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ATTAINING A STEADY AIR STREAM IN WIND TUNNELS

By L. Prandtl

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By L. Prandtl

Many experimental arrangements of varying kind involve the problem of insuring a large, steady air stream both as to volume and to time. For this reason a separate discussion of the methods by which this is achieved should prove of particular interest.

I. UNIFORMITY WITH RESPECT TO TIME

In but few cases will it be possible to draw air from a weighted gas tank or from a large pressure tank, or to exhaust air from the atmosphere by means of a previously evacuated tank. In this connection it may be noted that the last-mentioned arrangement insures an especially propitious uniformity with respect to time, because the inflow remains unchanged so long as the velocity of sound is not exceeded behind the narrowest point of the wind tunnel, notwithstanding the gradual pressure rise in the vacuum tank (reference 1). In suitable cases the air stream is maintained by a piston blower, compressor, or vacuum pump. Because of the unsymmetrical air delivery of such machines, a larger tank will have to be mounted between the machine and the working section. But in the majority of cases a fan will be used. The fan is fitted either in front of or behind the working chamber, so far as the air is not made to circulate from the pressure toward the suction side of the fan. When the fan aspires from free air it must be borne in mind that the air leaving through the other end, sets the air within the test chamber into rather irregularly eddying motion, and that the fan draws these eddies in again, whereby its rotational velocity is augmented, according to Helmholtz's vortex theory. A re-

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*"Herstellung einwandfreier Luftströme (Windkanäle). Reprint from Handbuch der Experimentalphysik, vol. IV, part 2, pp. 65-106.

volving fan generally produces a lower pressure gradient when the on-coming air itself revolves in the same direction as the fan, and a higher pressure gradient when revolving in the opposite direction.

To improve the time uniformity, it is therefore necessary to void such rotation prior to entry in the fan by some guide mechanism, such as a straightener or honeycomb. (See section II.) It is also recommended to lead the outflowing air through a screen, cellular plates, or lattice trunk, which insures a much steadier motion within the experiment chamber. With the fan mounted behind the working chamber the inflow is as a rule, steadier to begin with. In certain cases, however, a honeycomb for the air stream directly before the fan is also recommended. As concerns the types of fans, it is chiefly a matter of helical fans because of the small space required and their high efficiency. The types for low pressure gradients are not much unlike the orthodox airplane propellers. High pressures require propellers with numerous cambered blades and a guiding device for voiding slipstream rotation. This applies in particular to propellers mounted before the working chamber. With such propellers it is, above all, necessary to guard against undue flow resistance in the tunnel for the employed type. A drop in the rate of flow below a certain point due to increasing resistance, is followed by separation of flow from the propeller blades and irregular running of the propeller.

Centrifugal blowers are chiefly used with high resistance of the tunnel and to produce high speeds. But they require a large space compared to the helical fans. In most centrifugal fans the outgoing air leaves through a volute casing enclosing the blade. The enlargement of the volute casing fits only one particular rate of flow. This rate of flow can be usually recognized by the fact that the humming noise of the propeller is then at its minimum. The efficiency becomes less with the greater volumes of flow whereas the air delivery is uniform. But with smaller flow volumes it readily becomes profoundly irregular, because the rotating air first fills the volute casing and that part of it which cannot flow off on account of the undue high resistance, is then pushed back through the blades toward the suction side. As the wheel sets this part of the air in rotation, eddies are formed in the suction stream which, under certain circumstances, continue to grow and are then sucked away again from the wheel, thus producing an abnormal pulsating motion. Many fans in which the section of the passage does not correctly conform with the enlargement of the volute casing, manifest such pressure pulsation within a considerable range of operating conditions. This can be quite often remedied by closing the exit section of the wheel for a certain fraction, say, by fitting a strip of metal, or oilcloth or such, which, of course, must be guarded against being blown off.

Most electric motors are subject to speed variations due to fluctuations in voltage or frequency of the power supply; aside from that, the speed of d.c. motors especially, gradually changes as the motor warms up. Therefore, it is necessary to provide in some way for constant speed of the motor, or better yet, of the wind velocity, respectively, the dynamic pressure. The latter is especially recommended for air-resistance experiments. (See section V.) Any pressure difference existing in the tunnel which is proportional to the dynamic pressure, can be kept constant thereby. This may be achieved by micromanometer, manual regulation of the electric motor, or with an automatic regulator, which holds this pressure difference constant. This latter method has proved very satisfactory in the Göttingen laboratory, where it has been in use for twenty years. The essential part of the regulator is a pressure scale which can be loaded with weights until it balances under a certain pressure. Any deviation from this pressure closes an electric contact which actuates a small booster motor. The latter in turn adjusts a resistance and through it, changes the speed of the motor. Provision must be made for breaking the contact before the new equilibrium attitude is reached, in order to prevent permanent regulator oscillations. This can be effected in various ways as known from other regulator types. In one method the contacts are slowly pulled to the side concurrently with the regulation stage and resume their original setting after regulation by means of an oil damper. The scale itself must also be equipped with an oil damper to guard against oscillations due to shock. Descriptions of such regulators can be found in Z.V.D.I. 1909, p. 1715 (regulator of the Göttingen wind tunnel), also in R. Kroner's report: Experiments in Enlarged Tunnels," Forschungsheft No. 222 des Vereines Deutscher Ingenieure, 1920, page 22 (small special wind tunnel); further in Ergebnissen der Aerodynamischen Versuchsanstalt zu Göttingen, no. 1, 1921, page 20 (large Göttingen wind tunnel).

