Smoke Visualization in Wind Tunnels

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A few individuals played the key role in developing and refining this important tool of the aerodynamicist and designer.

The visualization of flow patterns has played a singularly important role in advancing our understanding of the mechanics of fluids. Visualization has led to the discovery of flow phenomena, has helped in the development of mathematical models for complex flow problems and in the verification of principles, and has been an important tool in the development of complicated engineering systems. Visual observation of flow phenomena was the first and, for a long time, the only experimental technique available. Dust or smoke particles in air and dirt or other debris in water provide the necessary contamination for flow visualization. Interest in flight led experimenters to visualize air flows in order to understand the mechanics of objects moving through the air.

Flow visualization in wind tunnels began with the work of Ludwig Mach of Vienna in 1893. Mach’s indraft wind tunnel had a cross-section of 180 x 250 mm and was driven by a centrifugal fan that could produce a speed of 10 m/sec. Wire mesh over the inlet straightened the flow. One side of the test section was glass and the others were black on the inside. The flow was observed and photographed using silk threads, cigarette smoke, and glowing iron particles. Mach obtained only smoke-flow photos for the flow past a plate perpendicular to the flow. The smoke was faint and difficult to make out, but studying it was a beginning.

In France, about 1899, E.J. Marey, who was famous for his photographic studies of animal locomotion, turned his attention to photographing air in motion. Marey, cognizant of the work of Mach, used a vertical wind tunnel with a 200 x 300-mm cross section. The front and sides of the test section were glass and the back was covered with black velvet. Air was drawn into the tunnel by a small suction fan after passing through fine silk gauze at the inlet. F-1 shows a sketch of this wind tunnel. Smoke from burning wood shavings entered the wind tunnel upstream of the gauze straighteners through a row of fine tubes. Marey made excellent smoke-flow photos using a magnesium flash.

The interest in smoke visualization seems to have waned somewhat in the first quarter of the century. Smoke experiments began in 1911 at the National Physical Laboratory in England. Around 1921 at the U.S. Naval Gun Factory A.F. Zahm may have used smoke to analyze the air flow over naval vessels. Ludwig Prandtl and his associates used smoke in their Gottingen wind tunnel in 1923 to study flow over airfoils and bluff bodies. Interest in this technique developed more rapidly after 1925. Around 1930, smoke visualization was used in England by L.F.G. Simmons, N.S. Dewey, and T. Tanner to study the flow about circular disks and symmetrical airfoils. The smoke was produced by titanium tetrachloride. In 1933, K.W. Clark used stannic chloride smoke in conjunction with other techniques to study the flow over several wings.

In 1932, for lectures at Cambridge Univ., W.S. Farren used a modified version of Simmons’ smoke tunnel at the National Physical Laboratory. The NACA built its first smoke tunnel about 1933 and a second one in 1938. These tunnels seem to have been used mostly for demonstrations. The tunnel built by R.W. Griswold, II, at Old Lyme, Conn., about 1940, used smoldering rotten wood to generate smoke.

Although the interest in the period from 1925 to
the early 1940s was in using smoke visualization to help solve practical aerodynamic problems, the smoke photographs were not as good as Marey’s. Many of the visual results were useful, but few if any significant quantitative results were obtained. All these tunnels were two-dimensional and various types of “smoke” were used, the most popular being obtained by burning rotten wood or using titanium tetrachloride.

The best of these early two-dimensional tunnels was developed by A.M. Lippisch in Germany. He obtained a large number of good smoke photos of the flow around plates, cylinders, and airfoils, including the Lippisch rotor wing. He also began developing an intermittent smoke-delivery system. Lippisch’s evaluation of the potential of the smoke tunnel is clear when he writes: “The value of the smoke tunnel consists chiefly in demonstrating the effects of a given body on the flow and to show the true course of flow in the case of special devices. Without carrying out tedious force measurements we are, therefore, in a position to develop aerodynamically good designs or to observe a special flow phenomenon which enable us, for instance, to determine the true causes of stalling effects.”

