APPLICATIONS OF THE COANDA EFFECT

When a liquid or gas flows along a solid surface, it tends to stick to the surface. This effect, named for a Romanian aircraft pioneer, has potential uses in such devices as burners and hovering vehicles

by Imants Reba

Everyone knows that it is not easy to pour a liquid smoothly out of a teapot spout or the mouth of a bottle. The liquid has an annoying tendency to flow around the lip and dribble down the curved surface of the spout or the side of the bottle. What causes the flow to bend and cling to the vessel's surface? Is it simply surface tension, as has usually been supposed? The answer is not quite so simple, and it has significant technological consequences.

In the year 1910 a young Romanian-born engineer named Henri Coanda tested a new flying machine he had built himself. He had been a student of Alexandre Gustave Eiffel, designer of the Eiffel Tower and one of the pioneers of modern aerodynamics, at the École Supérieure Aeronautique in Paris,

"TEAPOT EFFECT" is a low-speed form of the Coanda effect: water poured slowly from a glass tends to stick to the side of the glass in the same way that tea sticks to the spout of a teapot. High-speed fluids similarly adhere to a surface of suitable shape.

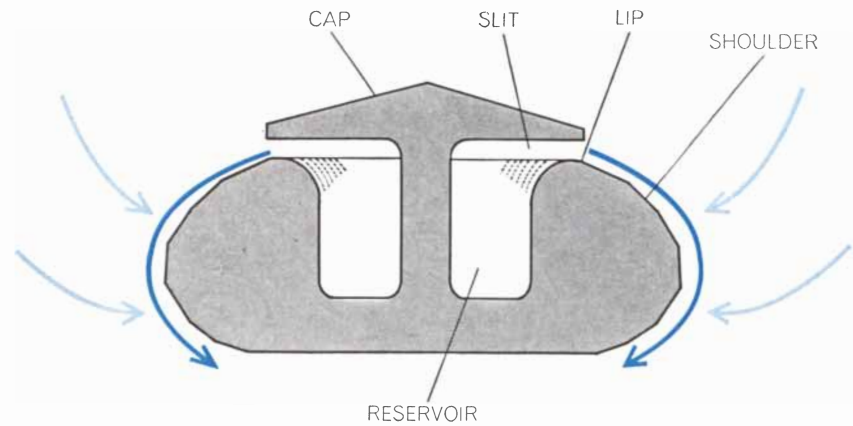
and the young engineer's approach to flying was both bold and imaginative. Coanda's machine was a kind of jet aircraft. It was equipped with an air compressor powered by a reciprocating engine; thrust was obtained by injecting fuel into the compressed air to provide a kind of afterburner. At the outset Coanda was confronted with the possibility that the flames from his two jet exhausts might set fire to the plane's fuselage, which was made of plywood. He therefore installed metal plates to deflect the exhaust flames away from the fuselage.

Coanda took his vehicle out for a test run on a field at Issy-les-Moulineaux, a Paris suburb. As he taxied across the field he saw with dismay that the deflecting plates, instead of diverting the exhaust away from the body of the plane, were actually sucking the flames toward it! Preoccupied with this surprising development and with handling the engine throttle, Coanda did not notice until the last moment that he was approaching the Paris city wall at high speed. He jerked back on the control stick, became airborne long enough to clear the wall, then crashed.

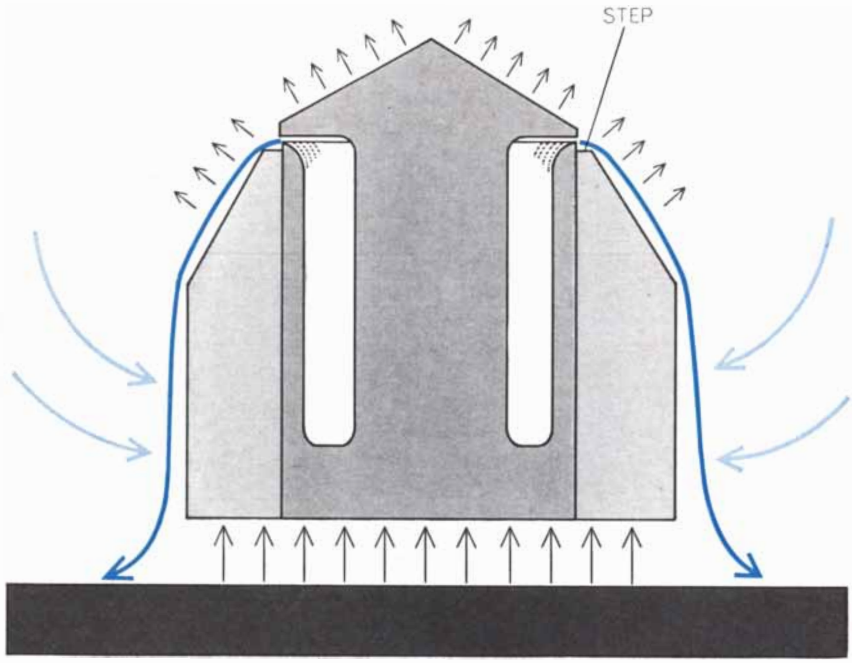
As far as is known, this was the first flight of a jet airplane. Reflecting on the incident, however, Coanda was less interested in the takeoff than in the strange phenomenon of the wrong-way bending of the jets by his deflector plates. At the first opportunity he discussed the event with Theodor von Kármán, the foremost theorist of aerodynamics, who was then working at the University of Göttingen. Von Kármán realized that the phenomenon was a new discovery and named it the Coanda effect.

Twenty-five years or more passed before any other investigator gave serious attention to the Coanda effect. Coanda himself went to work as chief engineer of the Bristol Aeroplane Company in Britain and became involved in various technical researches having nothing to do with this subject. In his spare time, however, he carried on experiments to examine the basic features of the effect and its possible uses.

