REPORT No. 524

A TURBULENCE INDICATOR UTILIZING THE DIFFUSION OF HEAT

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SUMMARY

In cooperation with the National Advisory Committee for Aeronautics, the National Bureau of Standards for several years has been studying methods of determining the turbulence in wind tunnels, especially by the "hot-wire" method and the sphere method. This paper describes a third method.

The effect of turbulence upon the diffusion of heat from a small electrically heated wire in an air stream was investigated. The turbulence of the stream was introduced by a series of geometrically similar screens placed one at a time across the upstream section of the tunnel. With the wire set at various distances from the screens, curves of temperature distribution were obtained by traversing the heated wake at a distance of 2 inches behind the wire with a small thermocouple. A single relation was found to exist between the width of the wake at half maximum and distance in screen wire diameters from the several screens. The correlation of width at half maximum with percentage turbulence, as measured by the "hot-wire" method, could be represented approximately by a single curve.

INTRODUCTION

The evaluation of wind-tunnel turbulence is by no means common practice in aerodynamic laboratories, even though turbulence is recognized as an important aerodynamic factor in wind-tunnel tests. This situation is due largely to the fact that a turbulence determination is attended with more difficulty and uncertainty than is the average aerodynamic measurement.

It is possible to determine quantitatively the ratio of the root-mean-square of the speed fluctuation at a point to the average speed. This quotient times 100 is usually called the percentage turbulence. The percentage turbulence may be measured by a modified hot-wire anemometer and accessory equipment, including an amplifier and an electrical network to compensate for the lag of the wire (references 1 and 2). The apparatus is expensive and cumbersome and its operation requires considerable skill and care on the part of the operator.

Simpler turbulence indicators, which, if desired, might be calibrated in terms of percentage turbulence by comparison with a "hot-wire" instrument, have been sought. A device of this sort, which has found wide use in comparing the turbulence of different wind tunnels, is the sphere (references 3, 4, and 5). The correlation of its critical Reynolds Number (defined as the Reynolds Number for which the drag coefficient is 0.3) with percentage turbulence has been made in several laboratories, but the universality of this correlation is still under investigation.

The present article describes a scheme of turbulence measurement based on the diffusion of heat from a heated wire. It has been found by experiment that the width of the heated wake increases as the turbulence increases, indicating a relation between the rate of diffusion and the degree of turbulence present in the air stream.

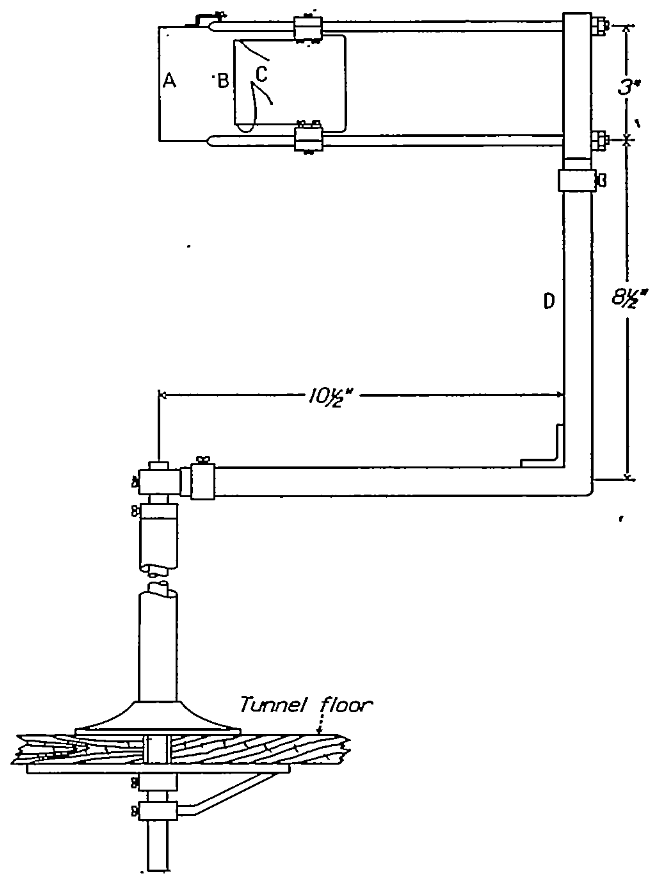

FIGURE 1.—Diagram of apparatus used to traverse the heated wake.

