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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 392

REDUCTION OF TURBULENCE IN WIND TUNNELS

By HUGH L. DRYDEN

1931

[redacted]

AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of one kilogram	kg	weight of one pound	lb.
Power	P	kg/m/s		horsepower	hp
Speed		km/h m/s	k. p. h. m. p. s.	mi./hr. ft./sec.	m. p. h. f. p. s.

2. GENERAL SYMBOLS, ETC.

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s$^2 = 32.1740$ ft./sec.^{2}

m, Mass $= \frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 750 mm $= 0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m$^3 = 0.07651$ lb./ft.^{3}

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\frac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed.

q, Dynamic (or impact) pressure $= \frac{1}{2}\rho V^2$.

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_0, Profile drag, absolute coefficient $C_{D_0} = \frac{D_0}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force.

i_w, Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting (relative to thrust line).

Q, Resultant moment.

Ω, Resultant angular velocity.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/s, the corresponding number is 274,000.

C_p, Center of pressure coefficient (ratio of distance of c. p. from leading edge to chord length).

α, Angle of attack.

ϵ, Angle of downwash.

α_0, Angle of attack, infinite aspect ratio.

α_i, Angle of attack, induced.

α_a, Angle of attack, absolute.

(Measured from zero lift position.)

γ, Flight path angle.

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By HUGH L. DRYDEN
Bureau of Standards

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NAVY BUILDING WASHINGTON, D. C.

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SUMMARY

A brief nonmathematical outline is given of modern views as to the nature of the effect of turbulence, and their bearing on the desirability of designing wind tunnels for small or large turbulence. Experiments made on a particular wind tunnel for the purpose of reducing the turbulence are described, to illustrate the influence of certain factors on the magnitude of the turbulence. Moderate changes in the size, shape, and wall thickness of cells of the honeycomb were found to have little effect. The addition of a room honeycomb at the entrance was also of little value in reducing the turbulence. The turbulence decreased with increasing distance between the honeycomb and the measuring station. A further decrease was obtained by using a large area reduction in the entrance cone, with the honeycomb at the extreme entrance end.

The measurements of turbulence were made by the use of spheres and also by the use of the hot wire anemometer as described in Reference 5. The present work was conducted with the cooperation and financial assistance of the National Advisory Committee for Aeronautics.

INTRODUCTION

The subject of turbulence is one of great interest in the field of aerodynamics, and many investigations are in progress in the aerodynamical laboratories of the world on various aspects of the subject. The recent international cooperative measurements inaugurated under the auspices of the National Physical Laboratory of Great Britain have shown that turbulence is a factor of considerable importance in determining the forces acting on bodies in an air stream, and the chief question of the day is whether it is desirable to have large or small turbulence in wind tunnels.

The recognition of the effect of turbulence in wind tunnel experiments came about somewhat as follows: About the year 1911, Eiffel (reference 1) measured the air resistance of a sphere in his newly constructed wind tunnel and published the value of the resistance coefficient as 0.18.[1] A year later, Föppl of the Aerodynamic Institute at Göttingen (reference 2), in a comparison of results with the Eiffel Laboratory, stated that Eiffel's published value was obviously in error, probably a misprint, and that the true value was 0.44 or nearly three times as great. Eiffel replied that the published value was correct and made further experiments on spheres of different diameters at several wind speeds which showed certain anomalous features, now familiar to students of aerodynamics.

The first clue to the explanation of the discrepancy was given by Wieselsberger (reference 3) who showed that he could obtain results in the Göttingen wind tunnel similar to those obtained by Eiffel. He accomplished this by producing a disturbance ahead of the sphere by placing an open-mesh screen across the air stream in front of the sphere, or by placing a wire ring on the surface of the sphere in a plane perpendicular to the wind direction. By these and numerous other experiments it has been established that the air resistance of a sphere depends not only on the diameter of the sphere, the speed, density, and viscosity of the air but also on the turbulence of the air stream.

Another type of body for which widely varying results have been obtained in different wind tunnels is the streamline body exemplified by the airplane strut and the airship hull. Values obtained at the National Physical Laboratory for the resistance of streamline bodies appeared to be on a lower level than values obtained at the wind tunnel of the Washington Navy Yard, and the nature of the scale effect was quite different. In 1923 the National Physical Laboratory began the circulation of two airship models for comparative tests in a large number of the wind tunnels of the world. The results in the United States wind tunnels (reference 4) show variations of 50 per cent from a mean value and it has recently been shown by experiment (reference 5) that these differences are due to differences in the turbulence of the several wind tunnels.

While these two examples illustrate the large effects of turbulence in wind tunnel experiments, the discovery of the effect itself is much older. Osborne Reynolds (reference 6), in his study of flow in pipes, records the first observations of the effect. For a sufficiently small Reynolds Number (product of the mean speed by the diameter divided by the kinematic viscosity), the flow in a pipe is laminar and takes place

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[1] Resistance coefficient equals the force divided by the product of cross-sectional area and velocity pressure.

in accordance with the laws of hydrodynamics for the steady flow of a viscous liquid. At large Reynolds Numbers, the flow is eddying and the movements of finite "molar" masses of the fluid as well as movements of single molecules transfer momentum from one layer of the fluid to another. In a definite experimental arrangement, the transition from one régime of flow to the other occurs at a definite value of the Reynolds Number, irrespective of the individual values of the speed, diameter of the pipe, and viscosity and density of the fluid. When a disturbance (turbulence) is present in the incoming flow, the value of the critical Reynolds Number is found to depend on the magnitude of the disturbance, decreasing as the turbulence increases until a certain lower limit is reached, beyond which further increase of turbulence has little effect. The turbulence in the incoming flow may be produced by objects placed near the entrance of the pipe, by honeycombs across the pipe, or by the shape of the entrance itself. The resistance coefficient of a pipe is a function of the turbulence as well as of the Reynolds Number, and for a certain range of Reynolds Numbers the effect is very large indeed.