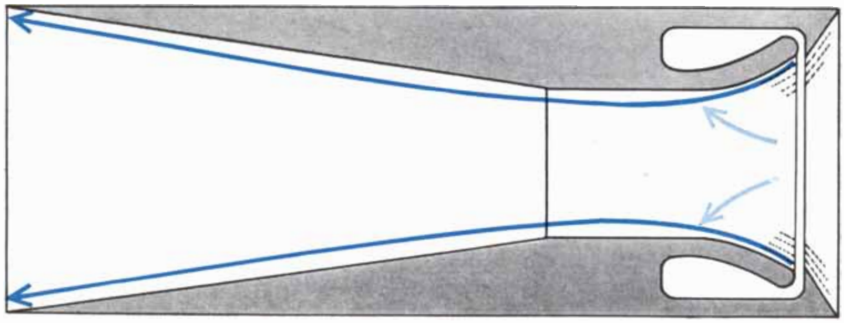
Consider a sheet of fluid (gaseous or liquid) that is discharged through a slit onto an extended and rounded lip. As in the case of the teapot spout, the sheetlike stream will attach itself to the curved surface and follow its contour. Coanda found that by constructing a shoulder composed of a series of



COANDA EFFECT was named for the tendency of a fluid, either gaseous or liquid, to cling to a surface that is near an orifice from which the fluid emerges. In this representation air from the reservoir emerges through the slit and, as shown by the dark color, closely follows the sides of the vessel. An important part of the effect is the tendency of the primary flow of air to entrain, or draw in, more air (*light color*) from the environment.



EXTERNAL NOZZLE was designed by the author in early tests of the Coanda effect as a means of generating lift. Pressure over the upper portion proved to be less than atmospheric; hence a vehicle with the shape of such a nozzle could be lifted by low pressure at top and higher pressure at bottom. Step near slit proved to be crucial in maintaining good lift.



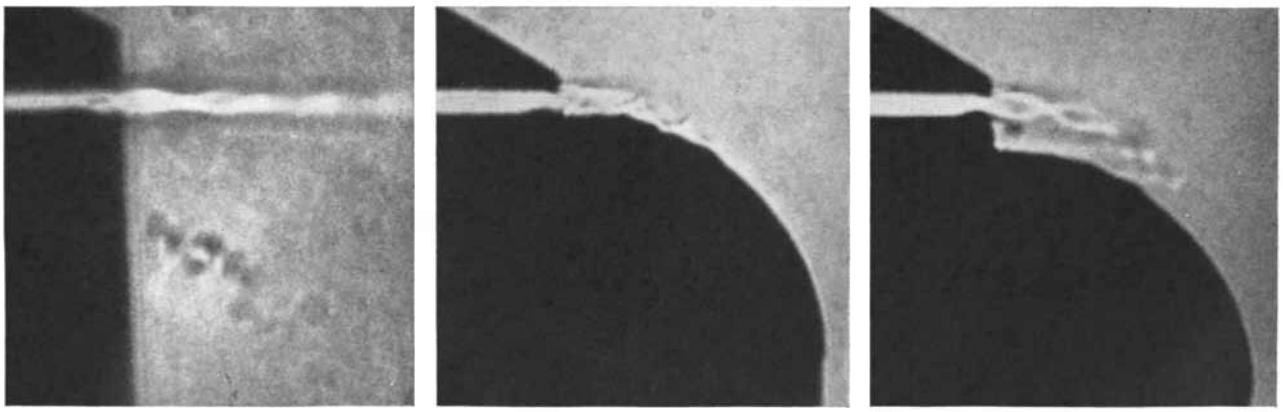
INTERNAL NOZZLE takes its name from the fact that the flow of air is through the inside of the nozzle. Otherwise the Coanda effect is the same as that in the external nozzle.

short, flat surfaces, each at a certain angle to the one before and each with a certain length, he could bend a jet stream around an arc of 180 degrees [*see top illustration on preceding page*]. Moreover, by experimenting with air blown through the slit he discovered that the deflected airstream sucked in air from the surroundings. As the jet flowed around the shoulder it entrained up to 20 times the amount of air in the original jet. Coanda measured the air pressure at various points along the surface over which the stream was flowing, and he established the significant fact that the pressure on the surface was less than atmospheric pressure: in other words, it represented a relative vacuum. Near the slit the existence of this vacuum accelerated the flow of the jet after it emerged from the slit.

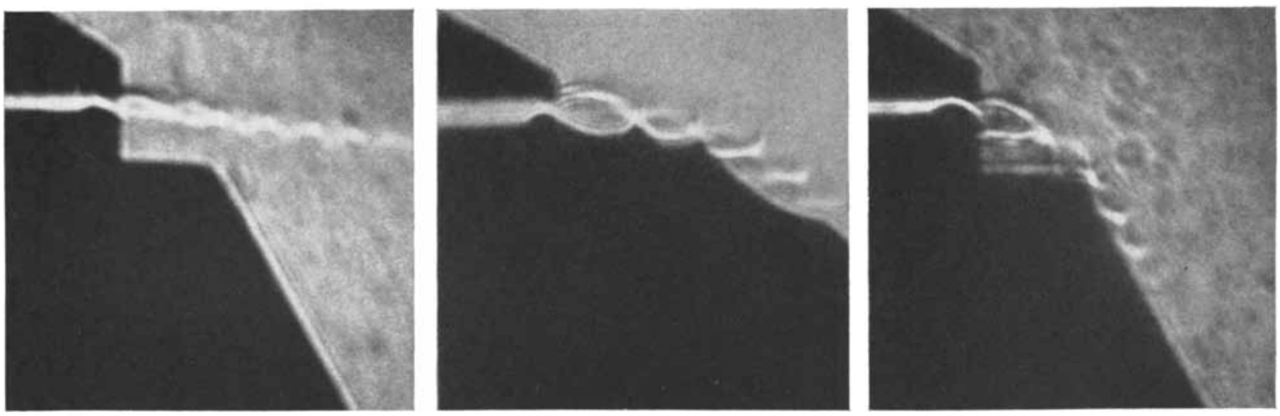
From his experiments and calculations Coanda derived a remarkable conclusion. The Coanda effect, he argued, could lift and propel a vehicle by a process that was the reverse of that in conventional propulsion systems. Instead of applying force at the rear of the vehicle (such as a rocket or a boat) to propel it against the resistance of the air or water in front, one could use the Coanda effect to generate a vacuum at the front, so that the higher pressure at the rear would impel rather than propel it. Similarly, a Coanda-generated vacuum above the vehicle would provide lift. In conventional aircraft-propulsion systems the necessary vacuum above the wings is generated by driving the vehicle forward at high speed; the Coanda system would accomplish the same purpose without any forward motion or moving parts simply by blowing air over a rounded shoulder.

