AERODYNAMIC FRICTION AND HEATING

presented by

1- by 3-Foot Supersonic Wind-Tunnel Section

Supersonic Free-Flight Section

Low Density & Heat Transfer Tunnel Section

Let us examine an enlarged view of the air adjacent to the surface of an aircraft in steady flight. On an actual airplane, the circle corresponds to a region about so big. The airspeed in this region is represented by these arrows. The air in immediate contact with the surface moves with the surface. Because of viscosity, the air at a small distance from the surface is also dragged along in the direction of flight. However, this effect decreases as the distance from the surface increases. Thus, the effects of viscosity are confined to this relatively thin boundary layer. Pulling the boundary layer along gives rise to a drag force or skin friction which retards the forward motion of the aircraft. The energy required to overcome the skin friction is dissipated in the boundary layer as heat. This aerodynamic heating causes the air in contact with the surface to be hotter than the air outside the boundary layer.

Skin friction is important at all flight speed; at a Mach number of 3 it may account for one-half the total drag of an aircraft. The temperature rise due to aerodynamic heating is unimportant at subsonic speeds but it increases as the speed increases. At a Mach number of 3, the temperature rise in the boundary layer is about 600° F and at a Mach number of 5 it is about 1600° F. In steady flight, the aircraft structure will eventually be heated to these temperatures by conduction of heat from the hot air in the boundary layer. However, the temperature of the structure will lag behind the temperature of the boundary-layer air since time is required for the heat to flow into the aircraft. The rate at which heat flows from the air to the structure is known as the rate of heat transfer.

With these properties of the boundary layer in mind, let us look at a shadow picture of an actual boundary layer. This picture was taken in the Ames Free-Flight Wind Tunnel at a Mach number of 3. Two distinct types of boundary layer are evident. The laminar boundary layer over the forward portion of the missile is a smooth, very thin layer next to the surface. The turbulent boundary layer over the afterpart of the missile appears as a fuzzy grey region. It has a turbulent, eddying motion. This region in which the boundary layer changes from laminar to turbulent is called the transition region.

Of the two types of boundary layer, the laminar layer gives the smaller skin friction and the lower rate of heat transfer. The relatively smooth flow of the laminar boundary layer produces a skin friction only about one-sixth as great as that produced by the eddying flow of the turbulent boundary layer. Since the rate at which energy is dissipated as heat in the boundary layer is proportional to the skin friction, the rate of heat transfer for the laminar boundary layer is also about one-sixth as fast as for the turbulent boundary layer.

Since both the skin friction and the rate of heat transfer are lower for the laminar than for the turbulent boundary layer, it is essential that the maximum possible extent of laminar boundary layer be maintained over the surface of a high-speed aircraft. In other words, transition should be as far aft on the aircraft as possible. In the absence of extraneous disturbances, the location of transition is determined by the speed and altitude of flight and by the shape of the surface in question. However, transition is very sensitive to small disturbances. This will be illustrated with the apparatus on your left.

We have a metal tube suspended in a vertical channel. A light beam is passed through the channel and the image of the tube is projected on this screen. The tube is heated electrically and in turn heats the adjacent air. As the warm air rises up the channel, a flow is established in the channel that is similar to the flow within the boundary layer on a body moving through air. The random fluctuations of the turbulent flow are so pronounced that they cast a faint shadow which can be seen as wiggly lines at the upper end of the channel. The flow in the laminar region at the lower end of the channel is uniform and hence casts no shadow. Transition occurs about here. The effect of various disturbances on transition can be demonstrated by introducing the distrubances and observing the shadow cast by the turbulent air in the channel.

First we place a small wire across the surface of the tube. Transition moves down the channel and occurs at the wire. When the wire is removed, transition returns to its original position. Therefore, it is important to maintain the surface of an aircraft as smooth as possible.

The effect of noise can be demonstrated by ringing a bell in the entrance to the channel. Transition will move down the channel while the bell is ringing and return to its normal position when the bell stops. Any high-frequency vibration in the air stream or in the surface of an aircraft would have the same effect. Such vibrations must be avoided.

If the flow at the entrance of the channel is agitated, the extent of the laminar boundary layer is again reduced. To illustrate, we blow very lightly through small air jets in the entrance. This time the turbulent flow extends almost all the way to the end of the tube. Disturbances of this type are encountered, for example, by an aircraft's tail surface when operating in the wake from a wing.

We have seen that very small disturbances can cause transition to move forward on the surfaces of an aircraft. These disturbances are difficult to eliminate completely in flight or in wind-tunnel testing. As a result, any attempt to predict the location of transition is usually subject to a great deal of uncertainty.