Quite recently there has appeared still another kind of regulator which, at the suggestion of Dr. M. Schilhansl, was constructed in a D.V.L. wind tunnel at Berlin-Adlershof (reference 2). This regulator can be used when there is a room containing positive pressure, before the working chamber. Suitable valves controlled by a regulator permit lateral escape of part of the air, whereby the speed of the main air stream is more or less reduced, according to the size of the lateral openings.

O. Schrenk (reference 3) demonstrated that the air stream itself could be utilized to regulate the openings. The weighted valve in figure 1 opens a little wider when the fan r.p.m. shows a slight increase. Then the volume of air per second delivered by the fan increases and the pressure drops again. With suitable valve design, it is thus possible to hold the pressure before the main opening just constant. Admittedly, certain conditions depending on the fan characteristics, must be borne in mind, as explained hereinafter.

II. LOCAL UNIFORMITY

This can best be obtained when still air drawn from a large chamber passes through a well rounded-off mouth to the working portion, because each air particle speeds with this arrangement through the pressure from rest (pressure p_0) to the lower pressure of the working chamber (p_1) and while doing so, attains a speed of

$$w = \sqrt{\frac{2\,(p_0 - p_1)^*}{\rho}}$$

according to Bernoulli's theorem. The pressure gradient $p_0 - p_1$ being common to all particles, they likewise assume the same speed and, because of the previously existent quiescence, no reciprocal rotation of the individual parts of the air stream is imminent, other than interferences next to the walls caused by the friction of the air stream. However, the disturbed zone is usually of limited extent. But the usual obstacle in practice is

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*ρ = air density = $\frac{1}{8}\left[\frac{\text{kg s}^2}{\text{m}^4}\right]$.

that it is impossible to consistently take away air from a room without corresponding replenishment, and that this replaced air is usually not sufficiently quiescent before it is sucked in again. Unless this replenishing is effected with care, the chamber frequently reveals rather severe rotary motions of air as effect of the outgoing air jet, and the suction of air in the mouth is then followed by the cited increase of this rotary motion. This can be guarded against up to a certain degree by straightening the flow. Generally speaking, a honeycomb is a guiding device through which the individual air filaments are rendered parallel. One type of honeycomb consists of crossed sheet-metal strips, such as shown in figure 3. The indentations of one section face upstream, those of the other downstream. The complete honeycomb viewed in stream direction then looks as illustrated in figure 2a. Such honeycombs can also be made of square or hexagon drawn thin metal tubes soldered together as in figure 2b. Even ordinary round tubes are suitable. Still another type consists of built-up straight and corrugated sheet-metal strip. (See fig. 2c.) Corrugated strip may also be used for building a honeycomb of design 2b. The strips are drawn through two indented rolls (fig. 4). To insure a final symmetrical corrugation, the indentations of the rolls must be unsymmetrical. As to the fineness of division of the honeycomb and the depth in stream direction, it may be stated that a depth equal to twice the division is quite acceptable, although by general preference, the depth equals four to seven times the division. To insure exact parallelism of the individual parts of the air stream, the honeycomb requires careful workmanship to insure parallelism in all its components.

A standard reference velocity is not obtained with the honeycomb, but can be achieved with screens. The flow resistance of a wire screen is approximately proportional to the square of the speed. Consequently, the resistance in a flow which locally manifests different speeds, is greater at the points of higher speed than at the points of lower speed. Together with the fact that the final pressure drop is about the same for all stream filaments the result is that the speedier filament expands upon striking the screen, the slower one contracts, and so the speeds become comparable upon passing through the screen. But this comparableness is always obtained at the expense of a great pressure drop in the screen. Putting the pressure drop in the screen at $p_1 - p_2 = c \frac{\rho w^2}{2}$, where c is a typical screen density factor, a previously existent, moderate velocity difference is approximately lowered to $\frac{1}{1 + c} a$. Disposing n screens, not too closely spaced, one behind the other, the pressure drop is $n\ c\ \frac{\rho\ w^2}{2}$ and the discrepancies are reduced in the ratio of $\left(\frac{1}{1 + c}\right)^n$. It is readily proved that such an arrangement of n screens with moderate c factors, say with $c = 1$, is more promising than one single screen of very close mesh and a resistance figure of $c' = n\ c$. For reasons of energy conservation, the screens are as far as possible mounted in a section in which the stream manifests lower speed.

Insofar as it pertains to local speed gradients constant in time as ascertained perhaps by a record of the velocity distribution with a static pressure gage, a wide-mesh screen can also be utilized very advantageously when the points of abnormal speed are covered with pieces of a much finer mesh screen. But instead of that a stirrup of wire or metal strip may be suspended on the upstream side of the honeycomb to contract the stream section wherever the speed is too high. The result must of course be checked by another velocity distribution reading, and it must be continued until the uniformity of the velocity is acceptable.

Another method consists of coating the points of abnormal speed on the screen with color varnish, such as dilute spirit varnish. This renders the individual wires thicker and thus raises the screen resistance. For the rest, the use of any screen requires careful attention because accumulated dust or rust increases the resistance unevenly and may readily vitiate a difficultly achieved uniform velocity distribution.