In aerodynamics the problem of propulsion is reduced to the problem of overcoming drag, a resistance whose components are high pressure at the nose of the vehicle and low pressure at the tail. Coanda's proposal, to put it briefly, consists of propelling the vehicle by means of "negative drag": low pressure at the nose and higher pressure at the rear. This suggestion is so completely contrary to ordinary concepts about the flow of a fluid around moving bodies that it has understandably met with great skepticism among aerodynamicists.

Undismayed by skeptics or by the general lack of interest in his ideas, Coanda proceeded to construct various nozzles embodying his effect and to design vehicles to be propelled by them. The fact that some of his designs took the shape of flying saucers has not helped matters. The Coanda effect might have been dismissed as an eccentric notion had it not attracted the attention of the team of Allied scientists that was assigned to investigate the German wartime research after the liberation of Paris in World War II. It was alleged that the Germans had conscripted Coanda into their jet-propulsion research. In any case, the Allied scientists examined Coanda's devices and suggested that the Coanda effect merited seri-



IMPORTANCE OF GEOMETRY in optimizing the Coanda effect is demonstrated by these shadow photographs. At left is the flow of an undeflected jet of air. With a curved surface outside the slit (*middle*) the air tends to follow the surface, but with distortions. A step at the exit of the slit (*right*) produced a better flow but not an ideal one because the air impinged on the surface.



FURTHER MODIFICATIONS showed (*left*) that too high a step can cause the flow to separate from the surface. With a grooved surface (*middle*) the flow was undistorted. A well-balanced geometry (*right*) provided an ideal flow that was tangent to the surface.

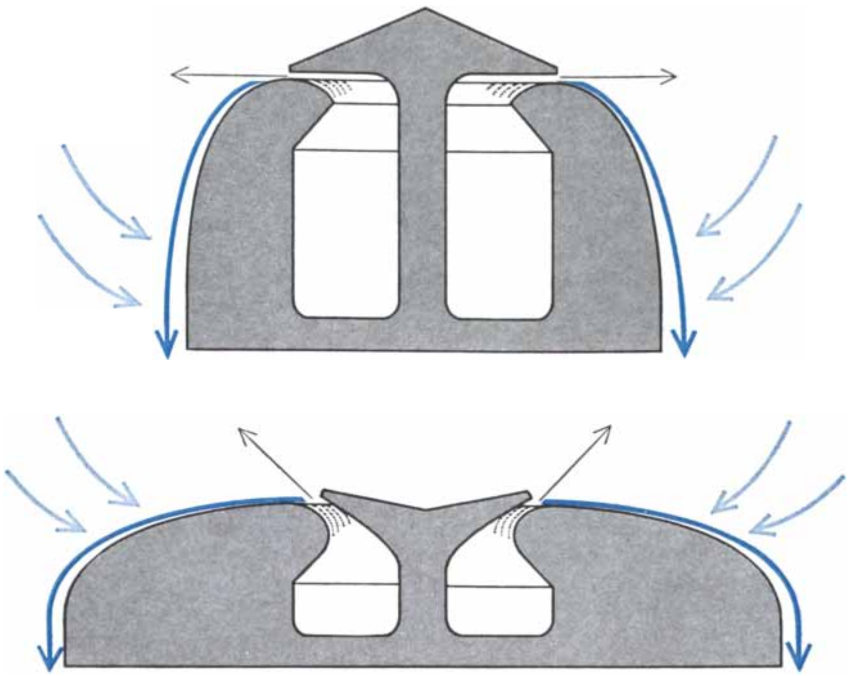
ous study. A theoretical analysis by von Kármán in 1949 and experiments at the Cornell Aeronautical Laboratory in 1952 supported Coanda. Several other investigators, however, reported that his claims could not be confirmed, and this discouraged a thoroughgoing evaluation of his ideas.

Happily unaware of the controversy among the experts, I was attracted to Coanda's concept by an article about him in a popular magazine in 1956. As a student at the Polytechnic Institute of Brooklyn, I was particularly interested in propulsion systems, and the unorthodox Coanda approach seemed exciting. When I went on to graduate studies at the institute, working as a research assistant in its newly established Rocket Propulsion Laboratory, I had the good fortune to obtain more technical information about the Coanda effect from T. Paul Torda, director of the laboratory, who had worked with von Kármán on the theoretical analysis.

I set out to test the effect with a nozzle of my own design. Coanda had experimented with both "external" and "internal" nozzles. In the former the deflecting shoulders were outside a tube; in the latter, inside [*see middle and bottom illustrations on page 85*]. My nozzle was of the external type: a roughly cone-shaped arrangement in which air blown outward through a slit circling the body would cascade over a shoulder angled 60 degrees from the slit. This form of the device was inspired by the thought that the Coanda effect might be applied to a "ground-effect machine," the type of vehicle that moves over the ground on a thin cushion of air. For such a machine one of the main problems is steering and related control, since it has no traction with the ground. It seemed that Coanda nozzles might provide such controls.

The first tests of the nozzle were successful. With a nozzle positioned upright in a model ground-effect machine, the Coanda phenomenon caused the model to take off and rise to a height of several inches when a fast stream of air was blown through the slit. Emerging from the slit at the speed of sound, the air accelerated to supersonic speed as soon as it began to flow over the shoulder.