APPARATUS

The apparatus for producing the heated wake and traversing it to determine its width is shown in figure 1. A platinum-iridium wire 2.8 inches long and 0.002

inch in diameter is located at A. At B two no. 36 wires, one of copper and the other of constantan, are soldered together forming one junction of a thermocouple. The other junction of the same size at C is placed just far enough from B to be completely outside the heated wake. The prongs carrying the heating wire and the thermocouple are attached rigidly to the arm D, which can be rotated about a vertical axis passing through the heating wire to carry the thermocouple B across the wake. The platinum-iridium wire was heated by an electric current ranging from 0.2 to 0.8 ampere, depending on the heating desired. The current could be maintained sufficiently constant by means of a rheostat and a 0 to 1 ampere range ammeter. The thermocouple was connected to a

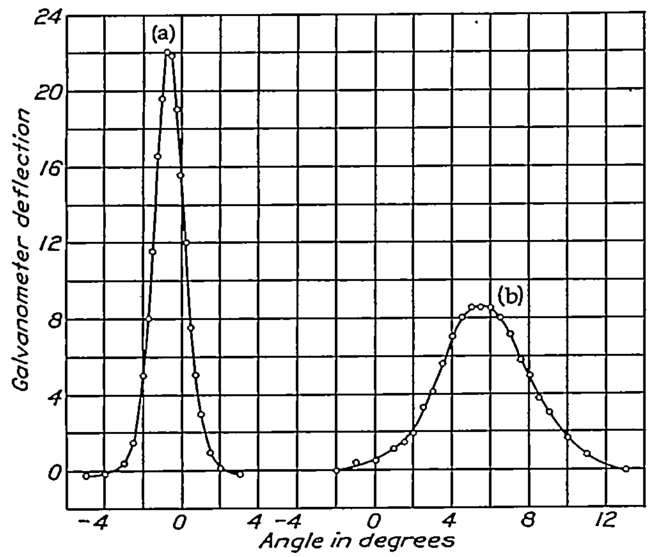

FIGURE 2.—Distribution curves obtained by traversing the heated wake at a distance of 2 inches from heated wire. Curve (a): 1.1 percent turbulence. Curve (b): 3.5 percent turbulence.

sensitive wall galvanometer (sensitivity 0.06 microvolt per mm per m scale distance).

Figure 2 shows two typical distribution curves obtained with the apparatus for a spacing of 2 inches between the heating wire and the thermocouple. Curve "a" corresponds to a turbulence of 1.1 percent and "b", to a turbulence of 3.5 percent. For both curves the heat input was 5.7 watts and the air speed 36 feet per second. Since the maximum ordinate of curve "a" corresponds to a temperature rise of only 3° C., and the copper-constantan thermocouple has a thermoelectric power of 41 microvolts per degree Centigrade, the necessity for a rather sensitive galvanometer is obvious.

THEORY

It is desirable that the heating wire have a small diameter so as to create little disturbance of the flow. The transverse flow of heat will be due to ordinary molecular conduction plus the eddy conduction arising from the turbulence initially present in the air stream. Let us consider first the case where the stream is completely free from turbulence and the wire produces a negligible disturbance. Regarding the wire as a line source of heat and the air speed as uniform, the temperature distribution is given at points not too close to the wire by the equation:[1]

$$\Delta T=\Delta T_{max}e^{\frac{-y^2\rho cv}{4kx}} \tag{1}$$

where y is distance across the wake measured from the center; x is distance downstream from the wire; ΔT is the temperature rise at any point (x, y); ΔT_{max} is the maximum temperature rise at the point $(x, 0)$; v is air speed and ρ, c, and k are density, specific heat at constant pressure, and thermal conductivity of the air, respectively.

It will be observed that equation (1) is analogous to the expression for the linear flow of heat from an instantaneous plane source. The approximations involved when applied to the present problem may be illustrated by visualizing the process described by equation (1). A line of air particles, after being heated by contact with the wire, is carried on in the x direction with the speed v. While the line moves through the distance x, during the time interval $\frac{x}{v}$, the heat flows outward from the line of particles in the $\pm y$ direction, and at x has attained the distribution given by equation (1). Clearly, the finite size of the wire, the conduction of heat in the x direction, the retardation of the flow by the wire and the stirring action due to whatever eddies are formed in the wake of the wire have been neglected.