With a honeycomb of design of figure 2, the following method may be applied: Mount double flaps (as shown in figure 5) at the upstream end of the honeycomb. These flaps can be bent apart, thus offering a controllable resistance against the on-coming air stream. The velocity distribution is markedly irregular next to the honeycomb but soon becomes uniform again farther on. It is best to experiment with the flaps until the existent discrepancies in velocity distribution are equalized.

Another method which requires more space but is uncommonly effective and much more economical, consists of giving the air stream coming, say, from a fan, a low speed by gradually expanding the tunnel section and then producing a pressure gradient through a contraction of the tunnel at the working section, wherein the air particles are speeded up again. The conditions here are similar to the aforesaid induction of quiescent air from a large chamber. When the wide section is n times the section behind the contraction, the mean speed in the wide section is the nth part of the speed in the narrow section. Then the pressure drop from the large to the small section is $p_1 - p_2 = \frac{\rho w^2}{2}\left(1 - \frac{1}{n^2}\right)$ conformable to Bernoulli's equation. The energy corresponding to this pressure drop is quantitatively bestowed on every air particle, and the fluctuations apply only to the relatively small arriving energy of $\frac{1}{n^2} \frac{\rho w^2}{2}$. To illustrate: With a contraction to 1/5 of the section the mean energy of the oncoming stream is only 1/25 against 24/25 imparted on the particles in the pressure gradient. Fluctuations of from ±25 percent in the on-coming energy then become ±1 percent in the final energy; which corresponds to a $\pm\frac{1}{2}$ percent velocity variation.

Careful avoidance of transverse motions and slipstream rotation through a honeycomb is, of course, necessary here also. If an air mass rotates about the stream direction as axis, its diameter, upon transition to the nth part of the section which is equivalent to a diametrical reduction to the $\sqrt{n}$th part, is likewise contracted to $\frac{1}{\sqrt{n}}$ of its original diameter. This also holds true for the periphery of a closed line plotted in the plane transverse to the tunnel axis. During its change from the large to the small section the mean speed of the rotaty motion rises $\sqrt{n}$ fold, according to Thomson. (See Prandtl, "Introduction to the Fundamental Principles of Hydrodynamics," section 9, vol. IV, part I, Handbuch der Experimentalphysik.) The principal speed in tunnel axis direction rises n fold, followed by a slight drop of the lateral inclination of the streamlines, namely to $1/\sqrt{n}$ fold. Instead of the Thomson formula, it is, of course, permissible to use Helmholtz's formula, according to which the angular velocity of rotation changes in proportion to the length of the piece of the vortex line.

With sectional contraction to the nth part, a piece of vortex line parallel to the tunnel axis is expanded to n-fold length and the angular velocity then rises n fold. Since at the same time the radius of the vortex filaments is reduced to the $\sqrt{n}$th part, the peripheral speed $(=\omega r)$ has increased to $\sqrt{n}$ times; the same result as before. A rotation about an axis athwart to stream direction gives a shorter piece of the vortex line to the $\sqrt{n}$th part, and likewise a reduction of the dimensions to the $\sqrt{n}$th part in the direction at right angles to the tunnel axis and the vortex line. The result is a reduction to the nth part in the velocity gradients. This relationship for the longitudinal velocity gradients is in perfect accord with the results obtained above with Bernoulli's equation (since the speed rose to n times and the gradients decreased to the nth part, the comparative deviations are reduced to $1/n^2$ times).

From the foregoing, it is concluded that, wherever possible, a wide chamber conformable to figure 6 should be mounted ahead of the working section and containing a carefully designed honeycomb in its entrance section. The transition to the experiment section should occur in well-rounded form, although a steep sectional contraction of the kind indicated in the figure is acceptable. Between this sectional contraction and the honeycomb a short parallel piece should be maintained, owing to the vitiating resistance to flow which otherwise occurs with the deflection of the stream directly behind the honeycomb. For eduction from a larger room, it is advisable to employ a suction flare as indicated by the dashed lines in figure 6.

The complete experimental set-up should be carefully checked for velocity distribution. As concerns the magnitude of the velocity, this is suitably effected with a static pressure gage. (See Muller-Peters, "Speed and Volume Measurements of Fluids," vol. IV, 1.) For verifying the direction, the use of long, light threads fastened to crossed wires at different points across the working section is convenient. The distribution of the static pressure is also very important for precise experiments. (See Peters, "Pressure Measurements," vol. IV, 1.)

III. DESIGN OF EXPERIMENT SECTION

The section in which the experiments are made, may be of the closed- or open-jet type.

a) Closed-Jet Type

The older wind tunnels (see Flachsbart, "History of Experimental Hydro- and Aerodynamics," ch. II, section 3c) were frequently of the closed type with parallel walls. With this design of type it must be borne in mind that the wall friction sets up a layer of retarded air growing in flow direction, as a result of which the section for the air not affected by friction becomes consistently smaller. Thus ensues a velocity increment and a correlated pressure drop according to Bernoulli's equation. In precise experiments, especially with solids of large volume, such as airship models, this pressure drop is very significant. Its effect is in the sense of seemingly increased resistance of the airship model, etc. In the British laboratories, where most wind tunnels of this type are to be found, the usual procedure, first employed by I. R. Pannell (reference 4), is to equate the force due to the pressure drop to the volume of the body times the pressure drop per unit length, in analogy to the Archimedean buoyancy. The British therefore call this force "horizontal buoyancy" and subtract it from the measured resistance. Since the airship body itself produces profound changes on the entire pressure distribution, the pressure drop is, of course, measured in the empty tunnel and assumed that the interference due to wall friction with and without the model has the same magnitude. G. I. Taylor has proved, a few years ago (reference 5) that, in order to rightly effect the pertinent correction, it is necessary to add the "apparent mass" for the accelerated motion to the air mass displaced by the body. Admittedly, this apparent mass is very small for airship bodies.

