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No. 191

THE EFFECT OF WIND TUNNEL TURBULENCE UPON THE FORCES MEASURED ON MODELS.

By W. L. LePage and J. T. Nichols,
Massachusetts Institute of Technology.

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Summary.

1. Reasons for inquiry.- The tests were undertaken to find the effect of turbulence in the air stream upon the lift and drag forces measured on models in the four-foot wind tunnel at the Massachusetts Institute of Technology.

2. Range of investigation.- Maximum lifts and minimum drags were measured on Göttingen-387 and R.A.F.-15 airfoils, minimum drag on a streamlined strut, and the static pressure gradients for different conditions of turbulence.

3. Results and further developments.- The results show that the scale of the turbulence (as defined in this report) has a marked effect upon the measured forces on models tested in the tunnel as well as on the pressure gradient, and it is recommended that further investigation of the phenomena be made with the aid of smoke and small wind vanes.

In order to obtain some idea of the effect of turbulence of flow in a wind tunnel on the forces measured upon models, it was decided to encourage such turbulence by the introduction of wire screens directly behind the honeycomb. The screens consisted of wire netting of various degrees of mesh stretched across the mouth of the tunnel immediately downstream from the honeycomb. Three such screens were used successively, one having a mesh of 3 per inch, another, 10 per inch, and a third, 20 per inch. Whatever turbulence existed in the tunnel before the introduction of a screen would undoubtedly be modified in either quality or quantity by the screens and connected information concerning its effects would, thereby, be obtained. As a means of detecting any such change in the condition of the turbulence, forces were measured upon two airfoils (R.A.F.15 and Göttingen 387) 18" span and 3" chord and on a streamlined strut 18" long and 1 1/4" wide and of fineness ratio 3. These tests were carried out at 40, 35, and 30 miles per hour, except for the ten-mesh screen where it was not possible to obtain 40 M.P.H. and for the twenty-mesh screen where it was found impossible to obtain more than 30 M.P.H., owing to the throttling effect of these finer screens.

The Results.

It was not considered necessary to measure more than the maximum lift and the minimum drag for each case, and these have been compared in the appended table of results with those measured previously in the large wind tunnel at 40 M.P.H.

In general it was found that the maximum lift and minimum drag of the two airfoils decreased for the same wind speed as the screen became finer, with the one exception, that the lift of the Göttingen airfoil at 30 M.P.H. was slightly greater for the fine screen than for the medium screen. In the case of the streamlined strut the results appeared to follow no such law, being apparently entirely unsystematic. If, however, from the minimum drags at 35 and 30 M.P.H. the drag at 40 M.P.H. is calculated assuming it to vary as the square of the velocity, some interesting deductions can then be drawn. The drag coefficient at any particular value of Vl is increased by the introduction of a screen, while the scale effect is of a very similar order apparently for all screens (See Fig. 1).

The drag readings of the spindle used to support the models have been included in the results of this report, and it will be seen that, at any one wind speed, these decrease as the screen becomes finer, except in the case of the finest screen (20 per inch). In changing from 35 M.P.H. to 30 M.P.H., the drag in this case was found to increase.

A further test was carried out on the two airfoils, in which the medium mesh screen (10 per inch) was placed within 12 inches of the leading edge of the model, and 23.5 inches downstream from the honeycomb. Comparing these results with those of the same screen placed directly behind the honeycomb, at 35 M.P.H., it will be seen that both maximum lift and minimum drag readings have increased.

For the purpose of comparison, the readings of maximum lift and minimum drag measured at 40 M.P.H. in the large tunnel, have been included in the table of results. These have been taken from a previous report on tests with the same models. It is considered that the turbulence in this tunnel is of a less violent nature than in the smaller tunnel, since the honeycomb is much farther away from the model, and that a comparison of results obtained with those of the present work might throw some light upon the probable effect of the screens upon the condition of the flow. From the R.A.F.15 results it would appear that the tests in the large tunnel are comparable with those in the small tunnel with a screen somewhat finer in mesh than three per inch, but probably not so fine as ten per inch. The lift and drag readings seem to conform with the descending numerical sequence of the small tunnel results, being a little lower than those for the three per inch screen. The Göttingen airfoil appears at first sight to be inconsistent. Though the lift is lower than that measured in the small tunnel, clear, the drag is higher. This lack of conformity in the results may be due to the known fact of there being a marked scale effect upon this section. For such a section, turbulence would tend to produce a reduced drag. These facts, therefore, show the comparison of the results obtained in the two tunnels to be extremely important in confirming the presence of turbulent flow in the small tunnel and its apparent decrease caused by the introduction of screens.

Effect upon Static Pressure Drop.

The drop in static pressure down the tunnel has been determined in the open tunnel and for a few cases with screens. The results are interesting. The large mesh screen (three per inch) decreased the total drop along the working section, and this becomes zero with the medium mesh screen (ten per inch) increasing very slightly again with the fine screen (twenty per inch).