There was, evidently, no serious consideration given then to obtaining quantitative data from such experiments.

About this same time, F.N.M. Brown at the Univ. of Notre Dame began his research in flow visualization. His first smoke tunnel, which became operational in 1937, was developed primarily for class-room demonstrations. It had a 38:1 contraction section and produced speeds of up to 3 m/sec. Brown made photos using titanium tetrachloride for smoke. In 1940 he began operating a three-dimensional indraft smoke tunnel. This tunnel had a single screen followed by a 9:1 contraction in area. Its 610 × 610-mm test section was about 914 mm long, and speeds of up to 12.2 m/sec could be attained using a 1 hp d.c. motor. Smoke was produced by coking wheat straw and was introduced upstream of the anti-turbulence screen through a row of tubes (a rake). Brown made another new three-dimensional smoke tunnel but made little progress with it during World War II. (In 1943, the first really successful oil-smoke generator was developed by Preston and Sweeting in England.)

In 1947 work began at the Univ. of Notre Dame...
on a research three-dimensional smoke tunnel. As a result of the lessons learned earlier, this smoke tunnel had five bronze screens at the inlet of the 12:1 Smith-and-Wang contraction section and the same size test section. With it useful speeds of 10.7 m/sec could be attained using a squirrel-cage fan driven by a 5-hp motor. Coked wheat straw produced the smoke. A total of 12,000 watts of steady lighting was used to photograph the flow.

This three-dimensional smoke tunnel evolved slowly into the one used today. F-2 shows the 1958 version of this tunnel, and F-3, the latest version of Brown's smoke tunnel. In conjunction with his smoke-tunnel development, Brown developed a movable smoke rake and the first easy-to-use kerosene smoke generator that could produce large quantities of smoke. He was also the first to take 3-D and stereo photographs of smoke flows.
In fact, most of the progress and refinement of smoke-visualization techniques are credited to Brown. The photos at the beginning of this article show examples of his work.

After World War II, aeronautical developments rapidly spread interest in two-dimensional smoke tunnels, associated equipment and techniques, and smoke-flow experiments. The most notable smoke tunnel outside of Brown’s laboratory was Lippisch’s. In the U.S., he had continued the work with two-dimensional smoke tunnels that he had begun in Germany in the late 1930s. His post-WW II smoke tunnel (F-4), with minor refinements, was the same as the one he used in Germany. But he switched from burning rotten wood to the oil-smoke generator developed by Preston and Sweeting.

A unique feature of Lippisch’s work was the development of periodic smoke injection to produce “time lines” in the test section. The velocity distribution around the model was obtained by taking high-speed movies of these “time lines.” Lippisch also built a three-dimensional smoke tunnel.

Smoke photos taken by Lippisch and published in 1958 are excellent. F-4 includes an example of the intermittent smoke-injection technique he developed. It shows three exposures of the smoke front as it passed over an airfoil section in the two-dimensional smoke tunnel. (H.V. Borst recently completed a book on the work of Lippisch.)

Only Lippisch and Brown seemed to realize that important quantitative data could be obtained from smoke-tunnel experiments. They had another thing in common. Although each kept a careful record of his smoke-tunnel research, very little of their work was published in the open literature. Thanks to the Arthur A. Collins Corp. of Dallas, Tex., all of Lippisch’s unpublished data reports have been preserved. The best record of Brown’s smoke-tunnel research will be found in the Master theses of his students and a few government contract reports.

Although Brown and Lippisch both established subsonic smoke-tunnel techniques still in use, Brown’s equipment offered important advantages over Lippisch’s. Brown’s three-dimensional tunnels, with much larger contraction ratios (24:1 compared to 12:1) and more anti-turbulence screens, have less turbulence at the higher velocities. In fact, by making smaller test sections while increasing the contraction to 48:1 and 96:1, Brown was able to achieve low turbulence at speeds up to about 60 m/sec. Furthermore, by introducing the smoke upstream of the screens instead of inside the tunnel, he kept the injection rake from adding to the disturbance in the test section. It is not surprising that Brown’s wind tunnels, smoke generators, and photo techniques have been extensively copied.