This shortcoming was also noticed in the old Göttingen tunnel of 1908, incidental to resistance measurements on airship models; and we attempted to overcome this by giving the tunnel a slight sectional enlargement, which was so tried out that the pressure in the empty tunnel remained constant along the tunnel axis (reference 6).

Lastly, on the subject of wind tunnels with negative pressure in the experiment section, it may be pointed out that the air entering through leakages also yields a pressure drop, inasmuch as the air speed in stream direction must increase in accord with the air flowing in through the leakage. The effect of this pressure drop on the model is the same as that described in the foregoing.

b) Open-Jet Type

To G. Eiffel (reference 7) goes the honor of having first employed an open jet in a large wind tunnel. Drawn from a large chamber, the jet entered through a flared entrance cone into the experiment chamber (fig. 16). Such a jet, if suitably parallel upon exit from the entrance cone, passes the free space rectilinearly and is only gradually dissolved - starting at the boundaries - by coalescence with the contiguous quiescent air. (See Tollmien, vol. IV, 1, regarding such mixing processes.) Information as to the serviceable part of the air jet will be found elsewhere in the report. The pressure in the jet axis is, apart from the immediate vicinity of entrance cone and exit-cone flare, very exactly constant, for which reason there is, with this type, no correction for buoyancy of the kind mentioned above. This is a great advantage which together with the substantially greater accessibility of the experimental object in the air stream continues to find more and more favor. Accuracy of workmanship on entrance cone and exit-cone flare is here of great importance. With an entrance cone which next to the flare shows none or only a short parallel piece the contraction in the flare continues to act to a small extent behind the cone end, which explains the existence of a slight pressure drop in the jet axis for a short distance outside of the entrance cone. This can be avoided with a very slightly flared exit. The amounts involved herein are minute and are conveniently determined on the complete entrance cone itself or, if necessary, in a model test for the entrance cone used. For an experimental cone of figure 7, which was quite satisfactory, the diameter increases by 0.01 D between a and b.

Aft of the working chamber the jet passes conveniently to an exit-cone flare and so to the propeller. The problem of best exit-cone flare has not been solved entirely satisfactorily. In the Eiffel, as well as in the Gottingen type, the air mass passing the exit cone flare must correspond with the air coming from the entrance cone. But, since the jet has in the meantime become mixed with parts of the surrounding air, the air volume has become greater, and this excess must in some way be removed again, or else this excess is ejected as a fairly strong blast from the exit-cone flare (fig. 8), in which case it is advisable to protect the observer as well as the test equipment from this blast. One possible means of amelioration is the fitting of a slot aft of the exit-cone flare through which the excess air can escape; another, is to provide perforations in this flare at the point where the entrained air impinges. In the Göttingen system the openings in the downstream passage, before or behind the blower, serve the same purpose, while the Eiffel system provides leakages in the suction chamber. (See descriptions of the respective tunnels in section VI.) To be sure, the conical air blast cannot be removed altogether.

The proportion of the narrowest section of the exit-cone flare is also very important. If too narrow it results in a pressure drop which is perceptible even part way in the free jet; if too wide, it is followed by a pressure rise. In any case, it is advisable to make the narrowest diameter slightly larger than that of the entrance cone. The amount, however, depends on the length of the free jet with respect to the entrance-cone diameter. According to Göttingen experiences, a minimum exit-cone flare diameter equal to 1.1 to 1.2 times the entrance-cone diameter is appropriate for a jet length equal to 1.5 times the entrance-cone diameter.

In this connection, we may mention the ready occurrence of oscillations, where the wind tunnel acts as organ pipe when the free jet is too long with respect to its diameter, or when the edge of the exit-cone flare is too short, or else the exit-cone flare is altogether absent. Such pulsations can be minimized or eliminated in the Göttingen type of tunnel by having recourse to an improved form of exit-cone flare or else by providing suitable openings in the return passage which is under negative pressure. By this means the natural oscillations of the air in this passage can be damped down as in a leaking organ pipe. A detailed account of such pulsations is to be found in O. Schrenk's report (reference 8).

The useful zone of satisfactory velocity distribution is substantially greater in the closed type of wind tunnel because of the more restricted extent of the frictional layer at the wall than with the open-jet type where the eddies in which the flowing air mixes with the surrounding still air, penetrate comparatively quickly into the jet. The acceptable zone is, so to speak, bounded by a cone whose generatrices emanate with 1:8 slope from the edge of the entrance cone. This would mean that at a distance equivalent to twice the entrance-cone diameter there is still a sound stream to the amount of 50 percent of the entrance-cone diameter. This length should suffice for most practical purposes. Velocity distributions of such free jets are described in Report II, Ergebnisse der Aerodynamischen Versuchsanstalt zu Göttingen, München, 1923, p. 71.