Conclusions.

Before any definite conclusions can be drawn from this work it would seem necessary to set down the idea which it is intended to indicate by the use of the term turbulence. The presence of vorticity in the air flow of a wind tunnel is unquestionable, and can be visualized by the introduction of a series of narrow silk streamers into the air stream. It is the structure of this so-called "turbulence" which has been investigated in the present work.

That the introduction of a wire screen into the air stream of a tunnel tends to produce a less turbulent flow is the general conclusion to be drawn from the foregoing experiment. It is also shown that the turbulence tends to die out more rapidly downstream as the screen becomes finer (assuming "no screen" as the datum condition).

In Fig. 2 is shown a characteristic type of curve of scale effect on the drag of a streamlined body. The dotted line curve represents a similar relation, the air stream possessing a higher degree of turbulence. It will be noted that the effect of the turbulence is to shift the curve up and to the left, increasing the drag at a given value of Vl. At low values of the Reynolds number, however, this condition ceases to hold, the drag at a given value of Vl being reduced when the Vl is small and increased when it is large. It must be pointed out in the case of the streamlined strut that the scale effect on this type of body is very large. As will be seen from Fig. 1, a decrease in the apparent turbulence as indicated by the introduction of a screen raises the curve of drag at values of Vl and moves it to the right. There seems every reason to believe that the curve for "no screen" in the tunnel will flatten out at higher values of Vl than appears on the curve, and that this will cause the curves to cross, introducing a phenomena similar to that just recorded, but at higher values of Reynolds numbers.

In connection with the observed effect of screens on the drop in static pressure down the tunnel, some interesting deductions may be drawn. It is unfortunate that the parallel section of the tunnel in which these experiments were carried out is very short, and satisfactory measurements of change in velocity from point to point down the tunnel cannot be made. Such measurements, however, have been made at the N.P.L., and the speed was found to increase 1/4% per foot of run (R&M 564).

Using the following statement of the first law of thermodynamics, we can deduce a relation between static pressure, wind speed, and rotational energy or the energy of turbulence:

$$U = \epsilon_h + \epsilon_t + \epsilon_p + \epsilon_r + \quad = \text{const.} \tag{1}$$

U = total energy in one pound of air.

ϵ_h = heat energy in one pound of air.

ϵ_t = translational energy in one pound of air.

ϵ_r = rotational energy in one pound of air.

ϵ_p = potential energy in one pound of air.

If we consider the changes taking place between two points, A and B, behind the honeycomb $\Delta U = 0$, we can assume as an approximation that $\Delta \epsilon_h = 0$ and that the expansion is adiabatic. Then we have:

$$\frac{1}{2g} v^2 + \frac{C^{-1/k}}{k - 1} p \frac{k - 1}{k} + \epsilon_r = \text{const.} \tag{2}$$

and

$$\frac{V}{g} \partial v + \frac{V_a}{K} \partial p + \partial \epsilon_r = 0 \tag{3}$$

Equation (3) enables one to form a mental picture of the energy changes taking place behind a screen or honeycomb in a wind tunnel. A unit mass of air directly behind the honeycomb has a certain total energy which is composed of kinetic energy of translation, kinetic energy of rotation, and potential energy. As this mass of air moves downstream in an ordinary tunnel the potential energy decreases (pressure drop) the kinetic energy of translation increases, accounting for a part of the decrease in potential energy, while the rotational kinetic energy decreases slowly, keeping the total constant.

Now the introduction of a fine mesh screen into the tunnel undoubtedly increases the absolute values of ϵ_r, and the observed fact that a fine-grained turbulence dies out rapidly indicates that ϵ_r is changing very rapidly behind such a screen, and if a screen of proper proportions is chosen the decrease in ϵ_r may just balance the usual losses in energy which cause a pressure drop down stream. It is, of course, understood that the pressure drop due to friction on the walls has been neglected in the above discussion, but, as will be seen by an inspection of Table I, the drop due to friction is a small part of the total drop, and we are safe in neglecting it in drawing qualitative conclusions.

The loss in pressure due to friction on the walls of the tunnel can be calculated by the equations of Fritzche and of Stanton and Pannell. Fritzche's equations are:

$$P = K \frac{l}{d} \delta V^2$$

P = drop in pressure in pounds.

l = length of pipe in feet.

d = diameter of pipe in feet.

δ = weight of one cubic foot of air in pounds.

V = velocity of flow in feet per second.

K = coefficient = $4.58 \times 10^{-4} \times d^{-.269} \times V^{-.148}$

Stanton's and Pannell's results are given by:

$$P = 4\ c\ \frac{l}{d}\ \frac{\delta}{g}\ V_m^2$$

in which P, l, d, δ, have the same meaning as before.