The next speaker will discuss the significance of skin friction and aerodynamic heating in terms of aircraft performance.

The preceding speaker has pointed out how the viscosity of air gives rise to skin friction and aerodynamic heating. The question which now arises is, "What is the importance of these two phenonomena and how do they affect the design and performance of supersonic airplanes and missiles?"

First, let us consider only the skin friction effects that will be encountered when aircraft are capable of flying relatively long distances at a Mach number of 3. Suppose, for comparison, that in the absence of skin friction such an aircraft has the range indicated by this arrow. The actual range of such an aircraft, with an all laminar boundary layer would be approximately as shown by this arrow. The difference is the effect of laminar skin friction. If the boundary layer were all turbulent, the range would be drastically reduced as shown by the third arrow. Comparison of the three arrows reveals that skin friction will have an important effect on the performance of long range, supersonic aircraft. The difference in range between the all-laminar case and the all-turbulent case indicates the importance of knowing, for the purposes of design, where transition will occur, and also illustrates the desirability of maintaining the maximum extent of laminar flow.

The effect of aerodynamic heating on performance is less direct than that of skin friction. First, it is necessary to understand the difficulties that might be encountered as a result of aerodynamic heating. The maximum temperature that will be developed in the boundary layer at a Mach number of 3 and at high altitude is about 550° F. The structure and contents of an aircraft would approach this temperature as the flight progressed. The question immediately occurs as to whether such a high temperature could be tolerated. Of course a pilot could never withstand such a temperature. This is also true of many kinds of cargo. An aluminum structure would be seriously weakened at this temperature. Furthermore, it is very unlikely that the structure would heat uniformly, and nonuniform heating would distort the shape of the wings and controls, and thus alter the lift and complicate the stability and control problem. It is apparent that these serious effects of aerodynamic heating must be recognized and provided for in the design of an aircraft that is to fly at Mach number of 3 or greater.

The best way to handle these problems is not clear at the present time. One method that has been employed to control the effects of aerodynamic heating on short range missiles is to provide insulation at the missile surface and thereby restrict the flow of heat into the interior. Another possible solution is to provide a refrigeration system to carry off the heat. A third is to make use of materials which, unlike aluminum, can withstand high temperatures without loss of strength. Any of these methods would involve considerable extra weight of structure or equipment. This extra weight means reduced performance. Thus, for a given airplane, the range is reduced when provision is made to counteract the effects of aerodynamic heating. As was the case with skin friction, the penalty that must be paid is more severe when the boundary layer is turbulent. To illustrate this point, let us return to the map. When measures are taken to counteract the aerodynamic heating, it is estimated that the range in our comparison would be reduced to something of this order (superimpose the long arrow) if the boundary layer is laminar. If, on the other hand, the boundary layer is all turbulent, the rate of heat transfer is six times greater and therefore extra weight in cooling equipment or insulation will be required. Thus, the range that is already severely limited due to skin friction, is again reduced and by a much greater percentage than was the case for a laminar boundary layer (superimpose the short arrow).

For an aircraft such as the one we are considering, the boundary layer would probably be predominately turbulent unless special measures were taken to delay transition. However, the situation may not be as bad as it first appears. Recent experimental and theoretical work indicates that cooling the surface of an aircraft tends to delay transition. Therefore, in addition to protecting the cargo and structure, cooling would have the beneficial effect of increasing the amount of laminar flow. This would tend to reduce the over-all skin friction and rate of heat transfer and thus counteract the reduction of range due to the weight of the cooling equipment. It is not known at present just how much the extent of the laminar boundary layer is increased for a given rate of cooling. This is one of the most important questions in this field of research.

The magnitude of the skin friction and the rate of heat transfer increase with Mach number and decrease with increasing altitude. Therefore, the problems we have considered become more difficult to cope with as Mach number increases but they may be alleviated by flying at a higher altitude. Unfortunately, power-plant requirements and wing-size limitations usually limit the altitude at which a given aircraft can fly and hence the skin friction and aerodynamic heating problems cannot be eliminated completely.

Thus we see that skin friction and aerodynamic heating have important effects on the design and performance of supersonic aircraft. The next speaker will discuss the research that has been done to aid the designer in estimating the magnitudes of the effects: Mr. __________.