The information now available on the effect of turbulence clears up many puzzling discrepancies in wind tunnel results, and indicates that no standardization of wind tunnels can result until a standard value of the turbulence is adopted and methods are known for controlling the turbulence in a given wind tunnel. The title of this paper suggests that the turbulence in wind tunnels should be as small as possible, a view that is not at all unanimously accepted, and the object of this paper is to present the arguments for and against this view and to indicate by experiments on a particular wind tunnel how a small turbulence may be secured.

The turbulence in a given wind tunnel has far-reaching effects on the results of measurements made in that tunnel. Not only will the value of the force coefficients at a given Reynolds Number be dependent on the value of the turbulence, but the whole nature of the variation of the force coefficient with Reynolds Number (i. e., the scale effect curve), on which the extrapolation to full scale depends, is governed by the amount of the turbulence. As is well known, the scale effect on an airship model in a wind tunnel of large turbulence shows a coefficient decreasing as the Reynolds Number increases, whereas in a tunnel of small turbulence the coefficient is much lower and usually increases with increasing Reynolds Number at the higher Reynolds Numbers. While the effects of turbulence are large only for certain types of bodies, it is reasonably certain that an effect is present in all cases, although often its magnitude is extremely small. Under these circumstances the importance of knowing the value of the turbulence in every wind tunnel experiment is obvious.

Modern views as to the nature of the effect of turbulence.—As a background for the discussion of the relative advantages and disadvantages of having small or large turbulence in wind tunnels, it is necessary to outline briefly the modern conception of the nature of the effect of turbulence. The views here presented hardly have the status of a well-developed theory, and some of the details may be subject to controversy. The outline, however, is believed to be substantially correct, and represents a combination of the contributions of many investigators including Prandtl, von Kármán, Burgers, and others.

The starting point is the boundary layer theory of Prandtl. It had long been noted that in a large part of the field of flow of air or water at moderately large Reynolds Numbers, the dissipation of energy is negligible and therefore that the effects of the viscosity of the fluid are negligible. There must, however, be some effect of viscosity on the flow, else there would be no drag. It occurred to Prandtl to assume that the effects of viscosity are confined to a thin layer or skin close to the surface of the body and to introduce this assumption in the general equations of motion of a viscous fluid. The result is a series of equations giving the velocity distribution in the layer, the thickness of the layer or equivalent parameter, and the skin friction on the surface when the pressure distribution along the body is known. The results of this theory have been abundantly confirmed by experiment for parts of the layer not too far from the point of origin at the nose or leading edge of the body.

Two phenomena intervene to make the formulas invalid for the entire boundary layer. The first is the phenomenon of separation, which takes place when the pressure outside the layer increases downstream. The fluid particles near the wall are dragged along by the friction of the neighboring particles but are retarded by the pressure. As the boundary layer thickens the retarding effect becomes predominant and finally causes a reversal of the flow. The reversal of flow, on account of the consequent accumulation of fluid, separates the flow from the surface, as observed on cylinders, and on airfoils at large angles of attack. The onset of separation is predicted by the equations of Prandtl, but the phenomena following the occurrence of separation introduce wide departures from the assumptions on which Prandtl's equations are derived.

The second phenomenon not contemplated in the basic assumptions is the onset of eddying flow in the boundary layer. The flow described by Prandtl's equations is laminar. Momentum is transferred from one layer to another by the motions of single molecules whose total effect is integrated in the viscosity coefficient. The experiments of Burgers and his pupil v. d. Hegge Zijnen show that the flow becomes eddying and that so long as the turbulence of the approaching stream is not altered, the transition occurs when the Reynolds Number formed from the speed at the outside of the boundary layer and the thickness of the boundary layer reaches a certain critical value. The critical value depends, however, on the turbulence of the approaching stream, decreasing as the turbulence increases.

The onset of eddying flow in the boundary layer, if occurring before separation of the layer, modifies the process of separation. In the eddying motion there is a more thorough mixing of the air particles, and the driving action of the outer layers on the inner layers (near the surface of the body) is greater. The air in the boundary layer is thus enabled to flow farther against an adverse pressure gradient and the process of separation is delayed. The delayed separation produced by the eddying motion in the boundary layer is responsible for the great variation of the drag coefficient of spheres and cylinders in the critical region. The hastening of the onset of eddying flow in the boundary layer is responsible for the effect of turbulence on the air resistance of spheres.

