Λ component of blocking factor dependent on shape of body

ν kinematic viscosity

ξ quantity used for correcting effect of body upon velocity measured by static-pressure orifices

ρ density of manometer liquid

σ component of blocking factor dependent on size of body

HISTORY OF DEVELOPMENT

Description of the Langley Two-Dimensional Low-Turbulence Tunnel

Because the shape of the air passages of the proposed pressure tunnel were unusual, and because of the fact that the means proposed for obtaining low turbulence had never been checked at high Reynolds numbers, it was desirable to build a model of the proposed tunnel to study its flow characteristics and to develop means for producing a satisfactory air stream. The Reynolds number of tests in such a model tunnel had to be at least as high as those in the lower range of flight Reynolds numbers in order to obtain a reliable indication of the effective turbulence level. A full-size model of the proposed tunnel, designed to operate only at atmospheric pressure, was therefore built. This tunnel is called the Langley two-dimensional low-turbulence tunnel.

This tunnel was completed in April 1938. It was originally designated the NACA ice tunnel because of the incorporation of refrigerating equipment in the design to permit icing experiments. The tunnel is of closed throat type, built of wood with a sheet steel lining. Because of the contemplated icing experiments, it was heavily insulated on the outside. Figure 1 shows the shape of the air passages of this tunnel. The test section is rectangular in shape, $7\frac{1}{2}$ feet high, and 3 feet wide, and was designed so that models could be tested completely spanning the 3-foot width. The test section is $7\frac{1}{2}$ feet long but models having chords as large as 100 inches have been tested. Power supplied by a 200-horsepower direct-current motor provides a maximum speed of about 155 miles per hour with a dynamic pressure of about 60 pounds per square foot. These conditions give a maximum Reynolds number of about 1.4×10^6 per foot of model chord.

Surveys of the air stream of the test section showed a variation in static and dynamic pressure of less than 0.25 percent of the dynamic pressure in the region normally occupied by the model. The angular variation of the air-stream direction in the same region was less than 0.2°. The variation in static pressure longitudinally over the length of the test section was 0.5 percent with a variation of only 0.25 percent over a 2-foot length at the model mounting point. Uniformity of the pressure gradient in a longitudinal direction was obtained by adjusting slots in the vertical walls of the test section to allow air to bleed out. A positive pressure is built up in the test section to accomplish this bleeding by means of a blower which discharges air into the tunnel through an annular slot downstream of the test section.

Boundary-layer control of the short exit cone of this tunnel, an unusual feature, is accomplished by means of two annular slots as shown in figure 1. Air from the boundary layer of the exit cone is sucked into the upstream slot by means of a 45-horsepower blower and is discharged into the tunnel with increased velocity through the downstream slot.

Previous experience with the Langley smoke-flow tunnel indicated that turbulence could be reduced by the use of a large area reduction through the entrance cone and dense screens in the large section ahead of the entrance cone. This experience was used in the design of the Langley two-dimensional low-turbulence tunnel. The section of the tunnel immediately ahead of the entrance cone was made 21 feet square, which gives an area reduction of about 19.6 to 1 between this section and the test section. In this large section a honeycomb made with 9-inch-square cells was installed. On the upstream side, the honeycomb was covered with a 30-mesh standard wire screen, and on the downstream side with a 60-mesh screen made of 0.0065-inch-diameter wire. The honeycomb was made up of nine sections, each 7 feet square. The unusually rapid expansion of the tunnel air passage immediately upstream of the honeycomb screens considerably reduced the length of the air passage. Such a rapid expansion is permissible because the dynamic pressure of the air stream at this point is relatively low and any unevenness of flow is smoothed out by the high pressure drop of the honeycomb screens.