In 1961, having joined the Armour Research Foundation, now the IIT Research Institute associated with the Illinois Institute of Technology, I was provided with funds for an investigation of the possible use of the Coanda effect



REORIENTATION OF SURFACES was necessary to progress from nozzle-like applications of the Coanda effect (*top*) to the wide-based shape (*bottom*) desirable for a ground-effect machine. The changes involved much experimentation with different configurations.

for propulsion. Coanda had said that a Coanda nozzle, by increasing the momentum of the gas flow, could produce twice as much thrust as an ideal straight nozzle with the same input of energy. Experimenters testing his claim had failed to achieve any augmentation of thrust by means of the Coanda effect. Their test devices, however, were quite simple in design, whereas Coanda had developed rather sophisticated nozzles of complicated geometry. It therefore remained possible that with proper design a gain in thrust could be demonstrated.

As a start in our testing program I designed a one-piece nozzle six inches in diameter with a shoulder in the form of a series of successively angled flat surfaces, according to Coanda's original design. The results of its first test were most disappointing. The airstream from the slit did not flow around the shoulder contour; it promptly detached itself unless the slit opening was made very small or the flow was very gentle and undisturbed. I went home from the laboratory frustrated and discouraged. But my assistant, Edward Wohlthausen, stayed on and carefully went over every feature of the nozzle's construction. He discovered a seemingly trivial difference, which turned out to be crucial, between this model and the one I had built originally at Brooklyn Polytech. My first model had had a small step down from the mouth of the slit. This small step at the aperture, only about a thirty-second of an inch deep, made the difference between the airstream's clinging to the shoulder and separating from it. With such a step the new model also worked.

We then proceeded to extensive testing of some 30 different shoulder configurations. With the help of shadowgraph photography that showed details of the flow, we obtained several interesting insights into the Coanda effect [*see illustrations on opposite page*]. The small step at the very lip of the slit is important because it turns the flow from the slit into an eddy, or vortex, which in this device rings the entire nozzle and therefore forms what is called a ring vortex. It is the vortex—or rather the low pressure generated within it—that causes the stream from the slit to bend and thus follow the contour of the shoulder. The curving of the stream around the shoulder produces a force directed radially outward; this force, tending to pull air away from the shoulder surface, apparently accounts for the relative vacuum, or suction, next to the surface. To maintain the suction, which prevents separation of the stream from the surface and causes the flow to accelerate, the stream must hug the shoulder surface closely without actually impinging on it or adhering to it.

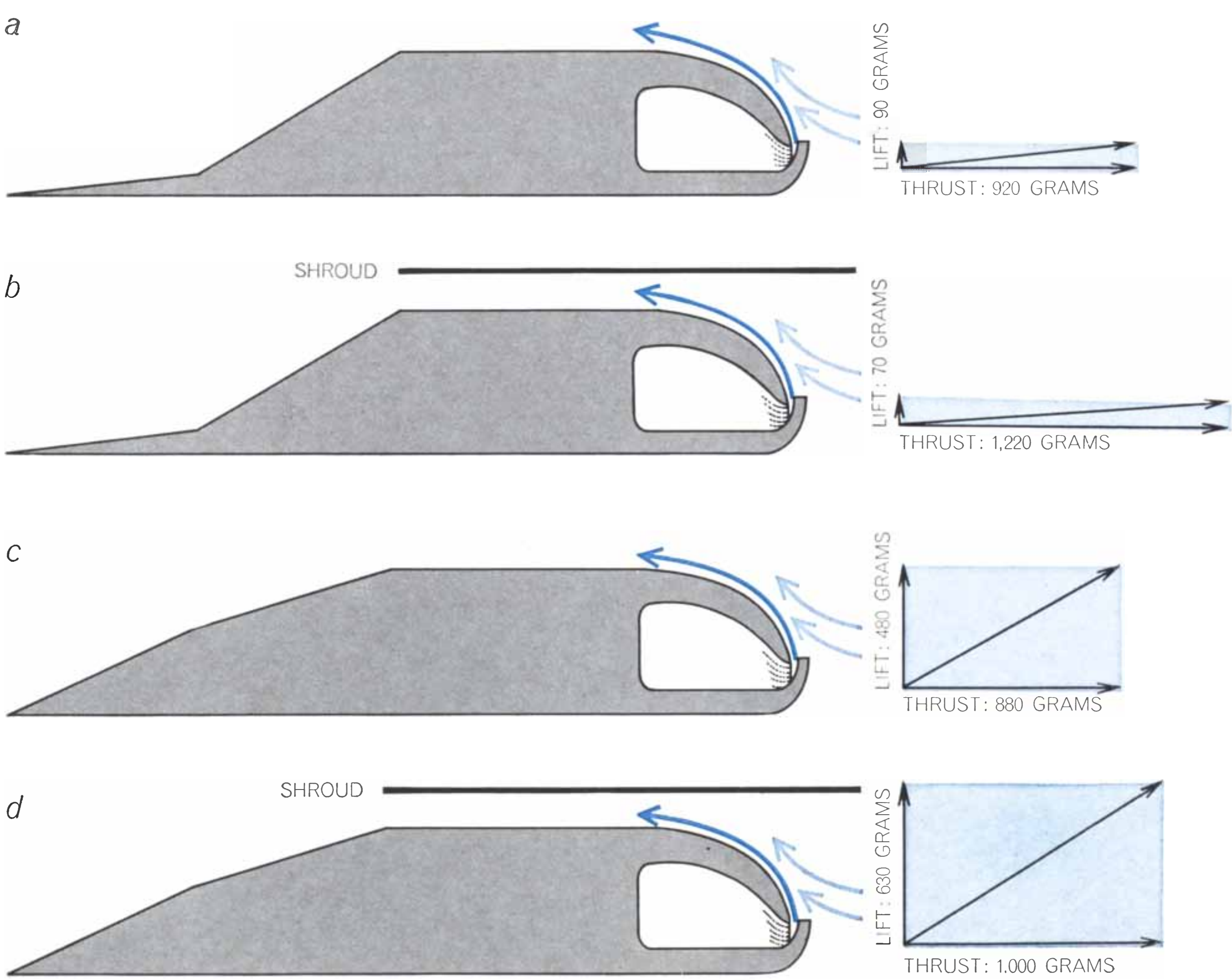
Our experiments showed clearly that the creation of a stable Coanda effect depends on the appropriate adjustment of many factors: the diameter of the slit, the strength of the jet, the depth of the step and various other details of the shoulder contour. Particularly crucial is the ratio of the slit diameter to the diameter of the nozzle as a whole. If the slit is too wide in relation to the shoulder breadth, the stream will tend to detach itself from the surface; if it is too narrow, the stream will tend to stick to the surface. Also important is the texture of the surface: a properly roughened surface helps to prevent distortion of the stream flow. In short, it takes a complex set of arrangements to produce a useful Coanda effect. It is no wonder that most investigators of the effect had found it to be an elusive phenomenon.