The preceding matters are presented in a more technical manner in reference 5, which includes a detailed application to spheres and airship models. It should be stated here that the mechanism of the breakdown of the laminar boundary layer and of the effect of turbulence is not yet fully understood. The author believes that the mechanism is essentially the same as that occurring in the phenomenon of separation, and that the breakdown would not occur if there were no fluctuation of the air speed at the edge of the boundary layer. The observed fluctuations of speed at a fixed point may be taken as an indication that at any one time there are variations of speed along the outer edge of the boundary layer. With the speed variations there will be associated variations of pressure, and in the regions where the speed is decreasing, the pressure will be increasing. The magnitude of the pressure gradient depends on the amplitude and frequency of the speed fluctuations, increasing as either increases. At a sufficient distance from the leading edge, the thickness of the boundary layer will be such that there will be a reversal of the direction of flow near the surface in those places where the pressure is increasing downstream. Larger speed fluctuations bring larger pressure gradients and an earlier reversal of flow. It seems very probable that such a reversal would give rise to the formation of eddies. This theory has not as yet been subjected to any mathematical check, and will be discussed in another paper.

Is small turbulence desirable?—In the light of this conception of the action of turbulence, the question arises as to the amount of turbulence that is most to be desired in wind tunnel experiments. At the large Reynolds Numbers encountered in full-scale airplanes and airships, the flow in the boundary layer is bound to be eddying over most of the body since the critical Reynolds Number is reached at a comparatively short distance from the nose. In wind-tunnel experiments, the flow in the boundary layer is likely to be laminar over most of the surface, especially if the turbulence is small. This difference in the character of the flow in the boundary layer often gives rise to large differences between force coefficients observed for the model and for the full-scale body. For example, the angle of attack at which burbling (i. e. separation) occurs on airfoils, especially thick airfoils, is often much smaller for the model.

The first suggestion which occurs to anyone receiving this information for the first time is to build wind tunnels with a high degree of turbulence, so that eddying flow will be established throughout most of the boundary layer. It is assumed that this procedure will give at small Reynolds Numbers a flow more like the flow of a nonturbulent air stream at large Reynolds Numbers than is the flow which is obtained at the same small Reynolds Numbers with small turbulence. Or it may be argued that turbulence is always present in the atmosphere and that this condition should be represented in the model experiments. It has been claimed for several wind tunnels that the turbulence in them is exactly that of the atmosphere, because of the agreement of extrapolated model coefficients with full-scale coefficients in a few cases. This is a specious argument, for the turbulence in the atmosphere is a highly variable quantity, and at any one place is different at different times. Furthermore, because of the effect of turbulence on the form of the "scale-effect" curve, it is possible to obtain the same extrapolated full-scale value from model values observed in different wind tunnels, even when the model values differ widely. For example, if the drag of an airship model is measured in a highly turbulent wind tunnel, the drag coefficient will be found to decrease with increasing Reynolds Number, and the extrapolated value for the full-scale Reynolds Number will be considerably lower than any of the measured values. If the drag of the same model is measured in a wind tunnel with small turbulence, the drag coefficient will be found to be lower than in the highly turbulent wind tunnel and the variation with Reynolds Number will be small. The full-scale value will then be assumed the same as the measured value, and it may happen that this value agrees closely with the full-scale value extrapolated from the turbulent wind-tunnel observations.

The argument for the use of wind tunnels with large turbulence is based on a great simplification of the actual phenomena, a simplification which is helpful at the beginning of a study of the problem, and is useful to nontechnical readers, but which often leads to misunderstanding. The words "laminar" and "eddying" are used to distinguish between two general types of flow as rough classifications, but all "eddying" flows are not identical; furthermore, different parts of one and the same boundary layer having eddying flow are not identical. The skin friction per unit area, the thickness, and the velocity distribution vary from point to point. The classification of flows into laminar and eddying is only a very rough and general classification; there is always a transition region between the two, in which the flow can not be unambiguously assigned to either classification. Thus while in a very general way, an increase in turbulence has an effect similar to the effect of an increase of Reynolds Number, a detailed examination (see for example reference 5) shows that the resemblance is only superficial.

Wieselsberger (reference 7) presents the arguments for a small turbulence as follows: "It has not yet been definitely ascertained as to whether, in the case of experiments with models, the turbulence is an advantage under all circumstances and has the same effect as the increasing of the Reynolds Number, since the information on this subject is still (1925) insufficient. It is quite conceivable, however (and this possibility must be taken into account), that, in certain cases, the air stream is affected by the turbulence in quite a different and perhaps undesirable manner. Besides, we often have to test in the wind tunnel full-scale objects, such as radiators, spars, and landing gear parts. In these cases, a turbulent stream would give a wrong idea of the actual relations. A turbulence-free air stream is also necessary for testing and calibrating instruments (for example, air-speed meters). Lastly, it may be remarked that a nonturbulent flow is very easily rendered turbulent to any desired degree by the interposition of a screen of wire or thread, if required for certain experiments, while the reverse is not so easily accomplished. We see, therefore, that the preference must unquestionably be given a wind tunnel with as smooth an air flow as possible."

Little needs to be added to this clear statement. It emphasizes again that turbulence is an important factor, whose value needs to be known. The adoption of small turbulence as an ideal to be sought in the design of wind tunnels does not preclude the possibility and desirability in many cases of carrying on experiments with a large turbulence.