If the air incident upon the wire is turbulent, there is an apparent conductivity expressed by $(k+\beta)$, where β is the eddy conductivity due to the turbulence. Equation (1) then becomes

$$\Delta T=\Delta T_{max}e^{\frac{-y^2\rho cv}{4(k+\beta)x}} \tag{2}$$

The width of the wake at half maximum temperature is selected to represent the width characteristic of the wake. From curves such as shown in figure 2 the angle subtended at the wire by the wake width at half maximum may be obtained. For convenience, the results will be expressed in terms of this angle rather than in actual width, the term angular width and the symbol α being used to designate the angle.

[1] The exact form of the temperature distribution behind a line source in laminar air flow as given by Drew (Trans. Am. Inst. Chem. Engineers, vol. 26, 1931, p. 30) is

$$\Delta T=\frac{q}{2\pi k}e^{\frac{\rho cvx}{2k}}K_0(z)$$

where q is the heat output per unit length of the wire, z stands for the combination $\left(\frac{\rho cv}{2k}\sqrt{x^2+y^2}\right)$ and $K_0(z)$ is a Bessel function of zero order. At large values of z, $K_0(z)$ may be set equal to $\sqrt{\frac{\pi}{2z}}e^{-z}$. After expanding $\sqrt{x^2+y^2}$ for $y<<x$ and neglecting small terms, equation (1) follows.

When $\frac{\Delta T}{\Delta T_{max}}=\frac{1}{2}$ in equation (1), y is the half width at half maximum. Making the substitution $2y=\frac{\alpha_0 x}{57.3}$ and solving for α_0, we obtain

$$\alpha_0=190.8\sqrt{\frac{k}{\rho\ cvx}} \tag{3}$$

where α_0 is the angular width in degrees at half maximum for laminar flow. Making a similar substitution in equation (2), we obtain

$$\alpha=190.8\sqrt{\frac{(k+\beta)}{\rho\ cvx}} \tag{4}$$

RESULTS

Measurements were made in the 4½-foot wind tunnel of the National Bureau of Standards, in an air stream made turbulent by a series of geometrically similar square-mesh screens placed one at a time across the upstream section of the tunnel. The amount of turbulence obtained from any one screen was varied by working at several distances from the screen. The first, second, and third columns of table I give, respectively, the mesh and wire diameter of the screens and the distance in wire diameters from the screens for the several working positions. The distance was measured

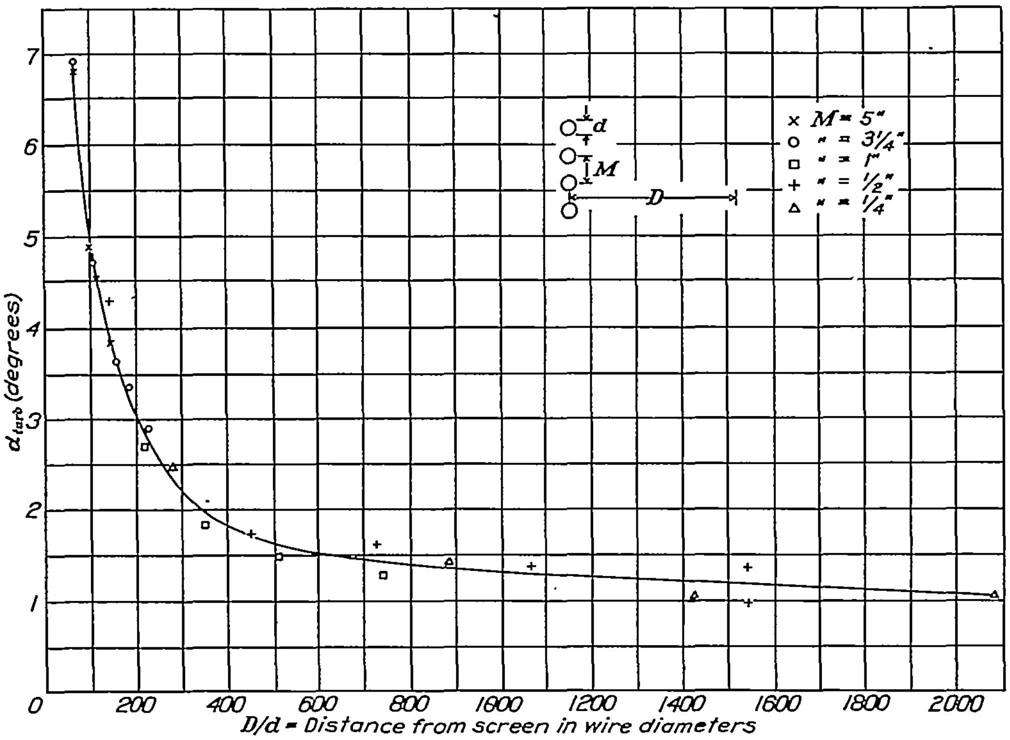

FIGURE 3.—Variation of α_{turb} with distance from screens expressed in screen wire diameters.