In the early 1950s, David Hazen at Princeton Univ. became interested in smoke visualization. He contracted with Lippisch to construct a two-dimensional smoke tunnel, 51 x 914 mm, similar to the one he had built in Darmstadt, Germany. While waiting for its delivery, Hazen built a 51 x 356-mm pilot smoke tunnel from rough sketches of Lippisch’s Darmstadt tunnel. The two-dimensional smoke tunnel built at Princeton consisted of an entrance bell with a fan, a diffuser, and a settling chamber with eight layers of screen and the smoke-injector stack. Followed by a contraction cone with the smoke-injector intake, the test section, the downstream diffuser, and, finally, a downstream fan. After leaving the downstream fan, the air was fed into a plenum chamber and exhausted in a high-speed jet to the outside. The test section measured 610 mm long, 356 mm high, and 51 mm wide.

Operated on two universal motors of approximately ½ hp, each driving two-bladed propellers, this tunnel gave a maximum test section velocity of 15.25 m/sec with the rear plenum chamber removed. For photography, all testing was done at speeds from 0.6 to 3 m/sec. At higher speeds the smoke lines diffused rapidly due to increased me-
Three-dimensional low-speed smoke tunnel at Princeton Univ. was later scaled up to almost twice the size.

Useful results were obtained in this tunnel and in the larger 51 x 914-mm tunnel built by Lippisch for Princeton. The two major improvements in the latter tunnel over the pilot one were its size and speed range. It also had a large contraction ratio of 19.5:1. Test velocities usually ranged between 9 and 12 m/sec, and, with a great deal of adjustment to the pitch and yaw of the injector tubes, smokelines could be maintained to a speed of 20 m/sec. Combined with the use of 406-to-610-mm-chord models, questions that the force and pressure distribution investigations had been unable to.

Mechanical vibration. According to Hazen and Lehnert: "This tunnel is notable for the fact that, although it contains a large number of incorrect design features, it proved the value of such flow visualization techniques and answered many of the
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Shown in F-5, it used a ¼-hp d.c. motor to deliver flow speeds from 0 to 9 m/sec, the Preston-and-Sweeting smoke generator, and a number of different types of smoke delivery. Smoke was supplied to the test section in single or multiple heavy streams, similar to the method used by Brown, by injecting from tubes in the honeycomb or in much finer streams from the injector rake in the first contraction section. Smoke was bled directly through holes in the model surface for some experiments. A large number of aerodynamic problems were studied; most of the results are contained in reports and student theses.

By scaling up this small three-dimensional tunnel, Hazen and his associates at Princeton built what may be the largest smoke tunnel in existence. Still operational, it has a test-section cross section of 914 x 1219 mm and develops flow speeds of up to 30 m/sec.

Expanding the technique of Brown, V.P. Goddard at the Univ. of Notre Dame built the world’s first and only supersonic smoke tunnel in 1959. F-6 shows this indraft tunnel. It has seven screens and an inlet contraction of about 96:1 to the nozzle throat. A modified Schlieren system permitted simultaneous photographing of smoke and shock-wave patterns. Using the same smoke-generation and injection techniques as in the subsonic tunnels, smoke photos were taken at speeds of up to 404 m/sec (Mach 1.38). F-6 includes examples of smokelines at supersonic speeds: a direct photo of the smoke lines in the tunnel with no model present and a simultaneous smokeline-Schlieren photo of the flow over a two-dimensional wedge.

By 1959 a few researchers realized that the smoke tunnel was an important research tool. The techniques established by Brown, Goddard, and Lippisch have not changed to the present day. As a result of unique data Brown obtained, especially on boundary-layer transition, there has been a very great interest in using these smoke techniques to study a wide variety of basic and applied fluid-dynamic problems.

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