The measurement of turbulence.—In the preceding discussion the word turbulence has been used, without precise definition, in the general sense of any departure from the ideal conditions of steady and uniform flow. In the absence of more complete knowledge of the mechanism of the breakdown of laminar flow and the onset of eddying flow, no completely satisfactory definition can be given. At any point in the air stream, the speed varies with the time in a very irregular manner, about some mean value, V. At any instant the speed differs from the mean value by an amount ΔV, which varies from instant to instant. Let us form the average value, dV, taken without regard to sign, in accordance with the definition

$$dV=\sqrt{\frac{1}{T}\int_0^T \overline{\Delta V}^2\, dt}$$

where t is the time and T is a time interval which is large in comparison with the period of the fluctuations of speed. dV is nothing more than a particular kind of average value of the deviation of the speed from its mean value, V; $1/2\ \rho\ \overline{dV}^2$, ρ being the density of the air, is the amount by which the kinetic energy of the air exceeds what it would have been had the velocity been constant and of value V. In reference 5, the quantity $\frac{dV}{V}$ was defined as the turbulence, and it was shown that the forces on spheres and streamline models can be correlated with its value.

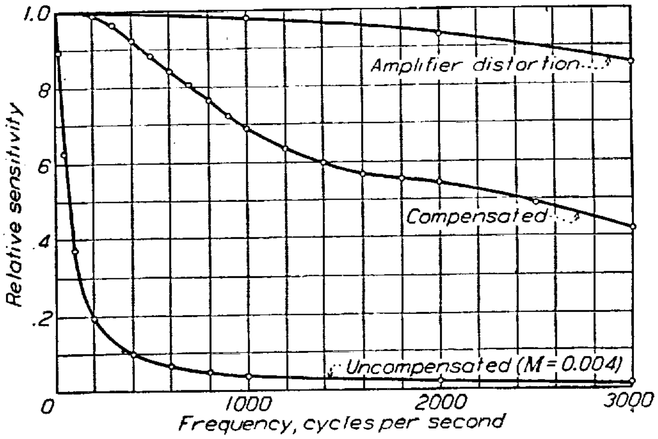

FIGURE 1.—Relative sensitivity of hot-wire anemometer to periodic variations in speed. The curves apply to the apparatus described in N. A. C. A. Technical Report No. 342, and the one of chief interest is that labeled compensated. The uppermost curve indicates the loss due to distortion in the amplifier; the remaining loss is due to defects of the compensating circuit. The lower curve shows the response when no compensation is introduced

The turbulence was measured by a hot-wire anemometer and associated apparatus. The sensitivity of such apparatus to variations in speed is constant up to a frequency of 100 per second, and then decreases rapidly, somewhat as shown in Figure 1. (Consequently, when used in a stream containing variations of widely different frequencies, its indications refer mainly to the variations having the lower frequencies.) This curve was determined by the method of reference 8.

The considerations at the end of the section on "Modern views as to the nature of the effect of turbulence" lead to the conclusion that fluctuations of high frequency are more effective in causing breakdown of the laminar flow than are those of low frequency, and it has been suggested by other investigators that the frequencies of importance are much higher than 100 cycles per second. The correlation of the force measurements with the mean amplitude of fluctuation as measured is, then, to be regarded as indicating merely that both the forces and the mean amplitude of low frequency fluctuations vary with the "real" turbulence. This interpretation may be the correct one. As yet, we have no experimental evidence for or against it. Experiments are now in progress at the Bureau of Standards, and also in Holland (reference 8), in an attempt to extend the frequency range and to determine the "spectral distribution" of the fluctuations.

Measurements on spheres have often been used as a qualitative method for the comparison of the turbulence in different wind tunnels. It was suggested in reference 5 that sphere results be expressed by giving the Reynolds Number for which the drag coefficient of the sphere is 0.3. For the experimental work to be described in this paper, both methods of measuring turbulence have been used, namely, the sphere method, and that of the hot-wire anemometer.

Description of wind tunnel and modifications.—The particular wind tunnel selected for experiments on the reduction of turbulence was the 54-inch wind tunnel of the Bureau of Standards, which was known to have a fairly large turbulence. When the measurements were begun, the tunnel was in the condition described in reference 5 and as shown in arrangement No. 1 on Figure 2. The features to be noted are the relatively small and abrupt area reduction in the entrance cone and the presence of an upstream honeycomb in the straight portion of the tunnel. In arrangement No. 2 a honeycomb of paper tubes 1 inch in diameter and 4 inches long was installed in the room close to the tunnel inlet. This honeycomb was a duplicate of the one already in place at the exit end. In arrangement No. 3 the upstream honeycomb in the straight portion of the tunnel was removed. In arrangement No. 4 an upstream honeycomb of round tubes of galvanized iron 3 inches in diameter and 12 inches long was installed as far upstream as practicable. In arrangement No. 5 the upstream honeycomb of 3-inch round cells was removed and replaced by a honeycomb made of paper tubes 1 inch in diameter and 4 inches long. In arrangement No. 6 the entrance cone was completely rebuilt. The entrance was made octagonal in cross section, 10 feet between opposite faces, and a honeycomb of 4-inch square cells, 12 inches long, was placed immediately at the entrance. The entrance was placed in the plane of the room honeycomb already in place. It will be noted that the differences between arrangements 1, 2, 3, 4, and 5 are in the honeycombs alone, whereas arrangement No. 6 is a radical change in the form of the entrance cone.

