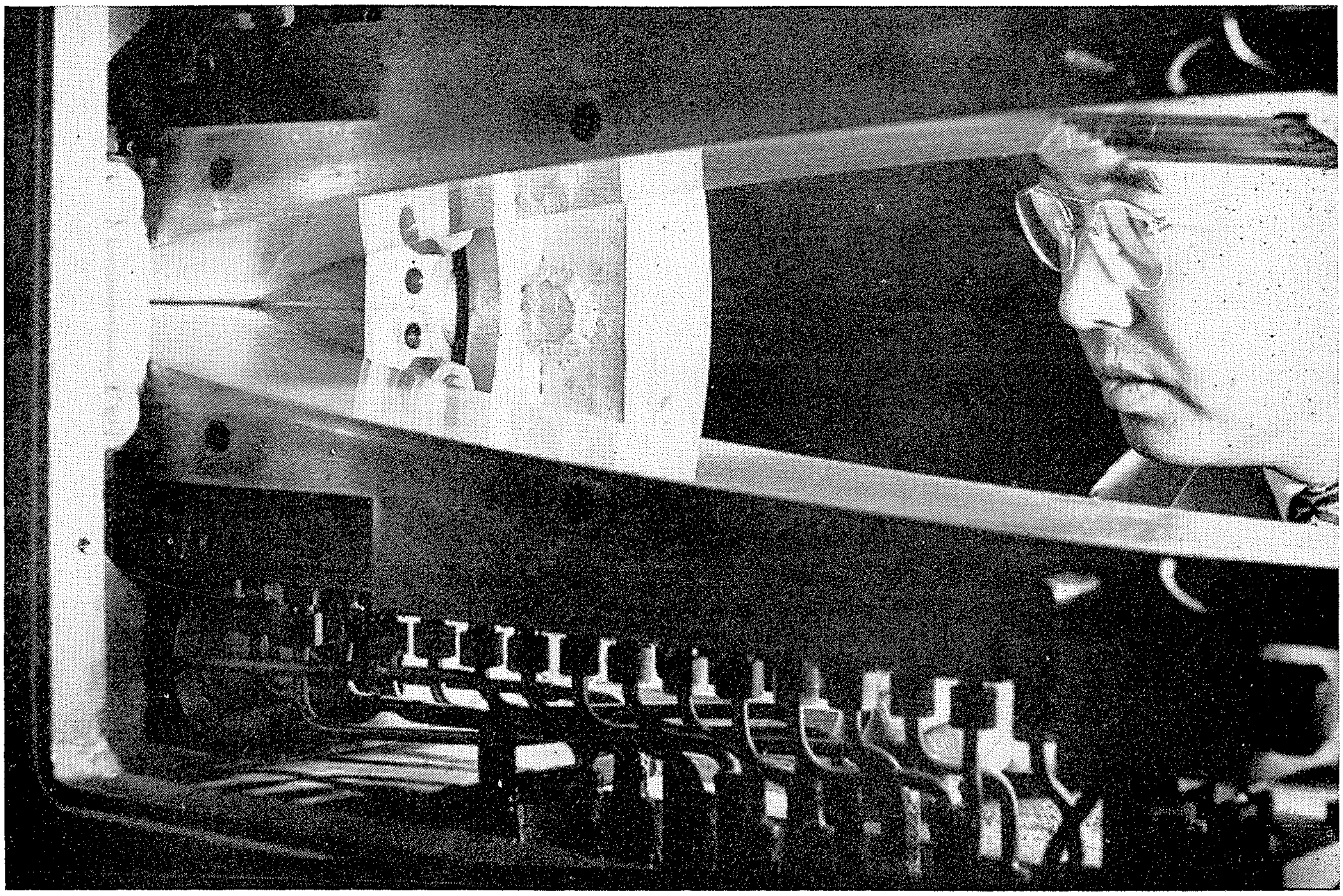


The principal part of a hypersonic tunnel is the set of contoured blocks of steel which comprise the nozzle.