It is apparent from the preceding discussions that the designer of a high-speed aircraft must be able to predict the skin friction for laminar and for turbulent flow, the rate of heat transfer for laminar and for turbulent flow, and the position at which transition occurs on the various surfaces of the aircraft. The ideal solution would be to determine this information experimentally in flight for all combinations of surface shapes, flight speeds, and altitudes of interest to the designer. Such a procedure would be extremely costly and would require years of experimentation; hence the designer must rely on theoretical results and small-scale flight and wind-tunnel tests with a few checks from full-scale flight tests.

This chart shows the theoretical variation of skin-friction drag with Mach number for an uncooled wing flying at a constant altitude. Similar curves can be calculated for bodies of revolution and other surface shapes. Notice that the predicted values for a turbulent boundary layer spread over a wide range as the Mach number increases. This uncertainty results from the fact that simplifying assumptions must be employed in the calculations and, since the basic nature of turbulent motion is not clearly understood, many different assumptions may be employed. Since the laminar boundary layer is better understood than the turbulent boundary layer, there is no such uncertainty in the laminar results, as is shown by this lower curve. The heat-transfer rate varies with Mach number in essentially the same manner as skin friction and the same spread is present in the theoretical predictions for turbulent boundary layers. Therefore, these two curves may be considered to represent either skin friction or rate of heat transfer.

Before these theoretical solutions can be employed with any confidence by the designer they must be verified experimentally. For many conditions at subsonic speeds, both laminar and turbulent skin-friction predictions have been substantiated by the NACA and other research organizations. In the supersonic speed range, experimental measurements of skin friction are being made at ever increasing speeds as new and higher speed testing facilities of a suitable nature become available. Reliable data for basic surface shapes have been obtained at Mach numbers up to approximately 3.5. The results for turbulent boundary layers define a curve that passes approximately through the center of the theoretical region. For laminar boundary layers, the theoretical predictions have proved to be quite accurate in the Mach number range for which experimental data are avilable as indicated by this curve. Research in progress at the present time will extend these experimental curves to Mach numbers of 5 and greater. The rate of heat transfer for laminar and turbulent boundary layers has been determined experimentally over approximately the same Mach number range and with approximately the same agreement with theory as was the case with skin friction.

In the preceding discussion we have shown that, for the Mach number range of primary interest at the present time, the skin friction and rate of heat transfer can be determined when the boundary layer is either all laminar or all turbulent. Now the questions arise, "Where does transition occur and how can the maximum extent of the laminar boundary layer be obtained?" Our studies of transition at supersonic speeds have demonstrated the complex influence of the various factors affecting transition and have indicated some important trends. For example, experimental investigations at both the Ames and Langley Laboratories have indicated that surface roughness plays an important role in determining the location of transition. As was mentioned previously, it has also been demonstrated experimentally that cooling the surface of a body can significantly increase the extent of the laminar boundary layer. Unfortunately, these experiments have only indicated trends. It has proved to be extremely difficult to isolate the effects of the individual factors affecting transition and to obtain quantitative information in existing supersonic wind tunnels. In general, such factors as air-stream turbulence, vibrations, and uniformity of flow cannot be controlled precisely. They tend to vary when other factors such as Mach number and Reynolds number are changed. The purpose of the alterations which are being made to the 1- by 3-foot blow-down wind tunnel is to provide a test facility which will allow better control of these factors. A large sphere is being installed just outside the building. The sphere will contain a series of screens. The sphere and screens should reduce the turbulence of the wind-tunnel air stream to a level comparable to that which occurs in the atmosphere.

Another method for obtaining quantitative data is to launch models at high speed into air which is still and therefore free of turbulence. This method is being used at the present time to investigate transition in the Ames supersonic free-flight wind tunnel. The results from this research have already shown that under properly controlled conditions, the extent of the laminar boundary layer can be increased significantly at high Mach numbers.

In summary then, we have shown that skin friction and aerodynamic heating have an important bearing on aircraft design; that we can predict with fair accuracy the skin friction and aerodynamic heating if we know the location of transition; and, we are now beginning to obtain quantitative information on the factors affecting transition.