RESULTS

The drag of a sphere was measured for a number of air speeds at each of the positions designated as upstream, working section, and downstream in Figure 2, except for arrangement No. 3 where only the upstream and downstream runs were made. For arrangements 1, 2, 4, and 5 a 5-inch sphere was used, whereas for arrangements 3 and 6 a sphere 8.6 inches in diameter was used. The same experimental arrangement was used for both spheres, namely, that shown in Figure 4 of reference 5 for the 8.6-inch sphere, a downstream spindle suspended by 4 wires arranged in 2 V's, with a shielded counterweight from a fifth wire. The drag was computed from the downstream deflection of the system and the weight. The drag of the spindle was measured with the sphere detached but supported in front of the spindle. The results are expressed in the usual manner as a plot of the drag coefficient, C_A, against the logarithm to base 10 of the Reynolds Number, R.

$$C_A=\frac{F}{\frac{\pi D^2}{4}\frac{1}{2}\rho V^2}$$

$$R=\frac{VD}{\nu}$$

where F is the drag force, D the diameter of the sphere, V the air speed, ρ the density of the air, and ν the kinematic viscosity of the air. The results for the six arrangements are given in Figures 3 to 8, inclusive.

It was suggested in reference 5 that the critical Reynolds Number for a sphere be defined as the value of the Reynolds Number at which the drag coefficient is 0.3. The values so obtained from the curves shown in Figures 3 to 8 are given in Table I.

Table I also contains the turbulence as measured by the hot-wire anemometer. The values given are the mean fluctuation of the speed at a given point expressed as a percentage of the mean speed. Each value represents the mean of two or more runs, each run consisting of observations at 6 to 10 speeds. For example, the value for arrangement 4, upstream, namely, 1.6, is the mean of the following results for 6 runs, 1.67, 1.68, 1.61, 1.77, 1.28, 1.31. The value for the fifth run, 1.28, is the mean of the following values, 1.55, 1.28, 1.10, 1.27, 1.27, 1.26, 1.45, 1.29, 1.23, 1.22, 1.27, while that for the fourth run, 1.77, is the mean of 1.64, 1.87, 1.78, 1.86, 1.80, 1.72, 1.75, and 1.73. As stated in reference 5, the values for a given run are in general more consistent among themselves than the values for different runs. The averages are given only to the first decimal place and it is believed that they are correct to ±0.2.

The information in the table needs to be supplemented, especially for arrangements 3 and 5. The sphere results apparently indicate that a tunnel without a honeycomb is the least turbulent. The observations in Figure 5 do not, however, tell the complete story. The drag of the sphere varied in