The first airfoil tests were made on a low-drag type of airfoil section, and the measured drag coefficient was 0.0030, about 50 percent less than had previously been measured on an airfoil of comparable thickness. This test was carried out in June 1938. Comparison of this drag coefficient with the laminar and turbulent skin-friction curves showed that the flow over the airfoil was laminar over more than half the surface. Comparison

of other airfoil test results with those obtained in flight also indicated that a very low turbulence level had been achieved. It was not considered probable, however, that the desired effective zero turbulence level, that is, a level at which the air-stream turbulence would have a vanishing effect upon boundary-layer transition, had been reached. Under favorable conditions, boundary-layer Reynolds numbers, R_δ, of about 5000 were measured in the tunnel for some airfoils compared with R_δ of 7500 to 9000 obtained in flight. (See reference 3.)

Turbulence measurements made in January 1940 with a National Bureau of Standards hot-wire anemometer also indicated that the air stream had a reasonably low turbulence level compared with other wind tunnels. The horizontal turbulence components, which are of the same order of magnitude as the vertical and longitudinal components, are plotted against Reynolds number in figure 2 and against spanwise position in figure 3. The spanwise survey indicated that large variations in the turbulence level were present at points corresponding to the relative positions of the joints between the 7-foot sections of the honeycomb upstream.

Turbulence measurements obtained by comparison of the critical Reynolds numbers of spheres were not made in the Langley two-dimensional low-turbulence tunnel. Previous comparative tests of spheres in the Langley 8-foot high-speed tunnel (reference 4) and in free air (reference 5) gave about the same results. Since tests of the NACA 0012 airfoil in the Langley 8-foot high-speed tunnel (reference 6) and in the Langley two-dimensional low-turbulence tunnel (reference 7) indicated a lower turbulence level in the latter tunnel, it was concluded that the general level of turbulence was too low for the sphere tests to give significant results.

Investigation to Reduce Turbulence Level

The results of turbulence surveys and comparative tests in the Langley two-dimensional low-turbulence tunnel and in flight clearly showed the desirability of further reduction of the turbulence level of the tunnel. The turbulence surveys also showed the necessity of eliminating, insofar as possible, the effects of any joints and supports of the screen. This result was believed to be obtainable by the proper installation of a number of additional screens.

Preliminary consideration of the physical factors involved suggested the likelihood that for a given pressure drop a number

of screens placed one behind the other would be more effective in reducing the turbulence level than a single screen to produce the given pressure drop. (This reasoning was later substantiated by a more detailed investigation by Dryden and his collaborators who were also working on the problem of turbulence reduction at about the same time at the National Bureau of Standards.) The realization that some defects might be present in any screen installation led to the suggestion that a number of screens, each with a pressure drop of about one q, would be a good compromise (where q is the dynamic pressure of the air stream at the screens). In a screen installation with such a pressure drop, the effects of the wake of a plugged spot would be expected to be about the same as the effects of the jet of an open spot.

Experiments were conducted during the latter part of 1939 in the Langley smoke-flow tunnel to obtain data that might be used in the design of an improved screen installation for the Langley two-dimensional low-turbulence tunnel. Screen models were mounted in the test section of the smoke-flow tunnel and visual observations were made of the smoke flow through the screen. Screens having a pressure drop of the order of one q were observed to have a marked effect on breaking up large eddies and to reduce markedly the magnitude of the fluctuating velocities associated with each eddy. With a 2-mesh screen having a wire diameter of 0.1 inch, it was found that, when the speed exceeded approximately 3 feet per second, the nature of the flow through the screen changed. Although the turbulence associated with large eddies was broken up, small-scale eddies were introduced by the wires themselves. Below this critical speed the flow appeared to be of the viscous type and no small eddies were observed.

On the basis of these experiments, consideration was given to the size of wire for the screens that were to be installed in the Langley two-dimensional low-turbulence tunnel in order that the Reynolds number for viscous flow might not be exceeded at the highest tunnel speed and thus turbulence from the wires themselves might be avoided. A wire size of 0.0065 was found to be suitable and, in order to obtain the desired pressure drop of one q, a 30-mesh screen with this wire diameter was selected.