Whereas, according to the foregoing, the free jet affords material advantages as far as measuring accuracy is concerned, aside from the enhanced accessibility of the measurements, it should equally be borne in mind that it manifests substantially greater flow resistances compared to the closed-jet type of tunnel, so that more powerful, hence more expensive motors are necessary to insure the same wind velocity.

c) Analysis of Velocity

Any of the various methods given by Müller and Peters in vol. IV, 1, can be applied for the determination of the velocity of the experimental air stream, although in practice, the following are preferred:

1. Closed jet type: The wind velocity is usually obtained with a Pitot survey apparatus designed so as to be rotatable in the air flow and thus provide an acceptable mean value of the velocity. The investigation of the stream processes about a solid (or its drag measurement) involves the problem of appropriate reference of the measured velocity to the ideal case, according to which the body moves within an air mass of infinite extent. The tunnel walls cause certain deviations of the type of flow from that ensuing in an infinite air mass. It can be deduced from theoretical considerations* and it has also

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*V. Valcovici, "Discontinuous Fluid Motions with Two Free Jets. Göttingen dissertation, 1913. In this thesis the potential flow is computed with Helmholtz's surfaces of discontinuity, which result with a plate at right angles to the air stream when the plate is a) in a channel with parallel wall; b) in an open jet. The exact drag coefficient is $\frac{2\pi}{4+\pi} = 0.8799$. Computing in case a) the drag

(Continued at bottom of page 13.)

been proved correct experimentally (reference 9) that the finite tunnel dimensions involve the least error when choosing the speed measured slightly aft and to the side of the body as that speed which is equated to that of the body in an infinite air mass. The velocity in front of the body is markedly lower and results, when equated to the speed in the infinite air mass (that is, computing the air resistance coefficients from the resistance measurements with it, for example), in substantially greater discrepancies because of the finite dimensions of the tunnel.

When, as in most closed wind-tunnel designs, the air is drawn from a large room (a hall, etc.), the pressure drop from the outside room up to the wind tunnel may also be used for velocity measurements; in which case, the pressure losses in the generally existent honeycomb are defined empirically (by comparing the pressure drop with the records of a static pressure gage moved about in the air stream). To allow for the aforementioned premise of velocity measurement laterally aft of the body, this can be closely approached by measuring the pressure drop between the outer room and a point at the wall downstream from the experimental object. To be sure, this is recommended only when the tunnel has been slightly widened in the aforementioned manner, so as to compensate the pressure drop due

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(Continued from page 12.)
coefficient by means of the velocity laterally aft of the plate, gives a drag coefficient c_{w_1}, which varies very little with the $\frac{\text{plate width}}{\text{tunnel width}}$ ratio. On the other hand, choosing the velocity in front of the plate gives a different drag coefficient c_{w_2}, which is much higher and extremely variable. (See table I.) With the jet we have drag coefficient c_{w_3}, which again is very little variable. (See table II.) b = plate width; B = width of tunnel, respectively, the jet.

Table I (tunnel)

$\frac{b}{B}$ = 0.045	0.125	0.279
c_{w_1} = 0.3816	0.826	0.8972
c_{w_2} = 1.378	1.994	3.59

Table II (jet)

$\frac{b}{B}$ = 0.035	0.138	0.309
c_{w_3} = 0.8786	0.8756	0.8680

to the growth of the frictional layer.*

2. Open-jet type: Owing to the constancy of the pressure on the jet surface, the velocity within the undisturbed jet is also constant, so that it is immaterial where the velocity is measured. Of course, it should be remembered that a pressure field is created in the vicinity of the body introduced into the air stream, which naturally entails speed changes. If there is no honeycomb in the entrance cone (honeycomb in the large section before the entrance cone), the pressure drop in the entrance cone lends itself very acceptably for the velocity determination. If p_0 is the pressure in the room surrounding the free jet, p_1 the pressure in the anteroom of the entrance cone, and if w is the jet velocity and w_1 the velocity in the large section before the entrance , Bernoulli's equation gives for the case of absent honeycomb between both sections,

$$p_1 - p_0 = \frac{\rho}{2} (w^2 - w_1{}^2)$$

Since, according to the continuity

$$w_1 F_1 = w F$$

where F = jet section and F_1 = large section before entrance cone, the dynamic pressure of the free jet is

$$q = \frac{\rho w^2}{2} = \frac{p_1 - p_0}{1 - \left(\frac{F}{F_1}\right)^2}$$

This relation has proved very accurate in check readings - so exact, in fact, that now it is conversely pre-

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*It may be pointed out that the dictum of velocity measurement laterally aft of the body is not wholly exact even if this rule is adhered to, because the velocity to one side of it is, strictly speaking, not constant because of the displacement effect of the body and the wake behind it. However, if the model is sufficiently small relative to the section of the air stream, the changes are so slight that the ensuing inaccuracies are within measuring accuracy. Unduly large models involve yet other sources of error (modified pressure distribution, etc.), so that the experiments here are always inaccurate.

ferred to compute the numerical coefficients of the static pressure gages by this method. If only a closed tunnel with honeycomb in the smallest cross section and one static pressure gage is available, the gage factor must be determined in some other fashion, probably by whirling arm calibration. In the first Göttingen wind tunnel the whirling arm calibration was the basis for the determination of the air resistance coefficients. If a wind tunnel of the closed type is equipped with a bell conformable to figure 6, the dynamic pressure q can be obtained exactly as with the free jet from the pressure difference recorded at stations a and b. With the dynamic pressure determined from the pressure drop in the entrance cone the results are completely free of any accidental errors in static pressure gage calibration.