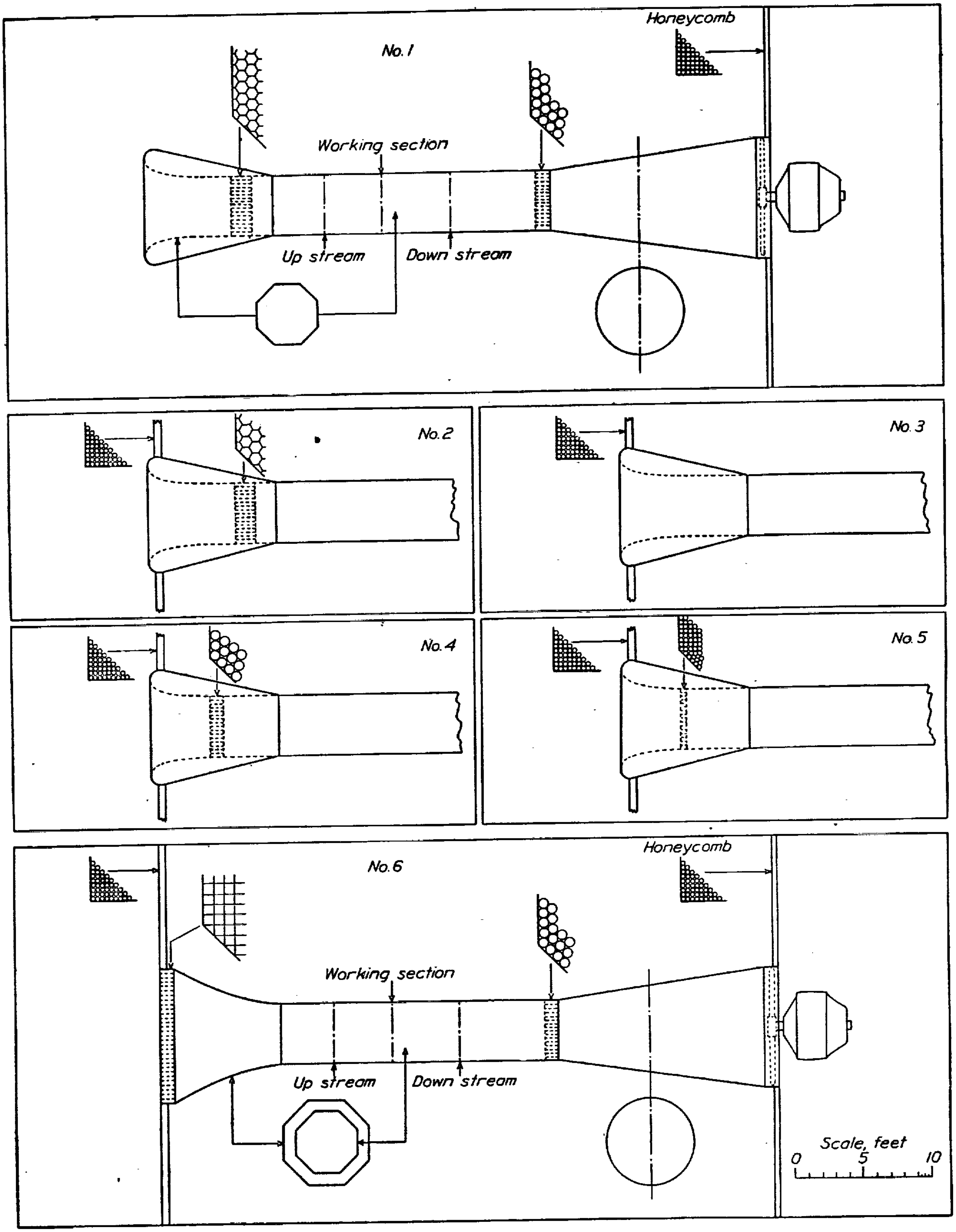

FIGURE 2.—Arrangement of parts of wind tunnel for various tests

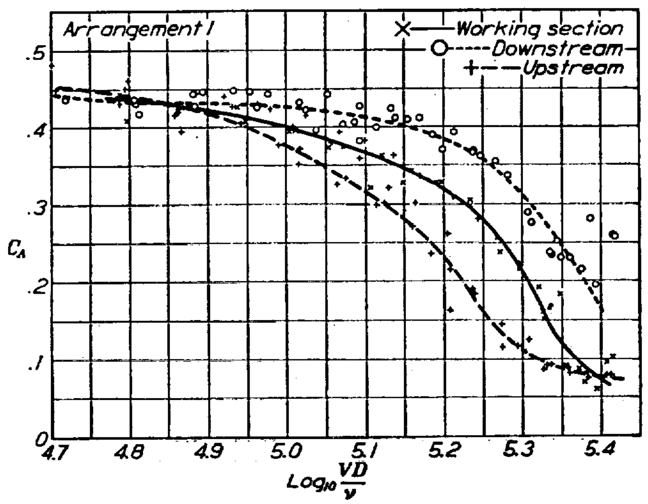

FIGURE 3.—Resistance coefficient of a sphere for arrangement 1

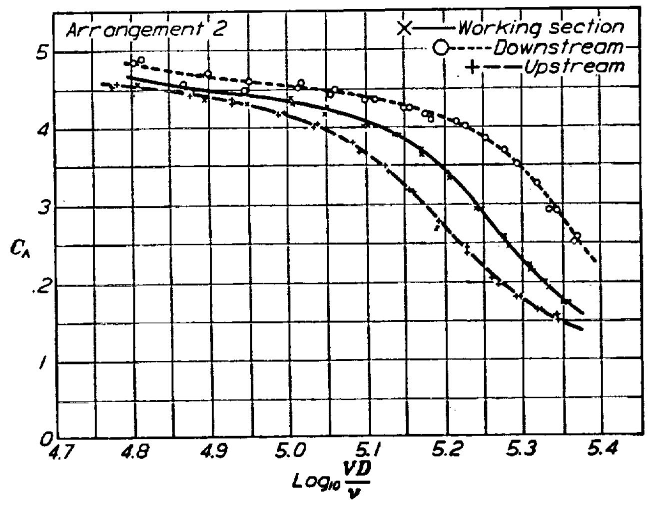

FIGURE 4.—Resistance coefficient of a sphere for arrangement 2

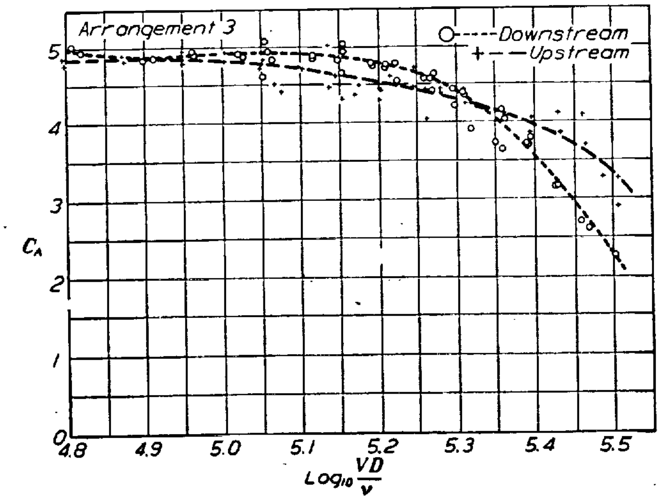

FIGURE 5.—Resistance coefficient of a sphere for arrangement 3

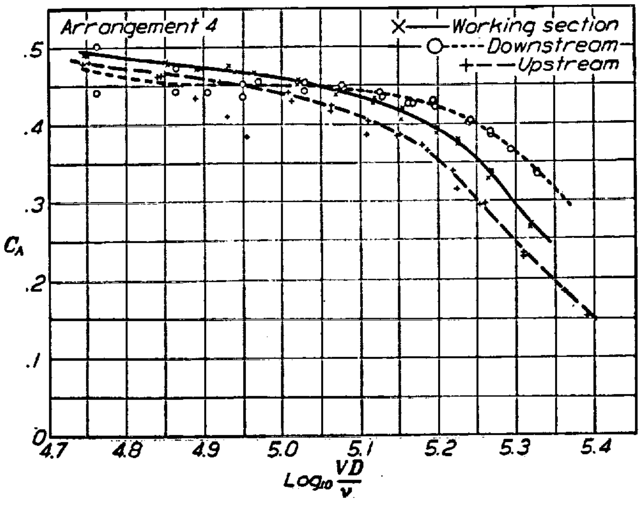

FIGURE 6.—Resistance coefficient of a sphere for arrangement 4

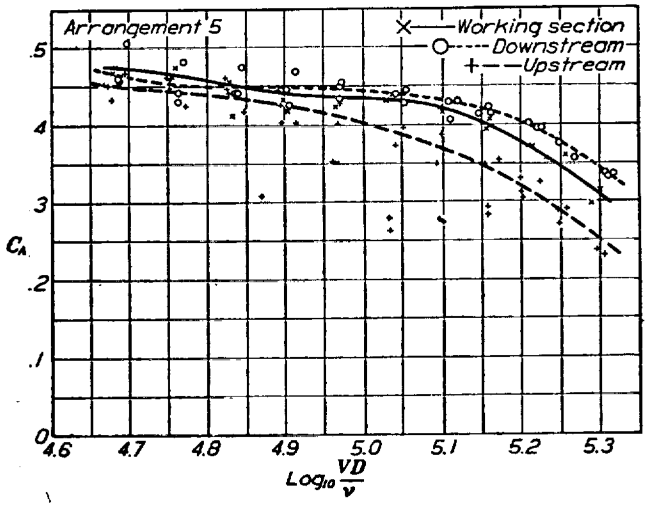

FIGURE 7.—Resistance coefficient of a sphere for arrangement 5

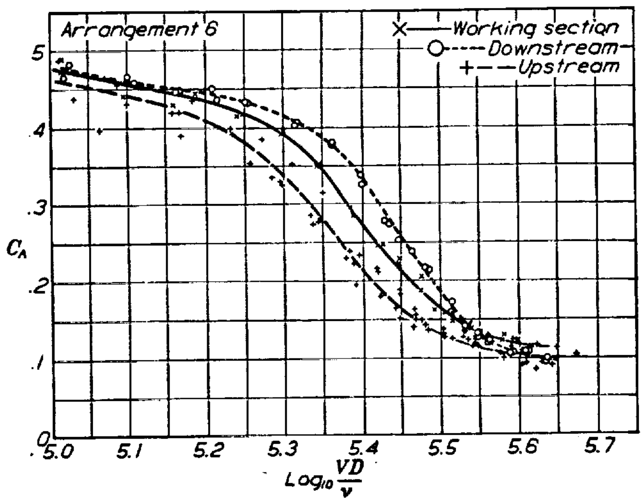

FIGURE 8.—Resistance coefficient of a sphere for arrangement 6

a very interesting manner, the sphere moving in jerks from one position of equilibrium to another. The observations represent the condition prevailing for the longest time. It is believed that the turbulence is very small in general, but that frequent disturbances sweep through the tunnel and break down the laminar flow in the boundary layer of the sphere. The taking of observations was difficult and time-consuming. The same behavior was indicated by the hot wire. Here, however, the period of the apparatus was so great (30 seconds or more) that the low values were never recorded. The sphere suspension was such that its period was only a few seconds, and the fluctuations could be more accurately observed. The operation of the tunnel in this condition was found to be impractical.

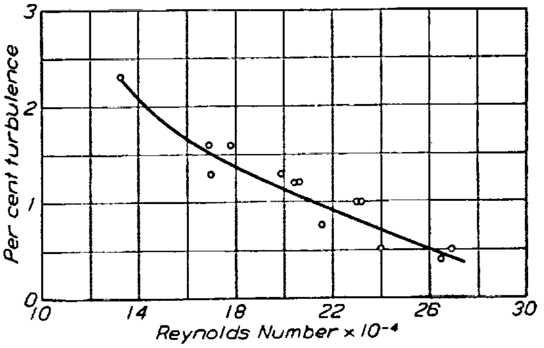

FIGURE 9.—Reynolds Number when C_A for sphere is 0.3, as a function of the turbulence

A great deal of difficulty was also experienced with arrangement 5 as indicated by the scattering of the results in Figure 7, especially for the upstream position. The trouble was found to be due in part to motion of the honeycomb under the action of the wind. The paper tubes forming the honeycomb were finally glued