where α is the angular width for turbulent flow. By squaring equation (4)

$$\alpha^2=\frac{36400\ k}{\rho\ cvx}+\frac{36400\ \beta}{\rho\ cvx}=\alpha_0^2+\alpha^2_{turb}$$

$$\alpha_{turb}=\sqrt{\alpha^2-\alpha_0^2} \tag{5}$$

where α_{turb} is the angular width due to the turbulence alone.

From the foregoing expressions, it is clear that the heat output does not have to be known.[2] It is necessary only that the heating be constant, during a traverse of the wake, and of sufficient magnitude to allow the temperature distribution to be measured.

[2] The temperature rise is so small that the variation of k with wake temperature may be neglected.

from the screen to a point midway between the heating wire and thermocouple. Since the screen pattern in the speed distribution persisted to about 65 wire diameters downstream from the screen, the measurements were made at distances greater than 65 diameters.

The fourth column of table I gives the observed angular widths for a 2-inch spacing between the heating wire and thermocouple. The values of α_{turb} calculated by equation (5) are given in the fifth column of table I. A comparison of these two columns shows that the effect of α_0 becomes less as α increases. From runs made at wind speeds ranging from 8 to 55 feet per second, it was found that α varied with the speed, but that α_{turb} was constant to within the limits of experimental uncertainties. Since $\alpha_{turb}=\sqrt{\frac{36400\beta}{\rho cvx}}$, the eddy conductivity β must therefore be proportional to the air-stream velocity v.

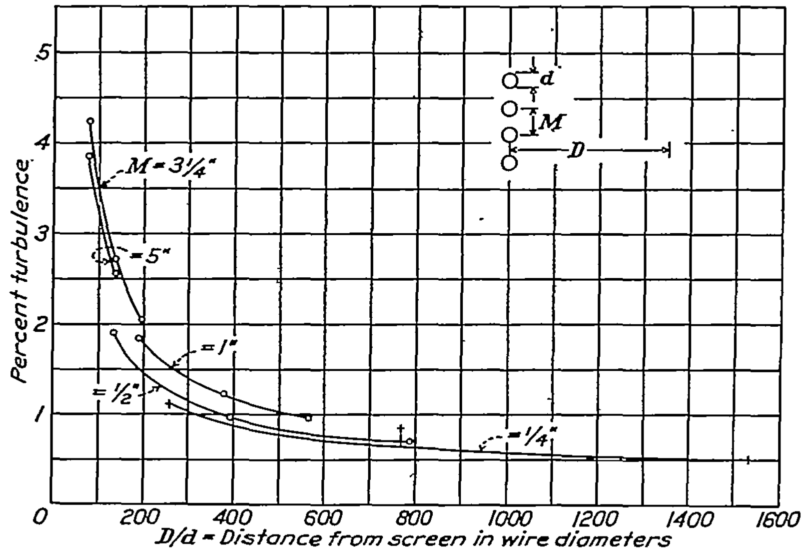

FIGURE 4.—Variation of percentage turbulence with distance from screens expressed in screen wire diameters.

Figure 3 shows the variation of α_{turb} with distance, expressed in screen diameters, from the several