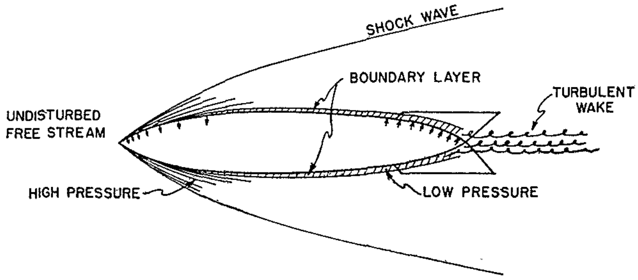
HYPERSONIC RESEARCH AT CALTECH

Studies of how air flows around a body at speeds "faster than supersonic" keep research ahead of the ever-growing needs for knowledge imposed by the high-speed flight of the future.

by JAMES M. KENDALL
Graduate Assistant in Aeronautics

PIONEERING WORK in one of the newest phases of aerodynamics is being carried forward at Caltech's Guggenheim Aeronautical Laboratory (GALCIT) by a research group under the direction of Dr. Henry T. Nagamatsu. The group is investigating, both experimentally and theoretically, how air flows around a body in the hypersonic speed regime. Literally, this means "faster than supersonic," and is arbitrarily taken to be Mach 5 and higher. The group is currently operating two hypersonic wind tunnels, one of which has recently achieved flow at Mach 11, or 11 times the speed of sound.

The reason for the extensive research program is the rapidly growing need for fundamental knowledge about hypersonic flow to be used in the design of high-speed



Shock wave pattern and growth of boundary layer on a body in hypersonic flow. The drag results from the pressures and from the boundary layers.

vehicles. The United States now has some 18 types of guided missiles, many of which are capable of very high Mach numbers. As early as the spring of 1949, a two-stage rocket consisting of a V-2 and a Bumper WAC attained a Mach number of about 7.5 during tests at White Sands. As newer missiles are designed, aerodynamic data at ever higher Mach numbers are needed. For example, a long-range ballistic rocket of 4000 miles range would require a speed corresponding to Mach 13 at the end of burning, and a rocket designed to escape from the earth would require about Mach 35 at the end of burning. But the hypersonic program at Caltech is definitely not concerned with the design of missiles or space stations. The models tested are not futuristic shapes; they are simple cones, spheres and wedges, because the information obtained from these is more basic.

Hypersonic flow differs from low-speed flow in several ways, many of which can only be regarded as disadvantageous to high-speed flight. One of these is extreme aerodynamic heating. Transfer of heat to a body surface is brought about on the region near the forward parts of the surface by rapid compression of the air as the body pierces the atmosphere. The after parts of the surface are heated by friction as the air flows over the surface, even though air is only slightly viscous. It so happens that these two processes produce nearly identical final temperatures, but the rate of heat transfer is in general widely different at different parts of the surface. The final temperature depends mostly on the Mach number of the flow.

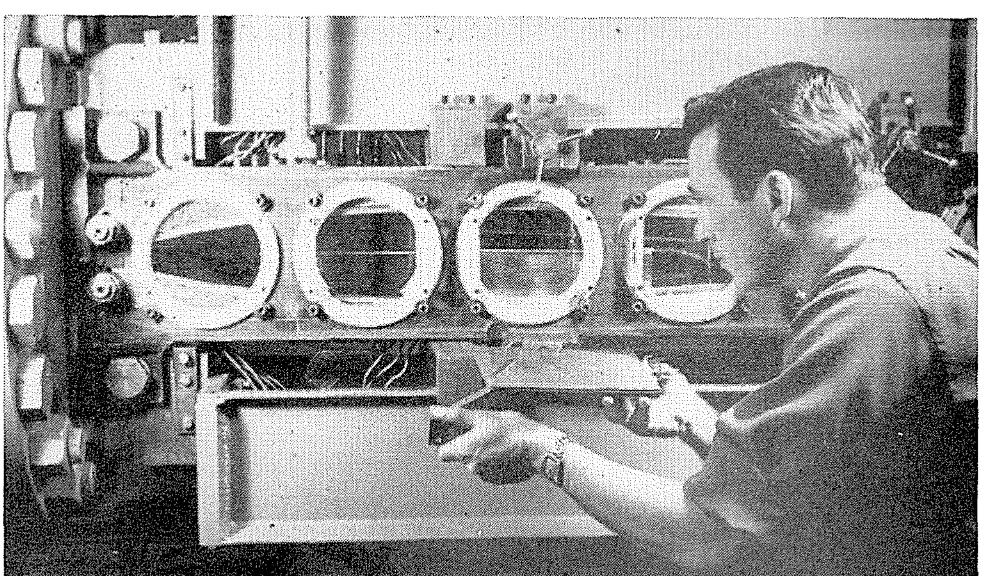
By way of illustration, two missiles sustaining flight at Mach 5 and 10 respectively, on a day when the air temperature is 70°F, are heated to 2650° F and 10,600°F. Because steel melts at about 2600°F, it is quite evident that high-speed missiles can withstand flights of only short duration so that time does not permit heating to the equilibrium temperature. Flight time decreases, however, as speed goes up, and a missile traveling vertically upward from sea level at Mach 5 would remain in the earth's atmosphere less than 10 seconds.