Relative to the determination of air resistance factors, it may be mentioned that it is very expedient to determine the dynamic pressure direct rather than the velocity, because density and velocity are used in the same manner in the formula as in the air resistance formula; for which reason the air density need not be known at all to determine a resistance factor in wind-tunnel experiments, since it becomes readily apparent with the direct introduction of the dynamic pressure in the resistance formula. Admittedly, it is a different problem when, say, the Reynolds Number is to be defined at which the measurements were made. Then air pressure and temperature of the air stream must be ascertained.

IV. FANS FOR WIND TUNNELS

Apart from what has been said about fans in section I, the following is also of significance: Centrifugal fans with diffusers require disproportionately much space, for which reason they are not much in use for wind-tunnel work. To be sure, they have an advantage over helical fans, in that their tip speed is substantially lower than that of helical fans for an identical inflow velocity of the air, hence are less noisy. (The noise of the fan increases materially with the tip speed, as shown elsewhere.) The tip speed $u = R\omega$ of centrifugal fans drops to 1.5 times the suction velocity w, as against 2.0 times with helical fans.

The trend of the pressure jump or variation $p_2 - p_1$[*] produced by a helical fan versus the rate of flow w with constant r.p.m., is as shown in figure 11. The right-hand part of the curves rising toward the left corresponds to the sound blade flow, the left-hand portion to the separated flow at the blades. The first attitude is absolutely essential for wind-tunnel operation. The choice of fan also depends, to some extent, on its location. The location of the fan in a section of very high velocity of a wind tunnel with little stream resistance results in a low fan load, and vice versa. To arrive at a criterion for the fan loading, one may compare the desired pressure difference $p_2 - p_1$ either with the dynamic pressure of the mean rate of flow $\frac{\rho}{2} w^2$ or the dynamic pressure of the peripheral speed of the blade tips $\frac{\rho}{2} u^2$. Whence the two nondimensional factors

$$c_s = \frac{p_2 - p_1}{\frac{\rho}{2} w^2} \;{}^{**}$$

and

$$\psi = \frac{p_2 - p_1}{\frac{\rho}{2} u^2}$$

Up to around $c_s = 5$ single-stage fans can be employed. Two-stage fans are acceptable up to about $c_s = 10$. Beyond these figures the flow separates at the blades, the efficiency drops rapidly and the cited hum occurs. The obtainable ψ value depends on the number, width and setting of the blades. Up to about $\psi = 0.08$, conventional airplane propellers may be used advantageously. By increasing the number of blades or the blade width up to $\psi = 0.15$ can be obtained, while a system of deflectors behind the impeller makes it possible to raise ψ up to about $\psi = 0.4$. For still higher ψ it is advisable to

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[*] p_1 = pressure before the fan; p_2 = pressure behind fan.

[**] This corresponds to the propeller load factor, also denoted by c_s. (See Flachsbart on propellers, ch. 1, sections 1 and 3, vol. IV, 3.) In the regulations for performance testing of fans and compressors, published by the Society of German Engineers (2d edition, Berlin, 1926), the reciprocal value $J = 1/c_s$, is used.

use a multistage fan with inserted guides. The appropriate amount of blade angle, measured at the outside radius, ranges between $\alpha = 15^\circ$ and $\alpha = 40^\circ$. Referring to figures 9 and 10, are two reliable fans: one for low, the other for high loading. The pressures produced by these two fans are graphed in figure 11. The efficiency of correctly designed fans of this type ranges between 0.7 and 0.85.

As to the fan noise, especially in high-speed wind tunnels, the following may be said: At high rate of motion, the individual blade makes a whistling or hissing noise so far as it moves through a homogeneous air mass. This part of the noise, however, is, in most cases, not audible for the sound produced when the blade whirls through inhomogeneous air, as a result of which there is a change in pressure on the wheel with every change of inflow velocity which moves as sound wave. According to small-scale experiments a propeller causes very little noise provided the inflow is fairly uniform (reference 10). The introduction of a bar into the inflow so that the eddies, set up by the bar, strike the fan, is immediately followed by an audible sound whose frequency corresponds with the time sequence of the propeller blades. In analogy herewith the principal part of the wind tunnel fan noise should be so visualized that all inhomogeneities of the stream are bisected by the propeller blades followed by a sound impulse at each cutting through. This is also the reason why the noise of the blades predominates most in the uproar. Naturally the resonance of these sounds plays an important role since the wind tunnel acts as a resonator.

Note.- The principal pressure differences on a blade occur with adhering flow on both sides as a result of such inflow disturbances which produce a change in angle of attack. If v is the speed of the blade and w a velocity variation athwart the blade motion, the variation of the angle of attack is $= w/v$, that is, the pressure variation at one of the two sides of the blade is approximately

$$\Delta p = \frac{1}{2} \frac{d c_a}{d\alpha} \frac{w}{v} \frac{\rho v^2}{2} = \text{number } \rho \; v \; w$$

Considered as plane wave this pressure variation is equivalent to a velocity of sound of

$$u = \frac{\Delta p}{\rho c} = \text{number } \frac{v\,w}{c}$$

c being the velocity of sound. The sound energy per unit volume is then measured by

$$\frac{\rho\,u^2}{2} = \text{number } \frac{\rho\,v^2\,w^2}{c^2}\,.$$

Usually another question of law of propagation is bound up with that of the plane wave, which supplies a numerical factor of the order of size of blade surface to tunnel section, depending on the local conditions, but which, being constant, is irrelevant for the subsequent analysis. The formula reveals the following: The mere increase in propeller r.p.m. with a given arrangement is followed by increased blade-tip speed and air-stream velocity and consequently, by greater mean velocity variation in the inhomogeneities of the air stream. According to our formula, this interprets as an increase in sound energy with the fourth power of the blade speed. The conditions are somewhat different when the same drawn-in air stream with given inhomogeneity w is one time attacked by a high-speed-low-pitch propeller, and another time by a low-speed-high-pitch propeller. In this case the sound energy obviously rises as the second power of the blade speed when disregarding the effect of the form factor.

