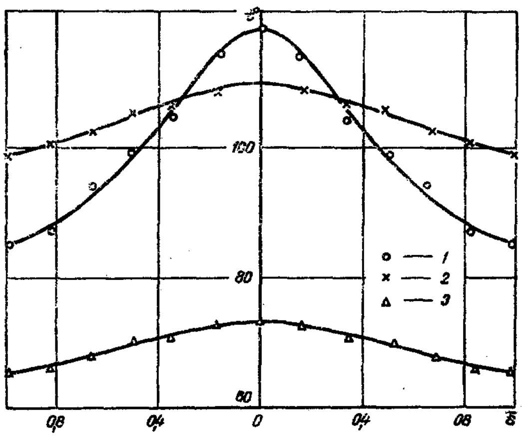

Fig. 3. Temperature distribution over the surface of a wedge in a hypersonic rarefied gas stream with M = 8, t_0 = 400°C, and p_0 = 63 torrs: 1) for a wedge with heat pipes not charged with the working liquid; 2) with heat pipes charged with acetone; 3) with heat pipes having condensers with liquid coolant.

leading edge of wedge with heat pipes cooled by liquid coolant; t_{3min}, temperature of outermost section of wedge surface with heat pipes cooled by liquid coolant; $\Delta t_1 = t_{1max} - t_{1min}$, temperature differential over surface of wedge with uncharged heat pipes; $\Delta t_2 = t_{2max} - t_{2min}$, temperature differential over surface of wedge with charged heat pipes; $\Delta t_3 = t_{3max} - t_{3min}$, temperature differential over surface of wedge with heat pipes cooled by liquid coolant; Δt_{cool}, temperature differential of coolant at inlet to and exit from heat pipe condenser; G_{cool}, coolant flow rate; $\bar{S} = s/l$, dimensionless coordinate equal to the ratio of the arc length from the critical point to the length of the generatrix; $c_{p\ cool}$, heat capacity of coolant; ρ_{cool}, density of coolant; F, area of wedge surface.

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