together and additional bracing was provided but the trouble never disappeared completely. We consider this honeycomb, or any type of honeycomb which changes position or deforms, to be completely unsatisfactory. The hot wire value for the downstream position with this arrangement is considered unreliable. It is based on a single run taken just before trouble developed with the amplifier and through an oversight no further measurements were made in this position.

Some of the measurements on arrangement 1 (fig. 3) also show a large spread. This arrangement has always shown a peculiar kind of unsteadiness of flow in which the speed as recorded by a Pitot tube drops by several per cent for periods as long as 15 to 30 seconds. Calibration runs have shown individual values of the ratio of the Pitot-static head to the static-plate head differing from the mean by as much as 4 per cent and mean deviations for 15 or 20 readings of as much as 1.5 to 2 per cent, so that a large number of runs had to be made to secure a precision of 1 per cent. This behavior was in marked contrast to that of arrangement 6. The fluctuations of the manometers for arrangement 6 are reduced to a fraction of those observed for arrangement 1. Maximum deviations in calibration runs are rarely as much as 1 per cent, and mean deviations are only 0.3 per cent.

The observations in Table I give new data on the calibration of a sphere as an instrument for measuring turbulence. The data, excluding the points marked "b," which have already been discussed, are plotted in Figure 9, together with the two points for the other wind tunnels at the Bureau of Standards as given in reference 5. All of the points fit a smooth curve (slightly different from that of reference 5) within the accuracy claimed for the observations. Six of the thirteen points are near the estimated maximum deviation and lend a little support to the view that the frequencies of the fluctuations may be of importance.