Obviously the effect depends primarily on the maintenance of a balance between the centrifugal force and the suction force as the stream flows around the shoulder and afterbody of the nozzle. We found by experiments that the efficiency of the effect could be enhanced by certain adjustments of the orientation of the slit and the slope of the shoulder; these controlled the distribution of pressure within the stream so that it did not separate from the surface.

Although we obtained high thrust efficiencies with such devices, we were not able to produce the gain in thrust (over the theoretical capabilities of conventional jet devices) that Coanda had said should be achievable. At this juncture, in the spring of 1963, Coanda himself visited my laboratory. (He was then 77 years old.) He examined the model with which I was working, bent over it and cupped his hands around the nozzle. The fluid in a manometer attached to the model promptly rose, showing an increase in the suction pressure. By simply forming a shroud around the nozzle with his hands Coanda had increased the device's production of thrust!

The shroud, Coanda explained, guides the streamlines of the entrained flow in a direction parallel to the surface of the model and thus enhances the suction pressure. Coanda went on to emphasize also the importance of proper design of the afterbody, or tail, beyond the shoulder. A suitably tapered afterbody, he said, would cause the flowing stream to exert a positive pressure on the rear of the body and thereby add to the propulsive thrust.

Not entirely convinced of this last argument, because it was so contrary to accepted ideas in aerodynamics, I nevertheless proceeded to build



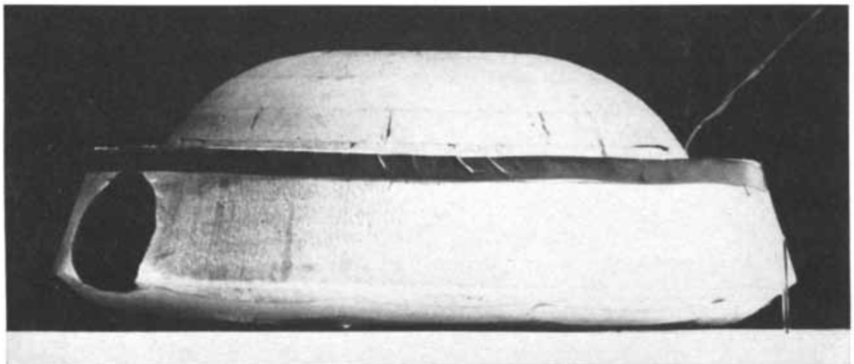
CONFIGURATION AND SHROUDING affect the performance of an airfoil. At *a* the Coanda effect over the airfoil at left produces the forces represented at right. At *b* the result of placing a shroud over the same airfoil is shown. An airfoil of different geometry appears unshrouded at *c* and shrouded at *d*. In each instance the data were obtained from an airfoil that was fixed rather than moving.

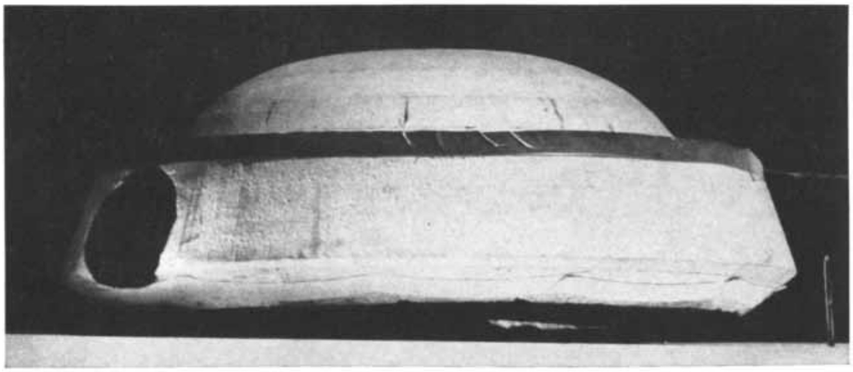
several models based on Coanda's recommendations. The shroud concept immediately proved its value in enhancing thrust. The afterbody theory, on the other hand, turned out to be harder to confirm. At length, after more than a year of experimenting with various afterbody configurations, we finally produced one that bore out Coanda's prediction [*see illustration on opposite page*]. This nozzle, with a shroud and a steeply tapered tail, produced a thrust 19 percent greater than that of an ideal jet lacking the augmentation of the Coanda effect.

Independent studies at the University of Toronto's Institute of Aerospace Science, at Pennsylvania State University and at the Research Center of the Huyck Corporation in Stamford, Conn., have also verified that Coanda nozzles are capable of augmenting thrust. Gains of up to 38 percent have been reported. Indeed, it can be said that Coanda's hypothesis of propulsion by negative drag has been confirmed.