However, this relationship is valid only when speed v is small compared to sonic velocity c. When approximated to the sonic velocity the compressibility effect produces yet higher pressures than the foregoing formula stipulates; the noise then becomes utterly insufferable. Besides, there are reasons of strength and efficiency which lead to blade speeds well below the velocity of sound.

With separated flow, that is, attitudes as illustrated in the left-hand part of the curves in figure 11, a change of angle of attack involves only minor pressure changes. Here the blade noise is usually silenced by a peculiar roar which can be explained by periodical breakaway and adherence of the blade stream.

V. PROPELLER DRIVE AND CONTROL

Most wind tunnels are driven by electric motors* and almost exclusively by d.c. motors and Ward-Leonard type of control, which permits speed control in the ratio of 1:10, or higher. Figure 12 illustrates such a hook-up. A driving motor A, usually of the three-phase induction type, actuates a d.c. generator whose field is adjustable within wide limits (for varying the generator voltage). The generator armature is short circuited with the armature of the constantly excited blower - d.c. motor set M - so that the speed of the motor is approximately proportionate to the adjusted voltage. The exciting currents are supplied by a small exciter, E.

The general method of regulation (see fig. 12a) is as follows: A regulating resistance R_1 gives the rough generator control, the influence of the magnetic field circuit of motor M with a resistance R_2, effecting a fine control of the r.p.m. of propeller V. The rough control is generally by hand, the fine control with automatic relay, either the propeller r.p.m. or the dynamic pressure of the air stream being kept constant. The former is obtained, for instance, by actuating an adjustable relay from a small tachometer generator T on the propeller shaft, which short-circuits and releases resistance R_2 in rapid sequence (so-called Tirril regulator). This arrangement is in use in various wind tunnels in the United States.

In the Göttingen wind tunnels the control is, as already stated, effected with dynamic-pressure balances. In contradistinction to the above hook-up, the fine control in the large Göttingen tunnel is not with resistance R_2 in the field circuit of motor M, but with a booster resistance R_1 in series with resistance R_3 and a resistance R_4 hooked up in parallel. (See fig. 12b.) With small resistance R_1 R_3 is principally effective; with large R_1, however, R_4 is effective. (A detailed description of this type of control can be found in Report

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*Occasionally one finds direct-driven internal combustion engines, as in the Zeppelin wind tunnel at Friedrichshafen (airship engines) and in the six-meter wind tunnel at Langley Field, Va. (U-boat Diesel engines).

I of Ergebnisse der Aerodynamischen Versuchsanstalt zu Göttingen, pp. 25-27.) Suffice it to say that the control is entirely automatic, i.e., including the rough control.

If d.c. power supply is available, the r.p.m. can also be regulated by a hook-up as shown in figure 13, which employs a potentiometer for low r.p.m. With switch S open, R_1 is the series resistance; when closed, the potentiometer. R_2 is the series resistance before the magnetic field. Accessibility to 3-wire lines affords still other possibilities. (Compare the hook-up of the small Göttingen wind tunnel, described in Report II, of Ergb. Aero. Vers., Göttingen, p. 2.)

As to the choice between controlling the propeller r.p.m. or the dynamic pressure, it may be remarked that for short, isolated experiments, wherein approximately constant barometric pressure and constant air pressure may be anticipated, both methods are equally good. In extended test programs a change in air density, due primarily to the heating of the air, is to be expected. Then, too, the dynamic pressure changes with constant propeller r.p.m., because of the modified resistance of the test object; for instance, due to changed angle of attack. However, there are times when it is of interest to maintain the same dynamic pressure, namely, when air resistance factors are to be determined, for which it is necessary to divide the recorded forces by the corresponding dynamic pressure. Hereby it is more expedient to divide all data of one test series by the same dynamic pressure rather than by an even only moderately changing dynamic pressure as occurs with constant r.p.m. This is the reason why the dynamic pressure regulation is given the preference at Göttingen. At times the r.p.m. regulation has the advantage insofar as commercially available equipment can be resorted to. Of course, constant dynamic pressure can also be insured with this regulation when the r.p.m. is readjusted at shorter intervals according to the readings of a dynamic pressure indicator.

VI. EXISTENT WIND TUNNELS

Hereinafter follows a somewhat more detailed description of some of the better known wind tunnels. No attempt is made toward completeness or historical aspect other than to show the progress which has been made to the present.*

Regarding the forerunners of the wind tunnels in ancient times, we refer to Flachsbart's "History of Experimental Hydro- and Aerodynamics."

1. The Wind Tunnel of the Motorluftschiff-Studiengesellschaft (Society for the Study of Engine-Driven Airships), Gottingen, built 1907-1908.

