AERODYNAMIC HEATING—THE TEMPERATURE BARRIER IN AERONAUTICS

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THE PROBLEM OF HEAT TRANSFER from fluids to solid bodies became of great importance as high-speed aircraft and ultra-fast missiles appeared in the development programs of military and civilian aviation. Before that, the application of heat-transfer theories to aircraft structures was mainly concerned with the computation of the surface necessary to transfer a given amount of heat; for example the heat rejected by the cylinder walls of an engine into the cooling liquid or the cooling air. The concept of aerodynamic heating—however—is not quite new. As a matter of fact Galileo mentions in one of his dialogues that, according to some sources of information, the Babylonians used to cook their eggs by putting them into a sling and whirling the sling around with high velocity. Galileo makes the remark that he really did not believe the story; on the contrary he believed that if the eggs were already hot they would be cooled by the air. He was right, for it can easily be calculated that, in order to bring the eggs to boiling temperature, a circumferential speed of $M = 1.3$ would be necessary.

The usual computation of heat transfer is based on the rule called Reynolds' analogy. Reynolds was the ingenious British scientist in the second half of the nineteenth century, who contributed fundamental ideas to the understanding of phenomena in viscous fluids. He compared the friction between a solid body and a moving fluid with the heat transfer between the same two components of the system. Evidently, the friction is a transfer of momentum, the heat transfer is a transfer of heat energy. Now we know that, for example in gases, the mechanisms of momentum and energy transfer are closely similar; they are effected by the collision of molecules in laminar flow, and by eddy diffusivity in the case of turbulent motion.

Let us consider first the laminar case, which is accessible to exact calculations. Both the transfer of momentum and the transfer of heat take place in the narrow domain near the wall of the moving body, called the boundary layer. We consider the case of supersonic flow with moderate Mach number; then the flow of a compressible fluid in the boundary layer can be computed without difficulty. Let us first assume that the body is thermally insulated, so that heat transfer is prevented. Then theory and experiment show that the temperature of the air at the surface is elevated practically to the same degree that corresponds to the temperature rise through normal impact, i.e., the adiabatic stagnation temperature. This relation was first found by L. Crocco for compressible fluids with Prandtl number one (Prandtl's number is the ratio between kinematic viscosity and temperature conductivity). It means physically that the heat produced by viscous forces between adjacent layers with flow velocity decreasing toward the body surface is equal to the heat produced by decreasing the velocity by an adiabatic-compression process. This fact was in the past not quite evident to many engineers. For example, in the case of a gas or steam turbine, some designers believed that if the gas is expanded to high velocity and low temperature between the combustion chamber and the moving turbine blades, the blades are exposed to the lower temperature corresponding to the expansion. In fact, the gas temperature at the blade surface will be equal to the stagnation temperature, i.e., a temperature comparable with the temperature in the combustion chamber.

In the general case of Prandtl number different from unity the "recovery temperature" is slightly less, approximately proportional to the square root of the Prandtl number.

The second important result of theoretical and experimental research is the fact that, if the body is not insulated, the heat transfer, i.e., the heat transferred from the gas to the body, is proportional to the difference between the recovery temperature and the wall temperature, instead of the difference between the ambient and the wall temperature as is the case at low velocity.

It is easy to see that this fact changes the whole physical picture as the Mach number increases. For air, the ratio between stagnation and ambient temperature is equal to unity plus one fifth of the square of the Mach number. Assume, for example, $M = 4$; then for 300 degrees K ambient temperature the stagnation temperature becomes equal to 1260 degrees K and for $M = 16$ to 15,700 degrees K. In other words, assuming the same heat-transfer coefficients, the body would receive a heat input as if it were at rest in a medium with the ambient temperature of 15,700 degrees K.

In the case of a turbulent boundary layer, the recovery temperature is of the same order as in the case of laminar flow; however, the heat-transfer coefficient corresponding to Reynolds' analogy is several times larger than in the laminar case.

This quite general consideration shows that designers have every reason to worry about the effect of aerodynamic heating on the structure, the crew and the passengers, and the equipment carried in the airplane or missile.

The situation becomes already uncomfortable at moderate Mach numbers, say $M = 2$. One may note with some satisfaction that the discomfort for the electronic equipment begins earlier than for the human pilot. As a matter of fact, a good pilot's brain is still working quite satisfactorily at a temperature at which the electronic brain becomes completely useless. The first component in the system which requires cooling is the electronic equipment, especially because of the high-temperature sensitivity of the transistors.

Effects of Aerodynamic Heating

The effects of aerodynamic heating on the structure might be of various natures. As main sources of danger, we may list the following:

1—Reduction of the elastic moduli with increasing temperature. This effect reduces considerably the resistance of all structural members against buckling and analogous phenomena of structural instability.

2—Reduction of yield point, ultimate stress, and especially fatigue stress by high temperature, causing breakdown of the structure.

3—Increasing rate of creep, which equally reduces the resistance of structural members exposed to buckling, and may concentrate high loading on members not designed for such loads.

4—High thermal stresses caused by uneven thermal extension of various structural members.