V_m = mean velocity which may be taken as .95 × normal tunnel speed.

C = coefficient which is approximately given by:

$$C = .00148 - .00021\ (\log Vd - 2.2).$$

The pressure drops due to friction alone for various tunnels have been computed on the basis of Stanton's and Pannell's results, and are included in Table I.

Table I.

Pressure Gradient for Various Wind Tunnels.

Location	Size	Drop lb/sq.ft/ ft.	Drop due to friction lb/sq.ft/dia.	Drop lb/sq.ft/ dia.	Distance from honeycomb
Washington Navy Yard	8×8	.0138	.041	.110	16'
M.I.T.	7.5' dia.	.0138	.041	.110	18'
N.P.L.	7×7 #1	.0137	.041	.096	15'
N.P.L.	7×7 #2	.0207	.041	.145	18'
N.P.L.	4×4 #1	.0248	.043	.099	7'
N.P.L.	4×4 #2	.0310	.043	.124	10'
M.I.T.	4' dia.	.0640	.043	.256	3'
N.P.L.	3×3	.0470	.044	.141	8'
N.A.C.A.	5' dia.	.0350	.042	.175	3'
Bur. Stan.	3' dia.	.0340	.044	.102	--
Bur. Stan.	10' dia.	.0077	.040	.077	--
Washington Navy Yard	with scr. 8×8	.0000	.041	.000	8'

Summary of Results.

Screen*	Speed M.P.H.	Max. lift (lb.)			Min. drag (lb.)			lb/sq.ft/ ft. Pressure drop
		Gott.387	RAF15	Gott.387	RAF15	Strut	Spindle	
(screen 33" upstream of the model)								
None	40	2.428	1.717	.0429	.0199	.0366	.0459	.064
3	40	2.181	1.591	.0403	.0198	.0404	.0433	.040
10	--	--	--	--	--	--	--	--
20	---	--	--	--	--	--	--	--
None	35	1.886	1.324	.0334	.0158	.0330	.0357	--
3	35	1.787	1.216	.0325	.0157	.0356	.0340	--
10	35	1.683	1.163	.0312	.0140	.0356	.0331	.000
20	35	--	--	--	--	--	--	--
None	30	1.386	0.980	.0283	.0115	.0275	.0259	--
3	30	1.309	0.893	.0260	.0113	.0321	.0253	--
10	30	1.219	0.851	.0244	.0101	.0309	.0248	--
20	30	1.222	0.832	.0236	.0093	.0331	.0266	.010
(screen 12" upstream of the model)								
10	35	1.820	1.259	.0362	.0170	--	--	--
(seven and one-half foot wind tunnel)								
None	40	2.210	1.534	.0482	.0193	--	--	--

* Number of meshes per inch.