Pressure distribution

A second unfortunate effect is that the pressure distribution about a body in high-speed flight is highly unsymmetrical fore and aft, so that a large drag results. High pressures occur on the nose of the body as it pushes aside the air in much the same fashion as a nail penetrates wood, while parts of the surface behind the thickest section of the body experience virtual vacuum, because it is difficult for the air to accelerate sidewards fast enough to follow the surface contour.

The power used to drive the body forward against the drag force due to the pressure is converted to heat by the dissipative action of the shock waves produced—as shown in the diagram at the top of this page.

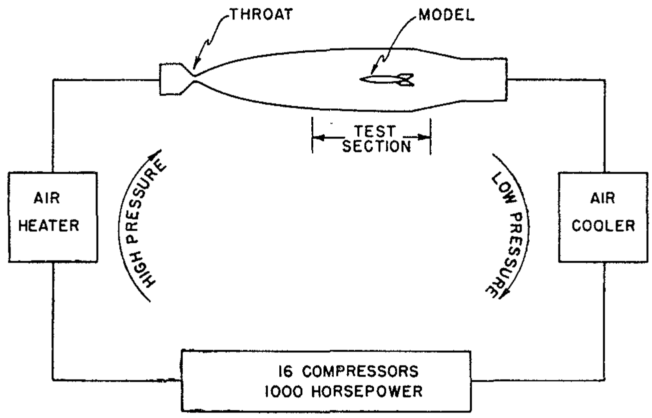
The shock waves are the interface of the lower pressures of the undisturbed free stream and the high pressures produced by the motion. These waves extend with decreasing strength to great distances from the body,



Leg 1 of the hypersonic wind tunnel. The worker here is checking a flat plate model before installing it in the tunnel for an experiment.

and their action is to deflect the air outward as the body contour passes by. It is of importance that the higher the Mach number, the closer the shock waves lie to the surface, and correspondingly the stronger they become. These changes produce subtle effects which are peculiar to hypersonic speeds.

For hypersonic studies, as with most other phases of aerodynamics, the basic instrument of experimental research is the wind tunnel. In 1885, Horatio Phillips used the first aerodynamic tunnel for experiments, and since that time tunnels have become ever more extensively used. The justification for wind-tunnel testing is usually a matter of economy in the form of reduction of design costs. At the present time, the development of a new aircraft requires a vast amount of research, the cost of which may well run into millions of dollars and take many months. The wind tunnel, wherein scale models are tested, offers a means of reducing time and costs, and offers to hypersonic research, in particular, certain ease of gathering data.



Components of a hypersonic wind tunnel system. The wind tunnel, in which scale models are tested, offers a means of reducing time and costs in the development of a new aircraft.