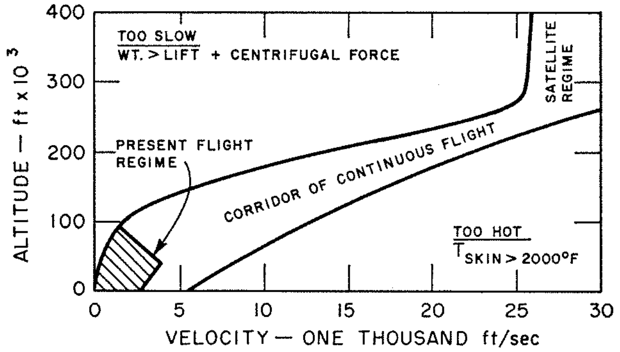
5—Loss of stiffness, especially torsional stiffness of wings by uneven temperature distribution.

6—In extreme cases, melting away of parts, whose melting point was exceeded by high local temperatures.

From the designer's viewpoint, the main problem is to determine the temperatures that can be expected in definite flight conditions. In recent years, much work has been done to determine the model rules for aerodynamic heating. If such rules can be established, it would be possible to test structures under simulated conditions representing the actual case of flight. Unfortunately, the scaling rules for heat transfer and stress distribution in structures are, in general, somewhat contradictory, so that some artifice is necessary to obtain exact information from model experiments.

For a general analysis, we want to distinguish between the stationary and transient states.

In continuous flight at constant speed, i.e., in a stationary state, an equilibrium is established between the heat input and the heat emission. The heat input per unit time and unit surface is equal to the product of the effective temperature difference and the heat transfer coefficient. The effective temperature difference is given by the difference between the recovery temperature and the wall temperature. The heat-transfer coefficient largely depends on the density of the air surrounding the body and therefore on the altitude. Hence, in order to determine the possibility of continuous flight without facing the dangers mentioned above, we have to consider two parameters: Mach number and altitude.



NOTE: SKIN TEMPERATURE ONE FEET AFT OF LEADING EDGE ON FLAT PLATE AT 5° ANGLE OF ATTACK.

FIGURE 1. Variation of velocity versus altitude for various values of dynamic pressure and equilibrium temperature.

Recently, Masson and Gazley of the Rand Corporation, presented an interesting diagram showing the possible ranges for continuous flight in the velocity-altitude coordinate system. Their diagram is reproduced in Fig. 1. The upper limit for the velocity is computed in this diagram somewhat arbitrarily. The main engineering problem consists of finding methods that allow an extension of the temperature barrier toward higher velocities. The heat emission in continuous flight by radiation varies at a rapid rate as the surface temperature increases and also varies with the altitude. Unfortunately, at surface temperatures permissible for current materials, the radiation represents a small amount in comparison with the heat input to be expected. Therefore, artificial means are necessary to reduce the heat input or to transfer heat from the airplane or missile to the surrounding space.

What are the possible means? A few examples will be quoted:

a—One may reduce the input; for instance some favorable effect can be expected from insulation between the external surface and the inner structural elements.

b—One can provide internal cooling by means of an expendable coolant, for example boiling water, which evaporates. In such cases the amount of the necessary coolant can be essentially reduced by insulation as mentioned under (a).

c—One can arrange internal cooling with refrigeration of the coolant. In this case the amount of coolant is reduced, but fuel must be expended for refrigeration.

d—One can apply transpiration or sweat cooling, consisting of pumping of a liquid, gas or vapor, through a porous skin.

e—Finally one can use mass-transfer cooling, consisting of a coating that sublimates or chemically dissociates with increasing temperature, thus keeping the temperature under the allowed limit.

In almost all cases, cooling requires essential increase in weight; however, for limited flight time the weight increase might be within reasonable limits.

The situation is more favorable in cases of high-altitude flight, when the heat input is relatively small or even negligible. Thus, satellites supposedly will have little difficulty in maintaining their thermal equilibrium during the period of their two hours' flight around the globe. Also, some high-altitude missiles probably can get along with compartment cooling that dissipates the heat produced by their own equipment.

If we consider transient flight, no great difficulties are expected for the period of accelerated flight of missiles, since probably the heat capacity of the structure can be increased so that the surface does not attain ultra-high temperature during the limited time-interval concerned. For example, in the case of a ballistic type of missile, the skin is heated until an equilibrium between heat input and radiation loss is reached. Fortunately, the heat input decreases with increasing altitude; and, as mentioned above, it becomes negligible outside of the atmosphere. Radiation continues to cool the missile, until it starts its period of return into the atmosphere. Then the heat input increases faster than the radiation, and we have to face the "re-entry problem." With a re-entry Mach number between 12 and 20, this is perhaps one of the most difficult problems one can imagine. At this extreme hypersonic velocity, we first obtain a shock which produces temperatures comparable with the stagnation temperatures of the order of 12,000 to 16,000 degrees K. The air dissociates at these temperatures and we have an extremely complicated problem of aerothermochemistry, eventually involving also magnetoaerodynamics if ionized particles are present. It is certainly a problem that constitutes a challenge to the best brains working in these domains of modern aerophysics. The satellite as presently conceived does not face the same problem since, provided telemetering and means of observation will work satisfactorily, we can let the missile burn like a meteorite created by the good Lord.