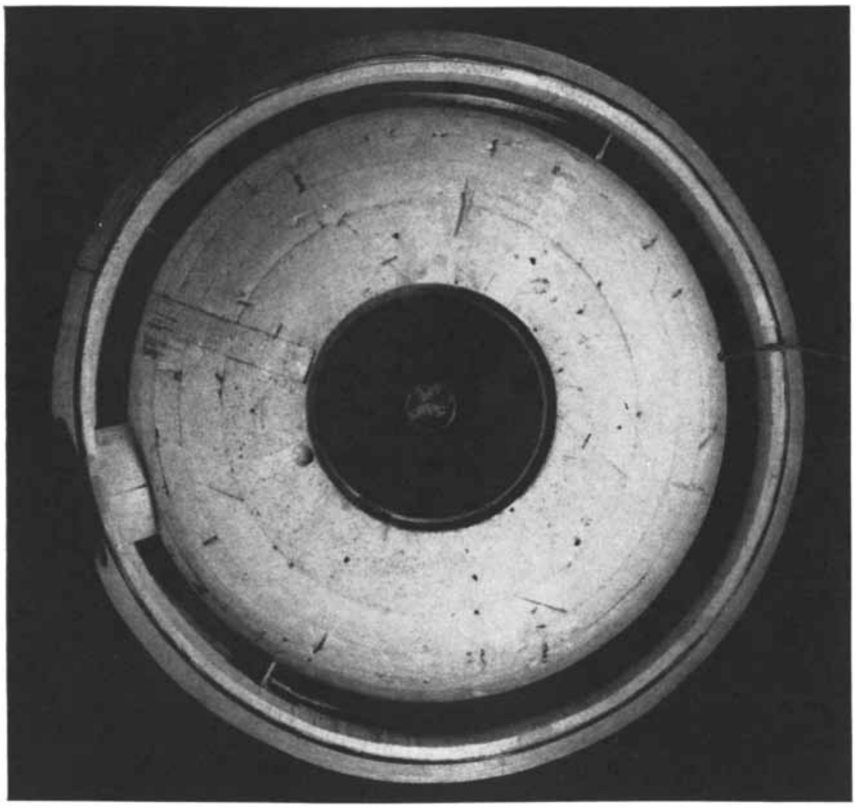
This is not to say that the Coanda effect is fully understood. There is no doubt that the gain in thrust with the Coanda type of nozzle derives from the fact that a jet sheet flowing around a curved wall entrains more outside fluid than a straight jet stream does. But the mystery remains: Why does it do so? The answer probably lies in the turbulences set up within a curving jet sheet; presumably they promote vigorous mixing of portions of the fluid and so increase the rate of entrainment at the outer edge of the sheet. In any case, we now know from experiments that the Coanda effect does work to augment thrust, and we therefore have a sound basis for exploring possible useful applications of the phenomenon. Indeed, it has already shown its usefulness in another field, namely the device known as the fluid amplifier, whose functioning depends on the Coanda effect [see "Fluid Control Devices," by Stanley W. Angrist; Scientific American, December, 1964].

The first device we built to test the practical application of Coanda thrust was a small model called GEM (for ground-effect machine). This dome-shaped model, two feet in diameter, has a ring slit at the top, a shoulder configuration in the form of an ellipse with its major axis parallel to the ground and a short, collar-shaped shroud around the lower part [*see illustrations at right*]. The slit is inclined at an angle of 45 degrees from the horizontal, so that the jet is directed upward—contrary to all





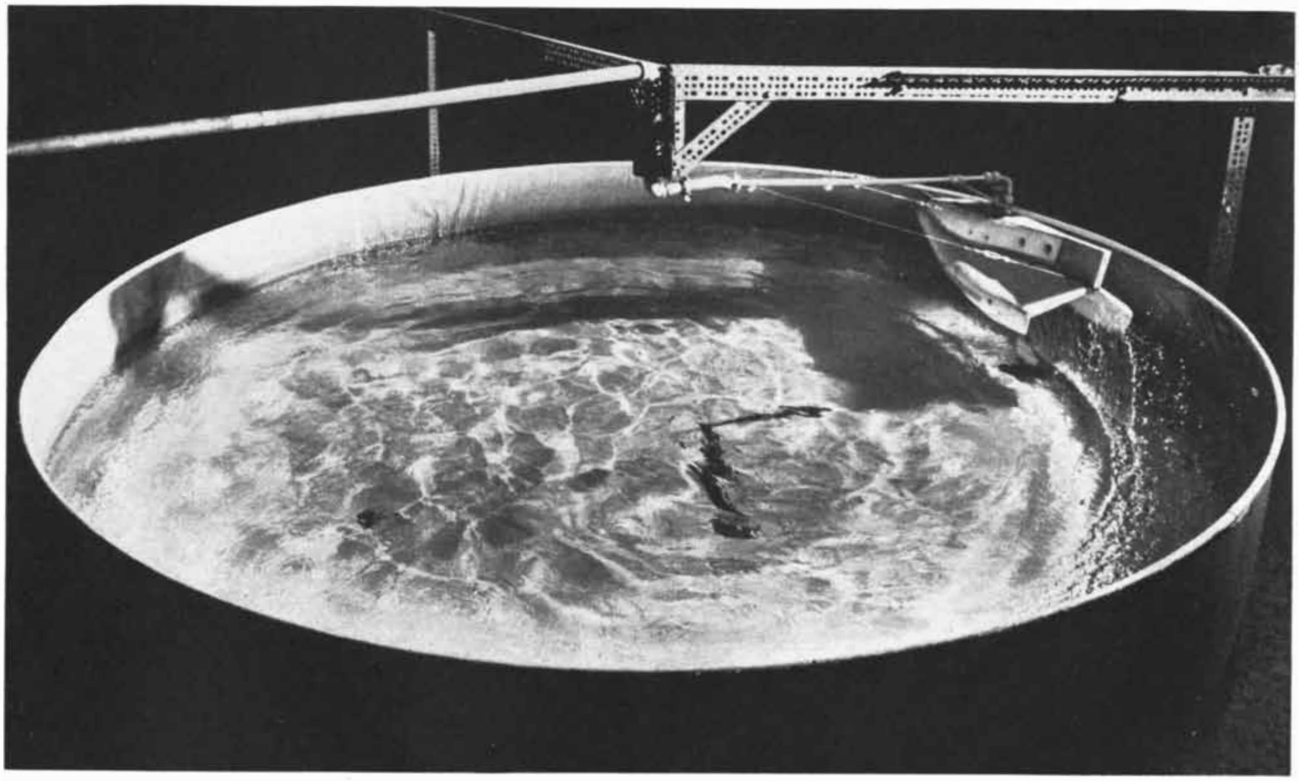
GROUND-EFFECT MACHINE, which is known by the acronym GEM, rests on a table at top and rises from the table at bottom. It achieves lift by means of air, but in an unusual way. Because of the Coanda effect the pressure at GEM's top is less than atmospheric. With this negative drag, or reduced resistance, over the upper portion of the surface, the higher pressure at the bottom lifts or drives the vehicle. The hole on the left side is the air intake.