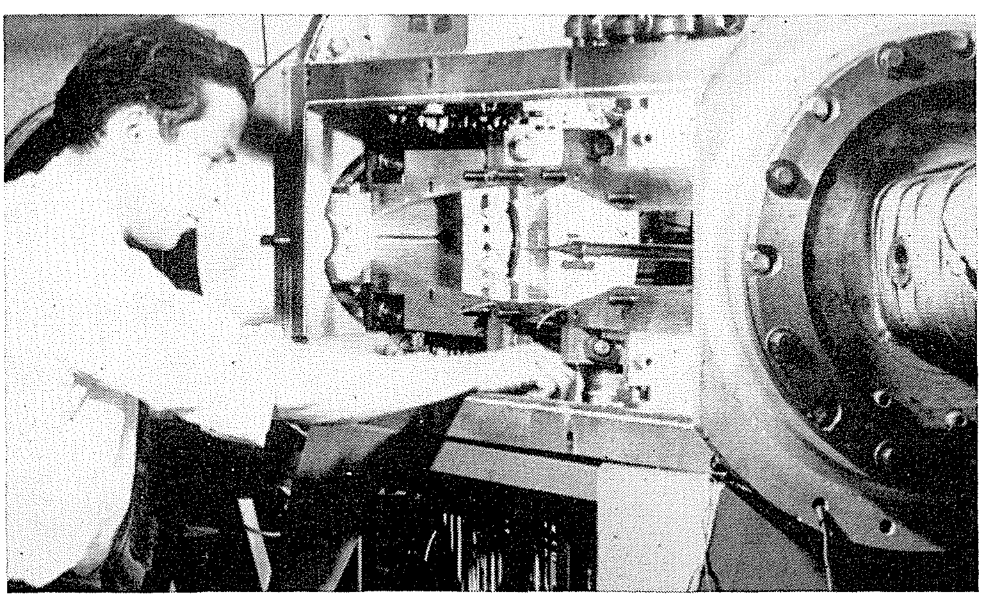
Similarity parameters

The comparison between data obtained in a tunnel and that needed for full-scale application is made on the basis of so-called similarity parameters. These are dimensionless numbers which depend on various important physical quantities, such as the density, viscosity, and speed of the air. The two most important of these parameters are the Mach number and the Reynolds number. The Mach number is the ratio of the air speed to the speed of sound. The Reynolds number depends on the viscosity, density, and speed of the air, and on the length of the body. This number, in a sense, provides a certain measure of all processes which depend on viscous effects, such as heat transfer rate and surface or skin friction.

This notion of similarity parameters is expressed by saying that the coefficient of drag of a body, for example, is a function of Mach number and Reynolds number, and if these two are adjusted to be the same in the tunnel as in the desired free-stream conditions, then the value of coefficient of drag measured is the correct one. It is on the basis of this similarity that one is able to use wind-tunnel measurements to predict full-scale performance.

The experimental facilities of the Caltech hypersonic group center around two tunnels referred to as Legs 1 and 2, both with 5-by-5-inch test sections. The principal part of a hypersonic tunnel is the set of contoured blocks of steel which comprise the nozzle. High pressure air enters the nozzle at a low Mach number, and when it gets to the narrowest part, which is known as the throat, it has attained Mach 1.

When air moves at supersonic speeds the familiar principle of "the larger the area, the slower the flow speed" is reversed. Thus the air is accelerated by a dif-



Leg 2 of the hypersonic wind tunnel. The sidewalls of the tunnel have been removed to show the 5-by-5-inch test section.

ference in pressure until it reaches a final high Mach number and a low pressure at the widest part of the nozzle, the test section.

As the air expands in going from the high to the low pressure, the temperature drops very sharply; for example, by a factor of 6 for Mach 5 and by a factor of 21 for Mach 10. Also, the speed of sound, which depends on temperature, goes down correspondingly, so that high Mach numbers may be produced with somewhat lower air speeds than might seem necessary at first thought. The actual air speed in Leg 2 operating at Mach 11 is about 3,000 miles per hour.

Heat and high Mach numbers

To prevent its temperature from dropping below the liquefaction point, the air must first be heated. It is this heating that places the limitation on producing higher Mach numbers in wind tunnels. A steam heat exchanger raises the temperature of the air supply of Leg 1 to 300°F, and 300 kilowatt electrical heater raises the temperature of the Leg 2 air supply to 1100°F, so that the temperature at the test section of either tunnel is not lower than —385°F, which is approximately the temperature of liquefaction. After the air passes the test section, a series of shock waves slows the air to low speeds, and simultaneously the temperature returns to that to which it was initially heated. The air must then be cooled by a water heat-absorber before it can be returned to the compressors.

