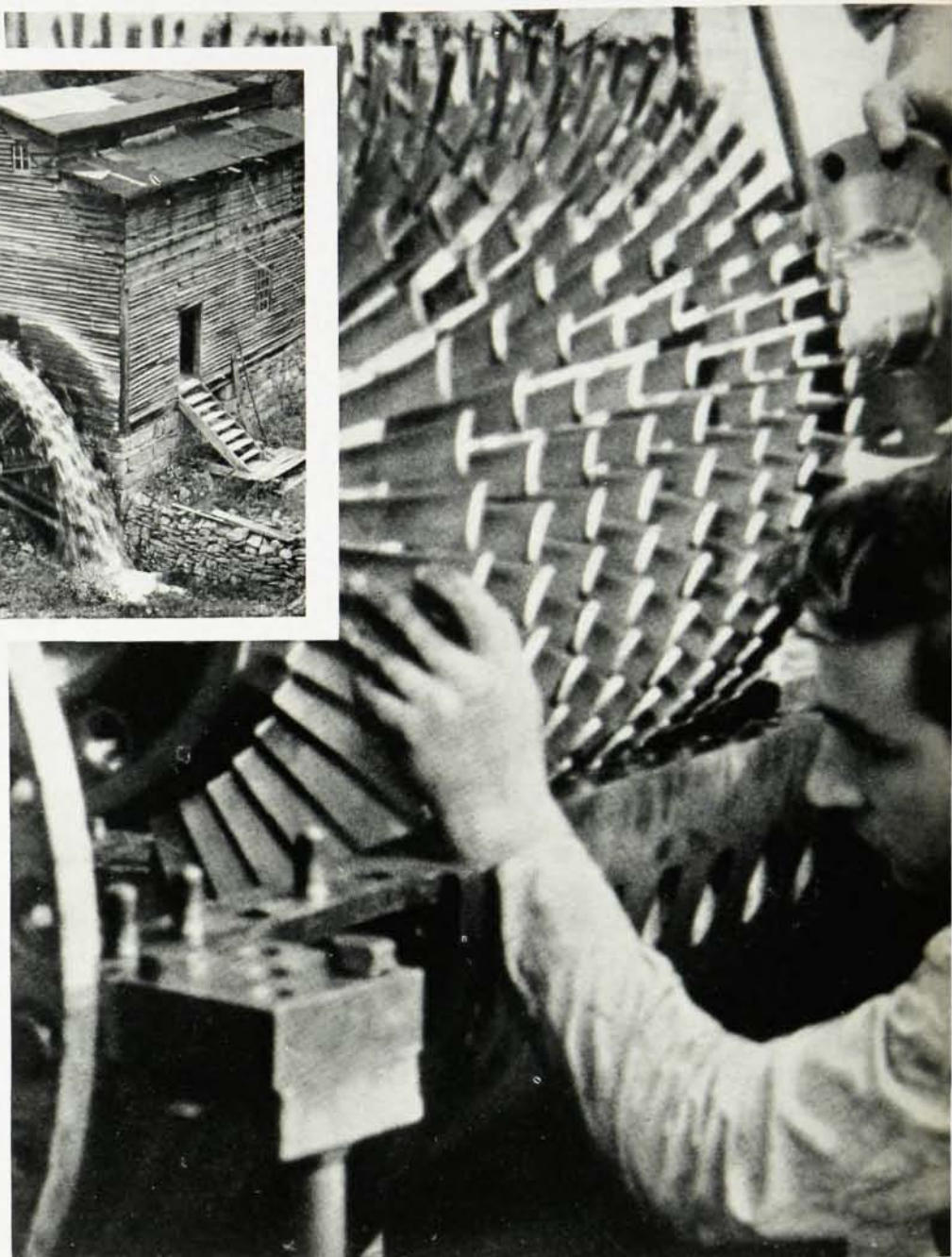


FROM ARCHIMEDES



Ewing Galloway



Gas turbine. Courtesy Westinghouse

TO SUPERSONICS

by James Bernard Kelley

. . . being some remarks on fluids.

In recent years the great interest in supersonic aerodynamics has overshadowed the other fields of fluid mechanics to a very large extent. The glamor and romance of high speed have caught the fancy of almost everyone so that one might suspect that little or no fluid mechanics exists outside the area of supersonics. Yet there is scarcely any field of physics which reaches further into antiquity for its origins and is at the same time more modern than fluid mechanics. Its history is studied with great names in science from Archimedes through the Bernoullis down to Jukowski, Prandtl, and von Karman in the present era.