The effect of the various modifications on the turbulence may be seen from Table I to be as follows: The addition of a room honeycomb at the entrance gave a measurable but small reduction in turbulence. The complete removal of the honeycomb gives the least turbulence, but the flow is subject to temporary disturbances following each other in rapid succession, which make operation in this condition impractical. Arrangement 4 gives some reduction, but as shown in Figure 10, the reduction is entirely due to increasing the distance from the honeycomb. Arrangement 5 gives results substantially identical with arrangement 4. From Figure 10 it appears that the value of the Reynolds Number when C_A for the sphere is 0.3 in the upstream position of arrangement 4 is somewhat high, a result also indicated by the hot-wire value. Arrangement 6 gives considerable improvement. A large part of the effect (at least half) is again due to

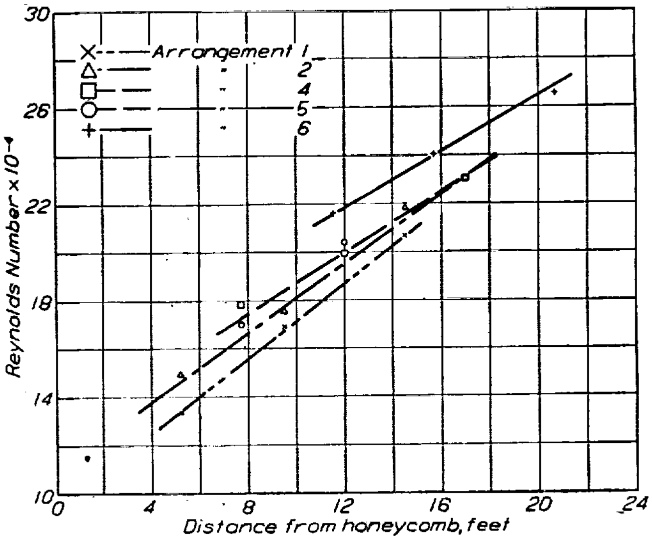

FIGURE 10.—Reynolds Number when C_A for sphere is 0.3, as a function of distance from the honeycomb for the several arrangements

he increased distance from the honeycomb as shown n Figure 10. The remainder is probably to be attributed to the lower initial intensity produced by the ower speed at the honeycomb.

CONCLUSION

The turbulence in the Bureau of Standards 54-inch vind tunnel at a fixed distance from the honeycomb vas not greatly reduced by modifications of the diameter, wall thickness, or shape of the honeycomb cells r the addition of a room honeycomb. Working at a reater distance from the honeycomb or moving the oneycomb upstream is effective in reducing the turulence. The use of a large area reduction in the entrance cone with the honeycomb in the slow-speed portion gives an additional reduction of turbulence and also greatly improves the general operating conditions.

ACKNOWLEDGMENT

The measurements described in this paper were made at various times over a period of 18 months by the members of the section of aerodynamics of the Bureau of Standards. Practically every member of the section took part in the work, and acknowledgment is made of their cooperation.

Bureau of Standards,
Washington, D. C., *March 7, 1931.*

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TABLE I.—REYNOLDS NUMBERS WHEN C_A FOR SPHERE IS 0.3 FOR THE SEVERAL ARRANGEMENTS, IN ORDER OF INCREASING VALUES OF *R* (DECREASING VALUES OF TURBULENCE).

Arrangement	Reynolds Number for sphere when C_A is 0.3	Average hot-wire value of turbulence (per cent)
1, upstream	[1] 133000	2.3
2, upstream	150000	----------
1, working section	[1] 169000	1.6
5, upstream	170000	1.3
2, working section	175000	----------
4, upstream	178000	1.6
4, working section	199000	1.3
5, working section	204000	1.2
1, downstream	[1] 206000	1.2
6, upstream	216000	0.75
2, downstream	218000	----------
4, downstream	230000	1.0
5, downstream	[2] 230000	[3] 1.4
6, working section	240000	0.5
6, downstream	265000	0.4
3, downstream	281000	[4] 0.8–1.4
3, upstream	338000	[4] 0.6–1.4

[1] These values differ slightly from those of Reference 5 as more points have been added and the curves redrawn.
[2] Extrapolated.
[3] Omitted from Figure 9.
[4] Omitted from Figure 9, erratic.

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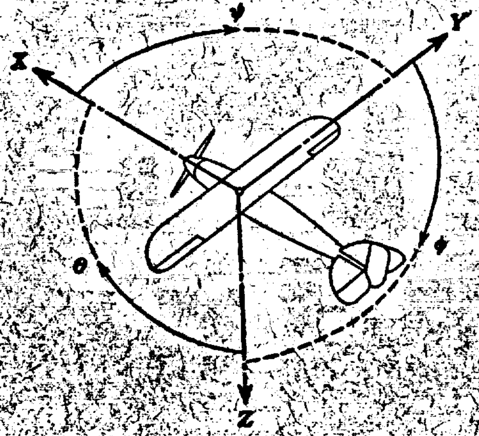

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	ϕ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	ψ	w	r

Absolute coefficients of moment

$$C_l=\frac{L}{qbS} \qquad C_m=\frac{M}{qcS} \qquad C_n=\frac{N}{qbS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p, Geometric pitch.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slipstream velocity.
T, Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$.
C_S, Speed power coefficient $=\sqrt[5]{\frac{\rho V^5}{P n^2}}$.
η, Efficiency.
n, Revolutions per second, r. p. s.
Φ, Effective helix angle $=\tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg.
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.