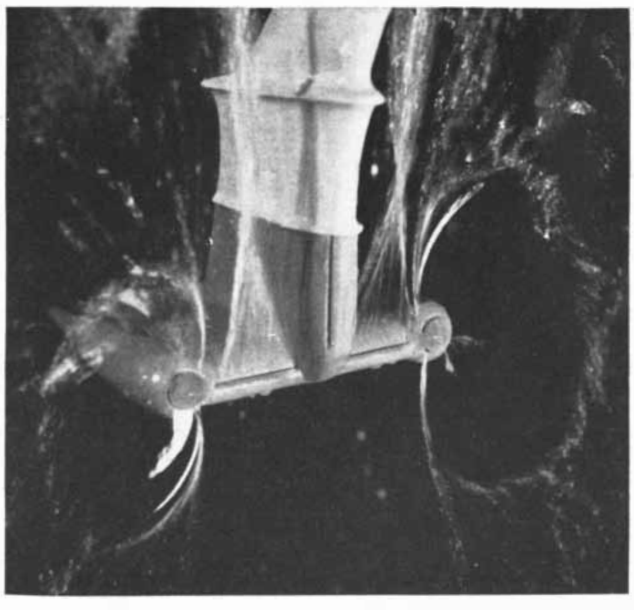
TOP VIEW of the GEM shows the slit from which the air emerges. The slit is the thin light circle near the outer edge of the dark central area. The dark circle just outside the slit is the step. This model, designed by the author, is approximately two feet in diameter.

conventional uses of jet thrust to generate lift. This vehicle is raised from the ground simply by the jet of air that produces a vacuum at the upper surface, flows around the shoulder and emerges at the bottom, thus producing the ground effect: pressure higher than that of the environment. The primary jet, generated by a small ducted fan, represents a comparatively modest application of power, the strength of the jet amounting to a pressure of four inches of water.

The cover hooding the slit at the top of the model can be tilted so that the slit is widened on one side and narrowed on the other; this maneuver, by skewing the distribution of force over the top surface, serves as a means of banking the vehicle in the air. By a simple modification of the vehicle's



HYDROFOIL CRAFT using the Coanda effect has achieved speeds of more than 19 knots in this pool. The model is about four feet long. The wings on the hull are for stabilizing the craft and for generating a ground effect; propulsion is from an underwater foil.



KEY PART of the hydrofoil is this foil with several slits for achieving the Coanda effect. Water emerging from the slits (*right*) tends to curve around the foil because of the Coanda effect, thereby creating a negative drag similar to that in the airborne GEM.

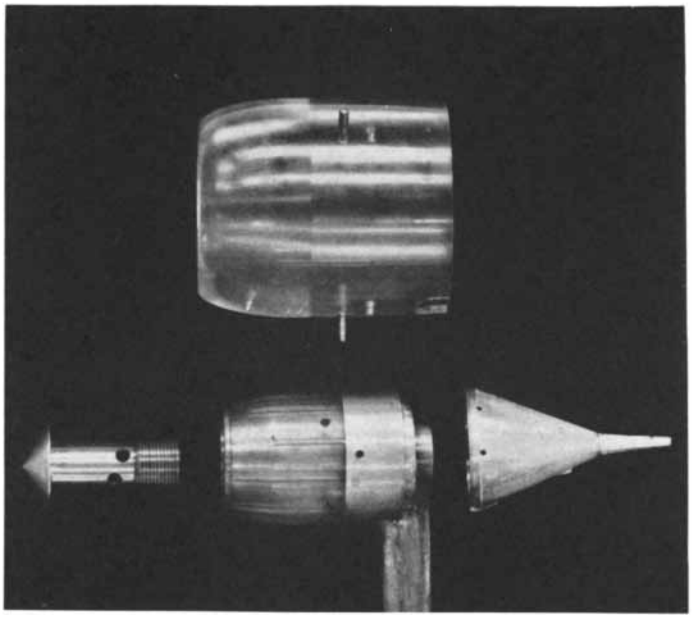
form it has been endowed with forward propulsion. In this model the configuration of the body is asymmetrical, and the resulting asymmetrical distribution of forces in the jet sheet provides forward thrust to the vehicle.

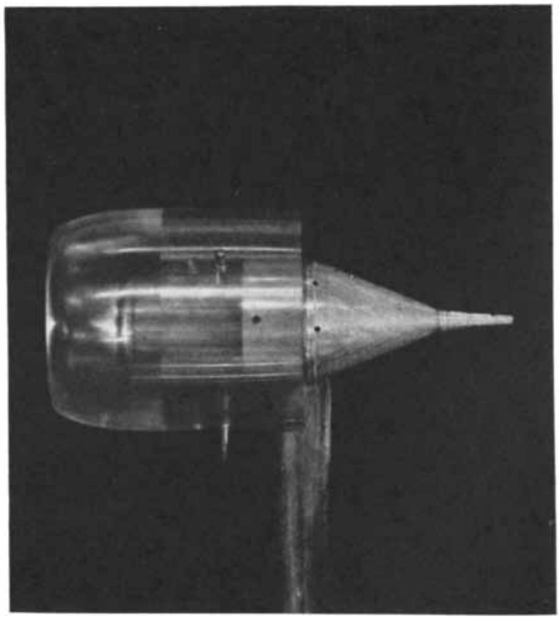
The Coanda system offers several improvements over the present versions of ground-effect machines. It should reduce the amount of power needed for propulsion, reduce the weight of the machine, permit steering of the vehicle by banking and make it easier to mount slopes.