Though gases have begun to replace liquids as the principal field of interest in fluid dynamics, it had for centuries centered around liquids. The applications of fluid mechanics range through all fields of engineering and even in those fields where they are not used directly they are helpful as analogies, as for example in the electrical field. The mechanical engineer of many years ago might have been concerned with the water wheel as a source of stationary power; mechanical engineers today are studying the gas turbine. Both engineers, together with the steam turbine designer, are concerned with the same fundamental problems; the only change has been in the medium in which the studies must be made.

A Few Effects

It is difficult to know who were really the first men or the first peoples to work with fluid mechanics. Certainly many of the ancient nations had irrigation and sewerage systems. Reservoirs and dams are by no means modern inventions. Somewhat in the manner in which the origin of the wheel has been lost so has much of the origin of fluid dynamics been lost. And also like the wheel much of fluid mechanics seems a natural result of human necessity which was bound to come about regardless of the age or condition of knowledge.

The first name which stands out is that of the Greek philosopher, Archimedes, whose commission from King Hiero of Syracuse to test the content of gold in his crown brought into being what is now

known as Archimedes' principle. What happened to Hiero's crown, beyond its getting wet, is not quite clear, but in any event it is supposed to have led Archimedes to the discovery of the principle which proves so convenient in determining density.

Another early experimentalist in fluid mechanics was the famous 17th Century French mathematician, Blaise Pascal. The principle which bears his name and which every student of physics learns in his first year study has made possible the hydraulic press and numerous hydraulic lifting devices. Based on Pascal's discovery—when pressure is applied to a liquid the pressure everywhere throughout the liquid is increased by the same amount—simple and inexpensive jacks can be made which will raise great weights.

But of all the developments of fluid mechanics none has outranked that of Daniel Bernoulli, the Swiss physicist and mathematician of the 18th Century. The famous Bernoulli theorem which was originally formulated for liquids holds equally well for gases and with appropriate modifications is used in modern supersonic aerodynamics. The Bernoulli theorem was the forerunner of the principle of the conservation of energy and there is no neater mathematical statement of that principle than that which the Bernoulli equation gives. In effect the Bernoulli theorem says that the sum of the kinetic and potential energies in a fluid must be equal to a constant. Therefore, as the pressure in a fluid changes, the velocity of the fluid must change in such a manner as to have the total energy remain constant. As the velocity is increased the pressure is decreased.

If unexpected, the Bernoulli effect can cause disaster. A merchant ship and a warship of the Royal Navy were moving in opposite directions along the Thames River; the warship was headed out to sea and the merchantman was going to its berth. Suddenly they sideswiped and the merchantman suffered severe damage as a result of striking

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the heavy armor plate of the warship. In the resulting legal action the attorneys for the shipping company vigorously denied the claim of the Admiralty that the merchantman was off its course and out in the warship's lane. Instead they maintained that the warship had passed too close aboard the merchantman and that Bernoulli's theorem quite easily explained what had happened. A venturi effect took place due to the contours of the hulls of the ships, thus causing the water to increase its velocity between the ships. The increased velocity, according to Bernoulli, would be accompanied by a decrease in pressure and the much lighter merchant ship was drawn up against the side of the warship and hence seriously damaged. The courts found for the Royal Navy—the jurists were lawyers all, no doubt—and the shipping company had to console itself with the knowledge that its plea was reasonable and entirely possible under the laws of physics.

More recently a speeding passenger train passed through a small station in a midwestern state. On the station waiting for another train were four people. Too late the station agent called to them to stand back. They were swept against the sides of the cars as the train rushed past and were killed, a tragic example of the unseen forces which can be so powerful and which Daniel Bernoulli had explained.

It Couldn't Be So

It was the German physicist Magnus in the middle of the 19th Century who first explained, at least partially, how a baseball curves, although he was not interested in athletics when he conducted his now famous experiments on rotating cylinders. In these experiments Magnus showed that if a rotating cylinder were placed in a moving fluid the cylinder would acquire what we call "lift". Subsequent experiments on other geometrical forms, including spheres, showed an identical effect. Therefore it seemed reasonable to expect a baseball or any other spherical object to be capable of being "lifted" in any number of directions.

Not many years ago a nationwide debate broke out as to whether pitchers could actually throw a so called curve ball. The argument was not with the Magnus effect, which was well established. Rather the question was whether a human arm could induce the conditions of velocity and rotation necessary to bring the Magnus effect about; the

argument was won by the affirmative. Highspeed cameras at several universities caught numerous instances of thrown balls curving large lateral distances from their original trajectories.

For years mathematicians had denied the possibility of flight for airplanes, although it is not clear how they explained gliding birds. At any rate the mathematical integration of the pressure distribution around a cylinder shows quite conclusively that the lift for that cylinder in a moving air stream would be zero. But surely the Magnus effect could not be denied because it took place before the very eyes of the doubters. Finally the German scientists Kutta, Jukowski, and a little later Prandtl explained both physically and mathematically what might be happening in what is called the "circulation theory of lift." Unfortunately, although the circulation theory explains the lift of the cylinder and supplies the missing term in the mathematical integration, circulation itself is unexplained. Physically it is not too difficult to see what could be happening in a rotating cylinder but what about an airfoil which is perfectly rigid and incapable of rotation? The answer to that question has never been given. Yet the circulation theory has worked to such an extent that the skies are today filled with flying aircraft.