When either tunnel is run without heating the supply air, the air becomes so cold that it condenses into tiny droplets of liquid air, which look like fog if illuminated by an intense beam of light passed into the tunnel through a window. No satisfactory comparison between data of condensed air flows and single-phase air flows has been obtained; most experiments, therefore, require the use of the air heaters.

Flow conditions

The contours of the nozzle blocks are of an exact shape which depends on the desired Mach number. The specific shape produces uniform flow conditions across the height of the tunnel at the test sections for only the one Mach number the nozzle was designed for. However, because the Mach number produced by a nozzle depends only on the height ratio of the throat and the test section, one may vary the Mach number by changing the throat height. The flow conditions across the test section height will still remain acceptably uniform for a fairly wide range of Mach numbers. The throat height for Leg 1, which normally operates at Mach 5.8, is .080 inches; for Leg 2, operating at Mach 8, it is .020 inches. Because the nozzle throat is so narrow for hypersonic flow, the rate of flow of air through it is correspondingly low, and consequently the power required to drive the compressors is not excessive. The 16 compressors, comprising 7 stages of compression, are driven by electric motors of about 1000 horsepower total.

As previously mentioned, the Mach number produced by a hypersonic tunnel depends only on the area ratio of throat to test section, and not on the pressure available. However, to keep the test section pressure at a realistic value in comparison with conditions a missile might meet, the supply air pressure is elevated. The supply pressure of both Legs 1 and 2 may be raised to 1000 pounds per square inch. In spite of this compression, the pressure falls to a hundredth of atmospheric pressure or less at the test section.

Observation of the flow over the model being tested, and the shock-wave configuration, is made possible by the use of a Schlieren apparatus. The Schlieren employs a beam of parallel rays of light from a mercury vapor arc which is passed through the test section of the tunnel, illuminating the model. The variations of air density in the regions of the model and of the shock waves refract the light, thus causing an increase or decrease of illumination in the image formed on the ground glass or photographic plate used for observation.

Operating schedules

Tunnel running time is scheduled, whenever possible, so that while one tunnel is running, the other is being instrumented and prepared to run. In this way, maximum usage of the compressor plant is obtained. Preparation takes somewhat longer in Leg 2 than in Leg 1, because the higher operating temperatures pose additional problems. For example, the plastic medical tubing used for connecting pressure probes in Leg 1 must be replaced by stainless steel hypodermic needle tubing in Leg 2. All joints made with this stainless steel tubing must be silver-soldered, because ordinary solder would melt.

There are two principal aspects of hypersonic flow that one may wish to study: the pressure distribution about a body, with its corresponding shock-wave configuration; and the viscous effects, which are known as boundary layer phenomena. However, the pressure distribution is already well understood as a result of the more classical compressible-flow theory. In fact, the shock-wave equations were deduced as early as 1870. Consequently, most hypersonic research is currently directed toward an understanding of boundary layer phenomena, which are of very great interest.

Boundary layer

The boundary layer is a layer of air that clings to a surface because of the viscosity of the air. It is responsible for both the viscous drag and the aerodynamic heating and may take two forms: laminar or turbulent. In the laminar form the air within it flows smoothly over the surface, and the speed varies in an orderly fashion between the surface and the outer edge of the boundary layer. On models in the tunnel, the laminar boundary layers get as thick as an eighth of an inch. In the turbulent form the flow in the boundary layer is highly irregular. It is not difficult to imagine that this chaotic flow produces more drag and heating than the streamlined laminar flow.

It is observed that as a surface moves through the air, a laminar layer forms at the front and extends to a rearward position which depends upon, among other things, the Reynolds number and the surface roughness. At this position, the flow in the boundary layer begins to be turbulent, and after another length, called the transition region, it is fully developed as a turbulent layer.