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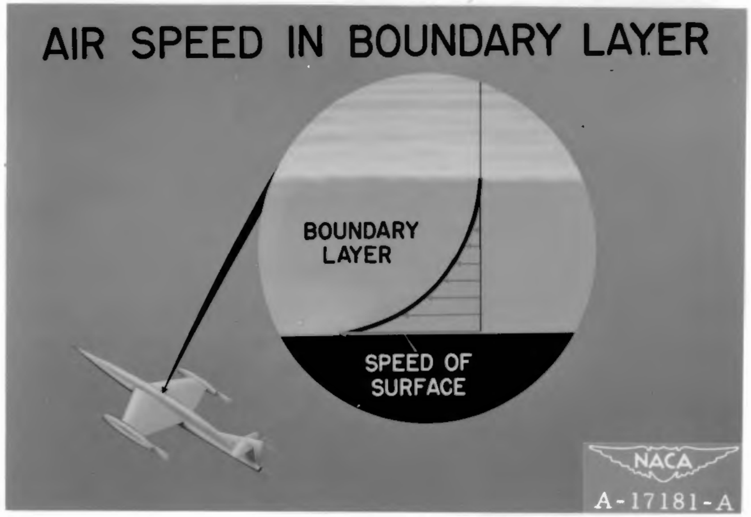
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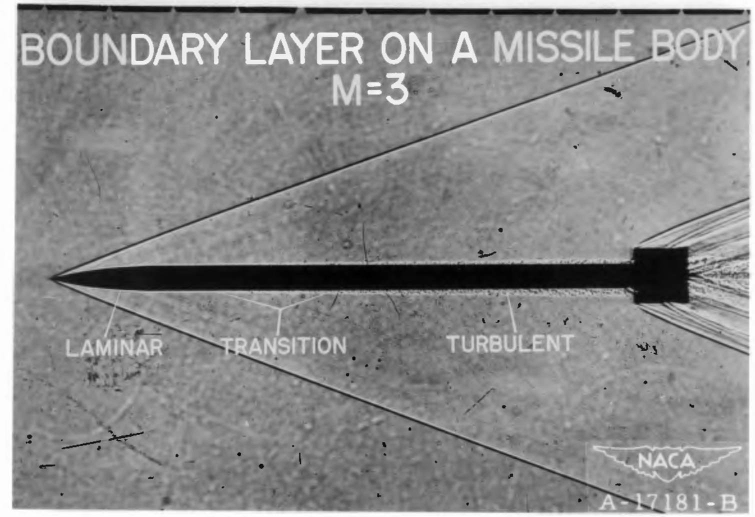
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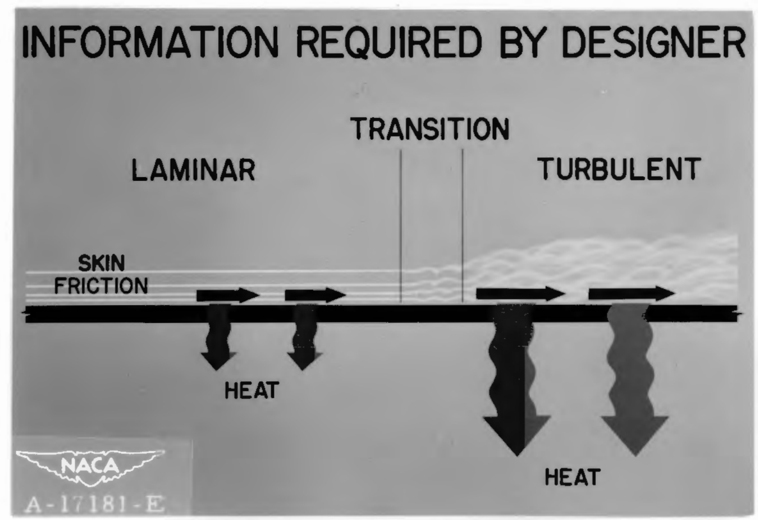
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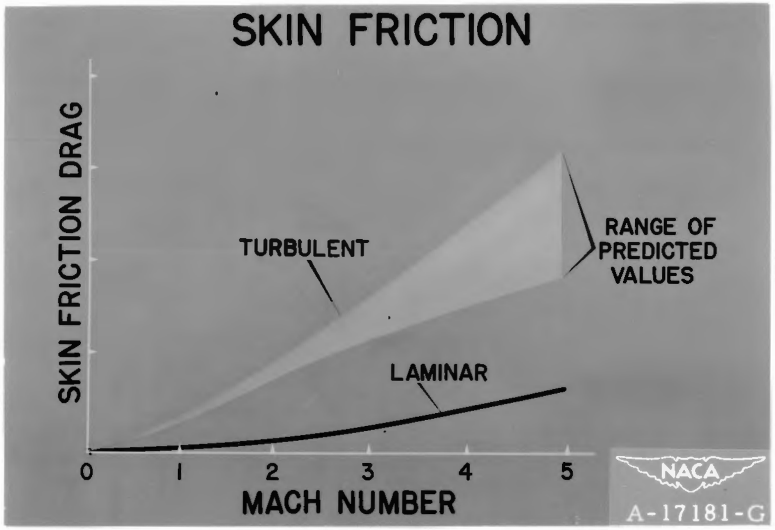
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