The estimated lift efficiency of the present rather crude model is about 25 pounds of lift per horsepower for a lift-off height of about a twentieth of the diameter of the vehicle. This performance is comparable to that of ground-effect vehicles operated by conventional means. It remains to be seen, however, if a vehicle of the Coanda type will retain comparable lift efficiency when it is scaled up to full size.

Another vehicle currently under development in our laboratory is a boat of the hydrofoil type, that is, a craft in which the foil lifts the hull out of the water. In this case, employing the Coanda effect, the hydrofoil is self-propelling: it provides not only the lift and controls but also the propulsion of the craft. Nozzles that emit jets of water are incorporated in the leading edges of the foil, the strut and water-intake pods. The craft has a hull with down-swept wings that I have designed to minimize drag, improve the craft's stability on the water and provide some additional lift by the ground effect [*see illustrations on opposite page*].

Our present model, four feet long and weighing 22 pounds, cruises at better than 20 miles per hour at the end of a tether in a circular pool 10 feet in diameter. It can lift its hull out of the water and ride on the hydrofoil at very low speed and without using any more power than is required for cruising. Control of the craft is accomplished by means of surfaces that do not protrude into the flow. Thanks to the large entrainment of fluid from the vicinity of the nozzles, the foil generates essentially no wake, very little spray and little noise. We believe the use of a "ventilating flow"—achieved by injection of small amounts of air—will minimize undesirable effects caused by cavitation (the formation and collapse of bubbles around the foil). If we are right, a full-scale version of the craft should be capable of speeds of more than 80 knots,



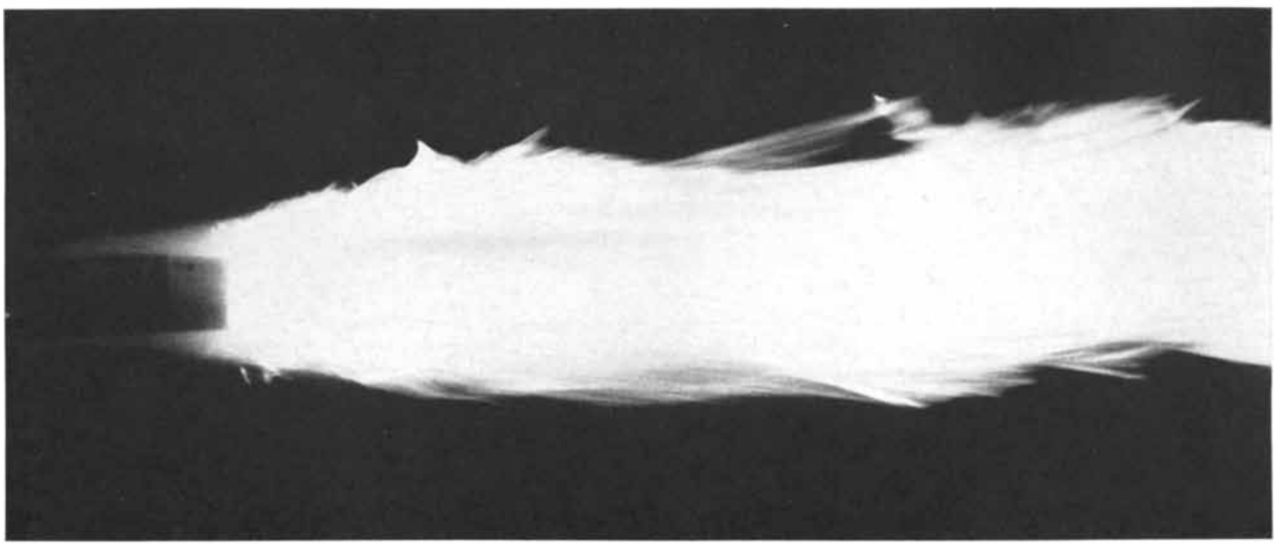


COANDA NOZZLE is shown disassembled at left and assembled at right. The plastic part is a shroud that enhances the Coanda effect. The conical part is the afterbody; pressure over it is slightly above atmospheric when the nozzle is operating to achieve thrust.

with a considerable saving of power over conventional high-speed hydrofoil boats.

Aside from the uses of the Coanda effect for propulsion systems, which are still in a highly experimental stage of development, there is another type of application in which the principle has already proved its value. Nozzles based on this principle are extraordinarily efficient as components of burners [*see illustration below*]. When properly shrouded, they produce an almost invisible flame with no smoke and essentially complete combustion of the fuel. In some applications most of the air for combustion is supplied by the nozzle's entrainment of air. In addition the nozzle can be used as a pump to recirculate unburned gases and thus produce blue-flame, smokeless combustion. To these advantages are added mechanical simplicity, compactness, comparatively low cost and the absence of moving parts. Attempts are now being made to adapt the Coanda nozzle to the burning of heavy fuel oils. Nozzles of this kind might also be employed in vehicle-propelling engines, and this possibility is now being considered.

It is in the field of propulsion, of course, that the prospects for employing the Coanda effect look most attractive. The promise of attaining a propulsion system that would produce its own dividend of power from the very nature of its design, that would have no moving parts such as propellers or fans, that could be blended into the contour of a vehicle without wasting space or significantly disturbing aerodynamic characteristics, that would be smaller, lighter and quieter than present engines—is indeed an incentive to further exploration of the Coanda effect.



TYPICAL FLAME in a burner using a Coanda nozzle is blue, smokeless, quiet and well concentrated when the nozzle is properly shrouded. Almost total combustion of fuel is achieved. Much of air for combustion comes from entrainment of air by the Coanda effect.