The Magnus effect was used a number of times in the design of ships. In place of sails or a propeller the ships were equipped with a number of upright cylinders which could rotate on their axes when driven by motors of relatively low horsepower. By adjusting the speed of the cylinders it is possible to steer and sail an ocean-going ship of considerable size much in the same manner that one would handle a sailing vessel. Although such ships are inexpensive to run they have the disadvantage of being very slow and ordinarily take two or three times as long to traverse the same distance as a conventional freighter of like tonnage. However, they have proved, on a small scale, to be interesting competitors in sailing races, where their strange method of power undoubtedly caused much head-scratching and rule-book-thumbing among race officials.

Architects can run into trouble if they are unwilling to recognize the effect fluid mechanics has upon stationary structures. For example, one of the early Zeppelin hangars in Germany exploded because it was improperly designed aerodynamically.

The curved surface of the roof acted as an airfoil and the roof was lifted right off the hangar when a good wind came along. Similarly, homes that are built in cyclone areas are stressed for compression. They should be stressed for tension as well, for high winds will tend to lift the roofs rather than crush them into the houses. It is common practice to be sure that chimney openings clear the peaks of roofs because of the action of wind over roof tops. If the chimneys did not clear the roof peaks, the smoke would be driven back down and the fire actually blown out of the fireplace or furnace during a wind-storm.

The Big Inch

Nondimensional parameters are always valuable to the experimental physicist. In fluid mechanics there is one such parameter which has stood out in its wide and continued application above all the others. This parameter is the Reynolds number, named for the British experimental physicist of the 19th Century who first used it. Reynolds made his studies with liquids in pipes, but his number is equally well adapted to problems in gas dynamics. Today, together with the Mach number, it is the most frequently encountered parameter in aerodynamics.

In his studies of flows in pipes, Reynolds discovered that there was some critical value of this parameter (the ratio of the product of the fluid's density and velocity and the diameter of the pipe, to the viscosity of the fluid) at which the flow through the pipe would change from laminar to turbulent. In laminar flow the fluid moves in thin sheets, or laminations, one sliding over the other. Turbulent flow, on the other hand, is just what the name implies, and is filled with eddy currents and vortices. Reynolds found that as he increased the velocity of flow the smooth, laminar structure of the fluid gradually changed to a swirling, turgid motion and that this change took place at a particular value of the nondimensional parameter which now bears his name. This value is called the critical Reynolds number and was found to be, at the lower limit, about 2320.

The German engineer Hagen and the French physicist Poiseuille, also working in the 19th Century, made some very interesting studies in pipe flow which were used in connection with the Big

Inch pipeline. The Big Inch—it is 24 inches in diameter—was used to carry petroleum from the Southwest to the East and other parts of the country during the recent war, thus saving millions of miles of truck, rail, and water travel for the needed fuel and engine oils. Hagen and Poiseuille showed by experiment as well as mathematically the form which a liquid flowing through a pipe would take. A fluid which is in the laminar range will have a long, sharp parabolic nose which will extend for great distances ahead of the main body of the fluid. This needle-nosed wedge of fluid takes up only a very small portion of the cross section of the pipe, the rest of the cross section being wasted. Turbulent flow, on the other hand, is blunt-nosed and leaves very little waste space. Therefore, although turbulent flow requires greater power to push it through the pipe, it was found that actually a saving was made by allowing the flow to become turbulent since more of the Big Inch could be used.

The blunt-nosed turbulent flow had another definite advantage. Since it was customary to run a number of different types of oil through the pipe at the same time—one after the other—the long-nosed laminar flow would require longer waits between different types. The turbulent flows permitted the different oils to be run into the Big Inch, one right after the other, with negligible mixing.

Aerodynamics

The use of Reynolds' number spread to aerodynamics. Since it has long been known that a body moving through still air and a stationary body past which air is moving will behave in the same fashion, the wind tunnel has become the chief experimental device for the aeronautical engineer. So that the results of wind tunnel experiments may be correlated with actual designs of full-scale airplanes, the nondimensional Reynolds number is used. The only change is that instead of the diameter of the pipe, the chord of the airfoil is substituted.

In common with all other fields of science, fluid mechanics suffered from prejudices and ignorance. As was pointed out earlier, for nearly one hundred years no research was done on the possibility of making an airplane because of the number of influential and big name mathematicians who said that an airplane was theoretically impossible. But the experiments of Magnus and the mathematical

researches of Kutta and Jukowski added to that of Prandtl brought about the circulation theory of lift and the present era of aeronautics.