Turbulence, drag and heating

Among various problems recently investigated in the hypersonic tunnels is that of how much the occurrence of turbulence changes the drag and heating, and what influences affect transition. Using a flat plate model which had a small element of its surface connected to a force balance, direct measurements of skin friction were made. The boundary layer at the measuring element was normally laminar, but could be made turbulent by injecting air through a series of small holes in the plate surface located across the width of the plate near its leading edge. It was found that when transition occurred, the skin friction increased 4 or 5 times. However, it was noted that the laminar boundary layer showed much less tendency to become turbulent at hypersonic Mach numbers than at lower speeds. The result of this behavior is that a missile would have a larger laminar boundary layer region at high speeds than at low, and hence not so high a viscous drag as predicted by lower speed measurements.

Shock wave effects

Another investigation has been concerned with the effect of the closeness of the shock wave to the boundary layer at the leading edge of a flat plate. It has been found that for a short distance rearward of the leading edge, the high pressure behind the shock wave influences the manner in which the boundary layer builds up, and produces an accompanying increase of skin friction and heat transfer. While this may sound like a matter of only academic interst, it is of importance to an understanding of the high heat-transfer conditions near the nose of a missile.

An investigation soon to be made will study a method of cooling a surface exposed to hypersonic flows in an attempt to overcome the adverse effects of aerodynamic heating. The surface to be cooled will be made of a porous material, so that a coolant gas may be ejected outward through the surface by pressure. It will act, in a sense, as a heat-insulator. To be studied are the effectiveness of the method and its influence on transition.

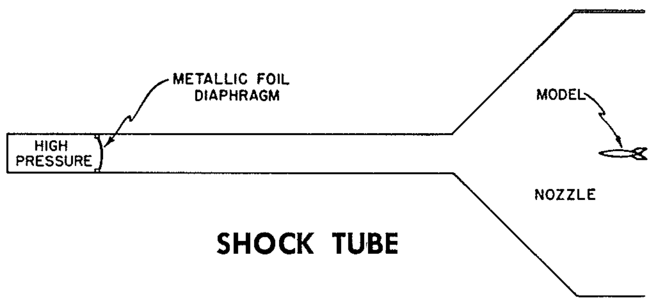
The group is developing two other means for producing high Mach number flows: a shock tube, and a helium tunnel. The shock tube (as shown in the diagram at right) essentially consists of a steel tube several feet long, closed at one end and leading into a nozzle at the other. A length of the tube near the closed end is made into a compartment by closing off with a diaphragm of metallic foil, and high pressure air is pumped into this chamber. When the diaphragm is burst by puncturing, a shock wave followed by a supersonic flow rushes down the tube until it reaches the nozzle. There it expands, just as in the wind tunnel, and produces flows of about Mach 6. The flow lasts only a few thousandths of a second, so that as it arrives at the model located in the nozzle, it must be observed by high-speed photography. The shock tube has as its advantage temperatures more nearly like those encountered in free flight conditions, rather than the temperatures of about —385°F in the wind tunnels.

Helium tunnel

The helium tunnel now undergoing testing is designed to produce flows of Mach 20. The helium tunnel, like the wind tunnel, produces high Mach numbers by expanding the gas in a nozzle. The advantage of helium over air is that its liquefaction temperature is so low that condensation does not occur, even without heating. The helium comes in steel cylinders from a commercial supplier, and although the tunnel exhausts three such cylinders in a matter of minutes, much valuable information about the shock-wave pattern and the pressure distribution on a model will be obtained.

While the projects that have been discussed are of an experimental nature, it should be realized that theoretical research receives equal emphasis. Because there is strong coordination of the two types of work, experiments are frequently suggested by analytical studies, and theory always modifies experiment when possible. Conversely, theoretical work many times depends upon experiment to guide it in the formulation of the problem.

The hypersonic program at GALCIT, sponsored by Army Ordnance and the Air Force, is part of a long-range program designed to put research ahead of the ever growing needs for knowledge imposed by the high-speed flight of the future.



The shock tube is also a means for producing high Mach number flows. It is a steel tube, closed at one end and leading into a nozzle at the other. A diaphragm closes off the end of the tube, and high pressure air is pumped into this chamber. When the diaphragm is broken by puncturing, the nozzle produces high temperature flows at about Mach 6.