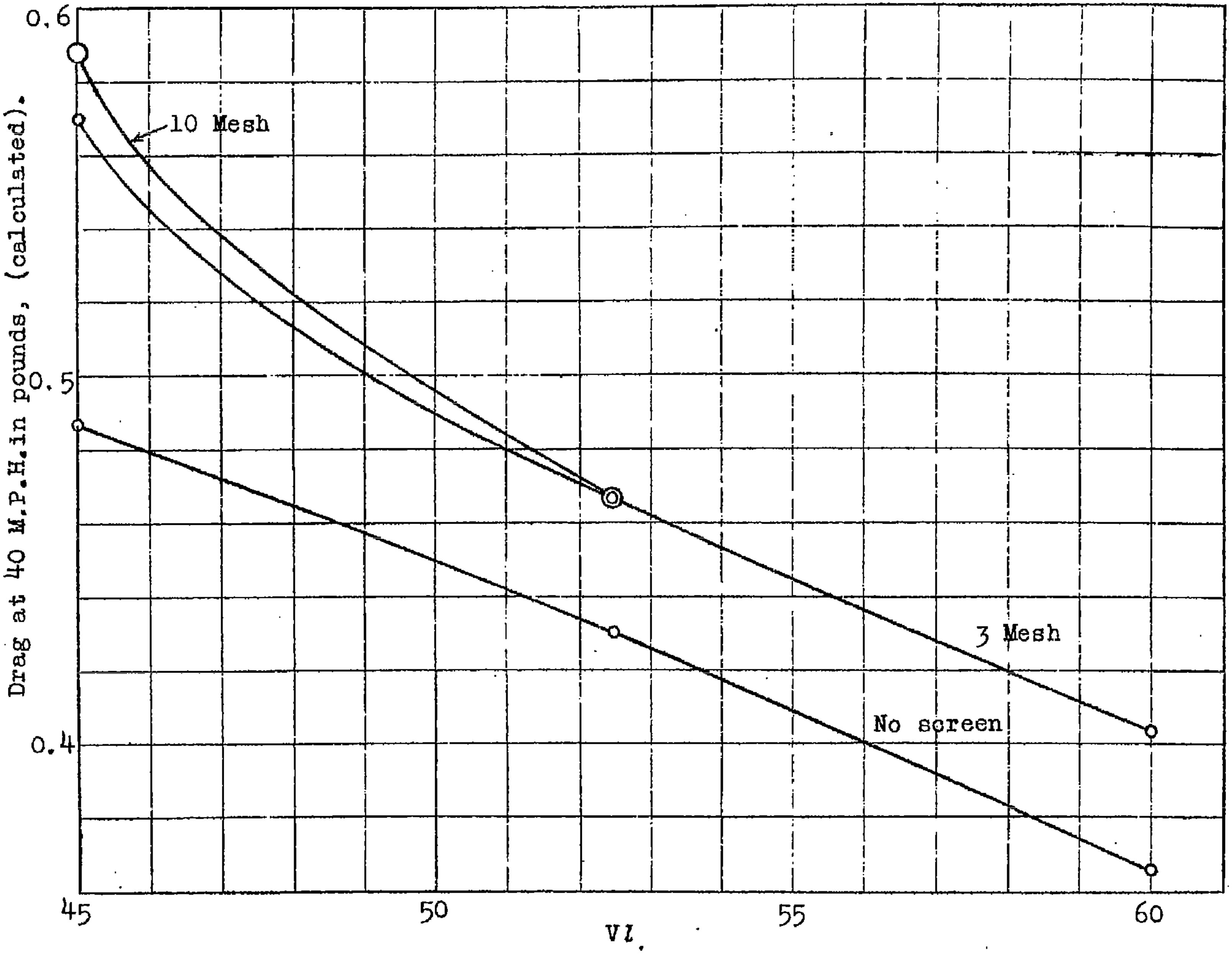

Fig.1. Change in scale effect on strut due to screens.

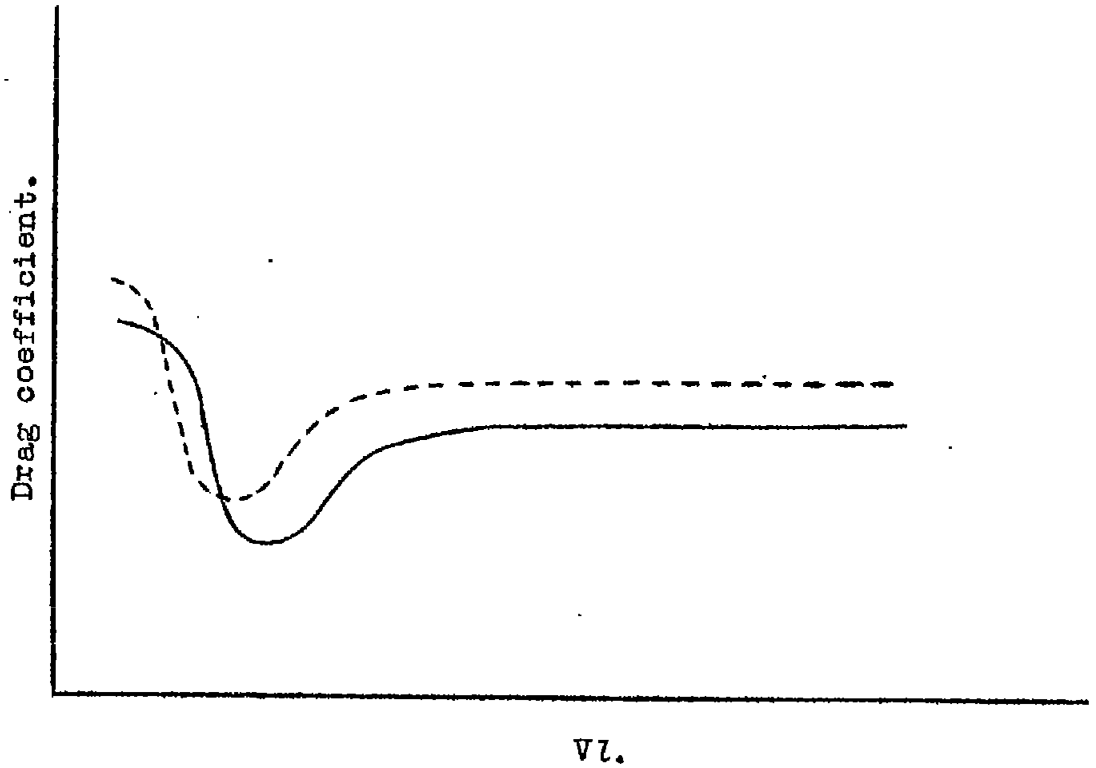

Fig.2. Curve of scale effect.

Fig.2.