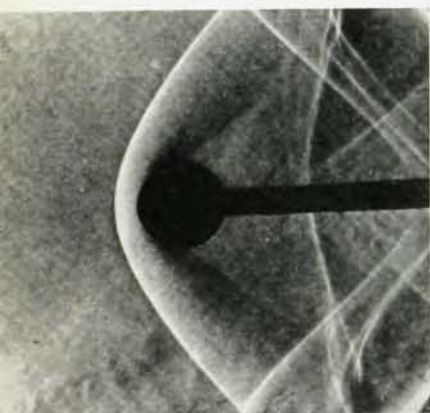
As the need for airplanes of higher and higher speeds became more pressing, the formerly limited field of supersonic aerodynamics came into full flower. Until World War II and its demands on aeronautical designers, supersonics had been limited to the studies made in ballistics. In no other area was there need for knowledge concerning the wave phenomena of high velocity flight. Prior to the second World War a 300 miles-per-hour airplane was something to view with awe. But jet propulsion and gas turbines changed that—even the conventional reciprocating engines were able to bring airplanes over the 500-miles-per-hour mark—and made knowledge, detailed knowledge concerning structural design, flow patterns, and shock loading, more than ever necessary. It was no longer possible to extrapolate from known data because the compressible flows have problems all their own which must be solved in their own special ways. Furthermore it was recognized that airplanes which were expected to fly at velocities of more than 400 miles per hour would have to be designed with considerable care, for errors as high as fifteen percent could creep into the calculated drag and lift forces at such a velocity, if the effect of compressibility was ignored.

Although ballistics is a much older study than aerodynamics, it still remained for the aerodynamicist to do a great deal of work in the field of compressible fluids. And that work is far from completed. Mathematically it is extremely complicated and tedious as well as uncertain. Therefore a great

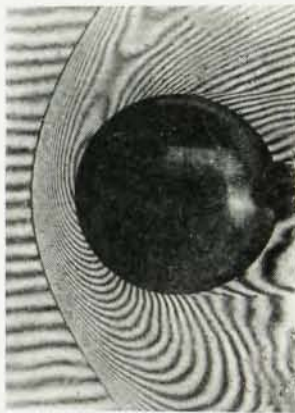
amount of reliance must be put on wind tunnel testing just as in the case of the noncompressible aerodynamics.

There are three usual methods of obtaining test results and these are, more or less in the order of frequency of use, the Schlieren method, the shadowgraph method, and the interferometer method. The illustrations show the results of these methods for a sphere at a Mach number of approximately 1.8. From these it would appear that the shadowgraph offers the best pictorial view. This is frequently the case. The interferometer method, which it can be noticed is very similar to the photoelastic interference patterns, is the most accurate and can be used for quantitative as well as qualitative studies. Referring to the shadowgraph one can get a good picture of both the shock and Mach waves as well as of the turbulent wave. The shock wave appears immediately ahead of the sphere while the Mach wave, whose angle is somewhat smaller, appears attached to the sphere.

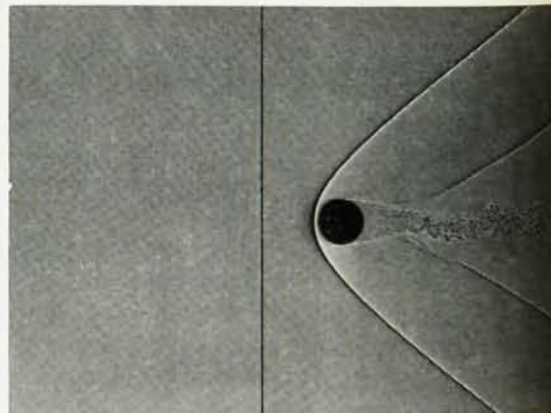
Fluid mechanics has travelled a long and interesting path from the ancient civilizations to the present time. Its mysteries and problems have had deep meaning in so many fields that no paper or book could hope to bring them all into the open. Most of these mysteries and problems still remain unsolved but gradually man is reaching the point where, even though he may not understand why he is doing what he is doing, he is still able to put the mysteries to work for him in thousands of everyday applications which mean greater health, faster travel, cheaper transportation, and safer dwellings.



Sphere in wind tunnel at Mach No. 1.8. Courtesy H. W. Liepmann and A. E. Puckett, Introduction to Aerodynamics of a Compressible Fluid, John Wiley and Sons, Inc.



Interferogram of the flow around a sphere at Mach 1.81. NACA photo



Shadowgraph of sphere in free flight at Mach 1.8. Courtesy A. C. Charters, Ballistic Research Laboratories, Aberdeen Proving Ground, Md.