Information published by Taylor on the decay of turbulence behind screens (reference 3) indicated that a spacing between the screens of approximately 100 times the length of one screen mesh would be more effective than closer spacing, so that, if turbulence were produced by any screen, this turbulence would have a chance to die out before reaching the next screen. The number of screens needed was indefinite, and the final level of

turbulence seemed to be determined by the amount of turbulence introduced by the last screen. Great care was therefore believed necessary in the fabrication and installation of the screens.

The screen wire was made of phosphor bronze and was woven in strips 7 feet wide with a special selvage as shown in figure 4(a). Three strips were sewed together with 0.0065-inch diameter wire, the strand of wire through each mesh at the selvage being carefully looped in such a manner that there was no overlapping of the strips and a joint was produced which presented minimum discontinuity. Brass strips were fastened around the four sides of the completed screen panel and the assembly was hung in place in the tunnel on springs, spaced 1 foot apart, attached to the brass-edge strips through cables and turnbuckles. Enough tension was put in the springs to hold the screen taut but not to allow the stress produced in the wires of the screen by the air stream and by tunnel expansion to be too high. Seven layers of screens, spaced 3 inches, were installed in the large section of the tunnel downstream of the honeycomb. Figure 4(b) shows schematically a section of one edge of the screen and the baffles which direct the air stream through the screens. The installation was completed in October 1940.

Turbulence measurements were again made with the National Bureau of Standards hot-wire apparatus in January 1941. The results, as shown in figures 2 and 3, indicated that the level of turbulence had been reduced to the order of one-tenth that of the turbulence level before the screen installation (to about 0.01 to 0.02 percent of free-stream velocity). The large spanwise variation formerly caused by the joints in the honeycomb was now seen to be very small. A gradual rise in the turbulence level with increased tunnel speed was found. This gradual rise in turbulence level might be influenced by an increase in noise level with increase in propeller speed. It may be pointed out that the turbulence level measured was so low that it approached the limit of accuracy of the apparatus.

Figure 5 shows the results of drag surveys on the NACA 67-215 airfoil section before and after the installation of the turbulence-reducing screens. The Reynolds number at which the drag began to rise with increasing Reynolds number showed a marked increase after the screens were installed. Since model conditions were the same for both tests, this increase indicates that the reduction in turbulence level was sufficient to affect the drag appreciably.

Information and experience obtained from work on the Langley two-dimensional low-turbulence tunnel proved invaluable

in the design and operation of the Langley two-dimensional low-turbulence pressure tunnel and was undoubtedly a large factor in the success of the latter tunnel.

THE LANGLEY TWO-DIMENSIONAL LOW-TURBULENCE PRESSURE TUNNEL

Description

Size and range of pressures.- The Langley two-dimensional low-turbulence pressure tunnel is a single-return closed-throat tunnel, the general arrangement of which is shown in figures 6 and 7. The tunnel is constructed of heavy steel plate so that the pressure of the air may be varied from approximately full vacuum to 10 atmospheres absolute, thereby giving a wide range of air densities. Reciprocating compressors with a capacity of 1200 cubic feet of free air per minute provide compressed air. Since the tunnel shell has a volume of about 83,000 cubic feet, a compression rate of approximately one atmosphere per hour is obtained. The tunnel has not been operated at pressures less than atmospheric.

Calculated by Braslow

65K Right

The test section is rectangular in shape, 3 feet wide, $7\frac{1}{2}$ feet high, and $7\frac{1}{2}$ feet long. Figure 8 is a view of the test section looking downstream. The air stream enters the test section through a relatively short entrance cone from a large square section giving a contraction ratio of 17.6 to 1.

The over-all size of the wind-tunnel shell is about 146 feet long and 58 feet wide with a maximum diameter of 26 feet. The test section and entrance and exit cones are surrounded by a 22-foot diameter section of the shell to provide a space to house much of the essential equipment. This space is called the test chamber. Figure 9 shows a view of the interior of the test chamber.

Curved turns at the ends of this tunnel are used instead of the conventional right angle corners to minimize the stress concentrations associated with the high air pressures used. The use of continuous splitter vanes instead of guide vanes, in the large turn as shown in figure 7(b), was also for structural reasons rather than aerodynamic.