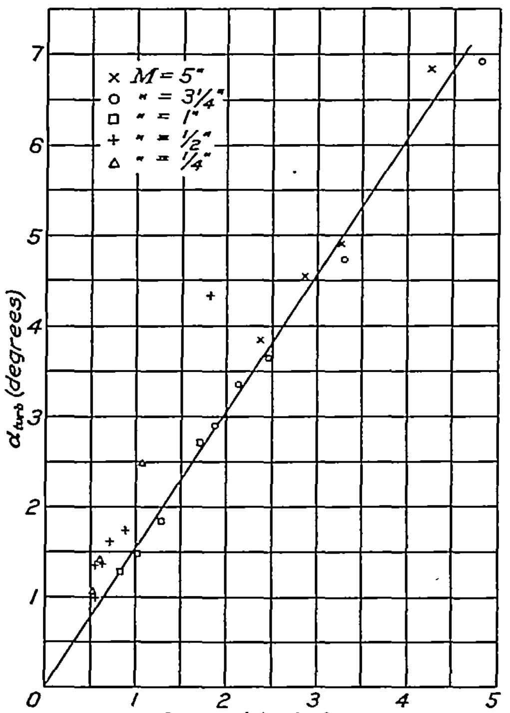

FIGURE 5.—Correlation of α_{turb} with percentage turbulence. M denotes the screen mesh. (See illustration in figs. 3 and 4.)

screens. Figure 4 is the corresponding diagram of percentage turbulence, measured by the "hot-wire" method, for the same series of screens.[3] It is significant that the points fall about a single curve in figure 3, whereas they follow a family of curves in figure 4. A possible interpretation of this result is that the "hot-wire" method differentiates between the scale of the turbulence produced by screens of different size, but that the diffusion method does not. It is reasonable to assume that the eddy size may bear a direct relation to the screen size. If so, it seems possible that the wire of about one centimeter length employed in the "hot-wire" method may average out the speed fluctuations to a progressively greater degree, and give a smaller response, as the eddies get progressively smaller. This subject is now under investigation at the National Bureau of Standards.

[3] These data were obtained by W. C. Mock, Jr., and the author in connection with another research project of the aerodynamic section.

Figure 5 shows the correlation of α_{turb} with percentage turbulence. Obviously, from figures 3 and 4 the correlation cannot be represented exactly by a single curve. However, the majority of points fall near a straight line passing through the origin, the marked deviations entering only for the ½-inch and ¼-inch mesh screens.

When the effect of spacing between the heating wire and thermocouple was investigated, it was found that α was essentially the same regardless of the spacing in the range from ½ inch to 6 inches. This means that the wake is wedge-shaped, the width at half maximum varying linearly with x. From these results β was calculated and found to be proportional to x.

It is possible to summarize all the results to date in an empirical equation for β of the following form:

$$\beta = K\,v\,x\left[\frac{\sqrt{\overline{v'^2}}}{v}\right]^2$$

where K is a constant of proportionality and $\sqrt{\overline{v'^2}}$ is the root-mean-square of the speed fluctuation. The constant K is equal to 0.63 ρ c.

A study of diffusion such as outlined here offers a promising field for future research both in theory and experiment.

NATIONAL BUREAU OF STANDARDS,
WASHINGTON, D. C., *March 8, 1935.*

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TABLE I

Mesh of screen (inches)	Screen wire diameter (inches)	Distance from screen in wire diameters	Angle subtended at wire by width at half maximum for 2-inch spacing between thermocouple and heating wire	
			α degrees	α_{turb} degrees
5 by 5	1.0	141	3.99	3.83
		114	4.68	4.54
		97	5.03	4.90
		66	6.92	6.82
3¼ by 3¼	.625	225	3.10	2.89
		183	3.53	3.35
		155	3.81	3.64
		106	4.85	4.72
		64	7.00	6.92
1 by 1	.192	739	1.70	1.28
		510	1.85	1.48
		349	2.15	1.84
		216	2.92	2.70
½ by ½	.092	1,540	1.75	1.35
		1,540	1.49	.988
		1,063	1.76	1.36
		727	1.96	1.61
		450	2.06	1.73
		141	4.46	4.32
¼ by ¼	.047	2,082	1.53	1.05
		1,423	1.53	1.05
		882	1.80	1.41
		276	2.72	2.48

Average wind speed = 36.2 ft. $(s.)^{-1}$ = 1,104 cm $(s)^{-1}$
Average air temperature = 18.3° C.
Average barometer reading = 753 mm Hg
$\rho = 1.220 \times 10^{-3}$ grams $(cm)^{-3}$
$c = 0.240$ cal. $(gram)^{-1}$ $(° C.)^{-1}$
$k = 5.60 \times 10^{-4}$ cal. $(s)^{-1}$ $(cm)^{-2}$ $[° C. (cm)^{-1}]^{-1}$
$x = 5.08$ cm
$\alpha_0 = 1.114°$