When this tunnel was designed, it was a matter of choice between an open type - the air being drawn from the atmosphere and returned to it. - and a circular closed type. But small-scale experiments manifested that, unless the wind tunnel could be housed within a large hall, the closed type was really preferable, because the interference by the outside wind was too severe even on comparatively calm days. The choice fell to the design shown in figure 14. To minimize the flow losses, as well as to guard against interference of the steady velocity distribution, we fitted deflecting vanes at the four corners as shown, slightly exaggerated, in figure 15. The underlying idea was to slice the air stream into so many bands, each band being returned separately in a narrow channel and afterward uniting again.

On the other hand, such vanes can induce eddies which are bound up with the fluctuation of the circulation about the blades, if there are accelerations and decelerations in the flow, such as occur in pulsating air streams. To insure the necessary steadiness for the working chamber, we first mounted a system of guides behind the 4-blade propeller V with large hub so as to divide the downflow over the whole section. Next came a coarse honeycomb G_1 with 10 by 10 cm section channel and metal flaps as in figure 5, at the upsteam end. After the passage through two deflectors, the second of finer mesh than the first, came the fine honeycomb G_2 of straight and corrugated metal strips spaced about 7 mm apart, ahead of which we later fitted a screen S. After prolonged, rather diffi-

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*Practically every civilized country has one or more wind tunnels, some in research laboratories, others in technical universities, etc. A list published recently, cites 19 wind tunnels in the United States alone, which by now may have been increased.

cult attempts in all directions, we obtained a fairly satisfactory uniformity (about $1\frac{1}{2}$ percent velocity fluctuation), but the dust and the oxidation of the screen, together with certain other causes, made the obtained uniformity very short-lived, and necessitated repeated readjustment. The velocity distribution was recorded with a static pressure gage, which could be moved horizontally and vertically across the whole channel section and which was connected to a recording cylinder. (This applies to both regulating work and model testing, as basis for the air speed used in computing the air resistance coefficients.) The space between propeller and fine honeycomb being made as tight as possible, while the experimental chamber was intentionally made untight,* the pressure in the channel was the same as in the observation room.

Owing to the high resistance of the narrow honeycomb and the screen combined with the vitiating propeller design, the speed with a 34 hp. motor barely reached 10 m/s. But aside from these shortcomings, the plant operated satisfactorily and remained up to 1917, the only public laboratory in Germany. A detailed description may be found in Z.V.D.I., vol. 53, 1909, p. 1711, as well as in different Yearbooks (1907-8 to 1912-13) of the Motorluftschiff-Studiengesellschaft.

2. Eiffel Tunnels at Champ de Mars, near Paris and at Auteuil, built in 1909 and 1911, respectively.

These wind tunnels operate, as already mentioned, with an open jet accessible from the experiment chamber. The latter is under negative pressure during operation. The air stream is circulated as a propeller draws air from the suction chamber, thus allowing an identical amount to enter therein via a funnel-shaped cone, and to pass through in the form of an open jet. In the first provisory plant at Champ de Mars (fig. 16) a centrifugal fan was used; in the final design at Auteuil (reference 11), a helical fan. (See fig. 17.) At the left is the entrance cone with two honeycombs G_1 and G_2, at the right an enlarged passage with propeller V and deflectors at the end. The sectional enlargement serves to minimize the exit energy of the air which must be considered lost. The result is that the

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*Provided with an open slot across the entire length of the test chamber, for inserting the Pitot bar.

propeller output is only about one third of the theoretical air output ($\rho \frac{F w^3}{2}$ with F = jet section, w = jet velocity). The diameter of the experimental air stream at Champ de Mars was at first = 1.50 m (4.92 ft.), subsequently = 2.0 m (6.56 ft.), the speed = 20 m/s (65.6 ft./sec.), respectively 12 m/s (39.4 ft./sec.), with 68 hp. motor. The jet in the Auteuil tunnel was = 2.0 m, the motor of 60 hp., and the speed, 32 m/s (104.9 ft./sec.). Incidentally, the Auteuil laboratory housed, besides the main tunnel, also a copy of the modified Champ de Mars tunnel, but whether it was ever actually used, the writer does not know.

Inasmuch as the air entering the hall from the experiment chamber is left to itself and the irregular shape of the hall containing divers installations undoubtedly produces considerable turbulence, the air is apt to arrive before the entrance cone with a fairly unsteady velocity distribution both as to time and space. The honeycomb appears to have been fitted later on to effect somewhat better stream conditions. The stay in the suction chamber is somewhat uncomfortable, especially at high air speeds, although the system seems to have proved satisfactory in Paris, as well as at other places where this type has been used.

A larger, modern version of the Eiffel type is found at Issy les Moulineaux (fig. 18), built in 1923, with an entrance-cone diameter of 3.0 m (9.8 ft.), and a maximum speed of approximately 80 m/s (262.5 ft./sec.) with 1,000 hp. power plant. E. Rothé gives a description in his "Cours de physique, part III - Aérologie et Aérodynamique," (Paris, 1928), p. 258.

3. The N.P.L. Type and Related Designs

A special system of closed-jet type wind tunnel has been developed by the National Physical Laboratory at Teddington, England. The first design, built in 1912 (reference 12), was 4 feet square in section. Air was drawn into the cone-shaped mouth from a large room, and passed through a honeycomb into the experiment chamber. After a small enlargement follows a conventional propeller and behind that, to mitigate the exit of the air, a long trunk or cage of fairly closely spaced wooden strips, between which the air re-enters the room. This insures negative pressure in the experiment chamber relative to the observation chamber; for which reason, this wind tunnel must be kept very tight.

Numerous wind tunnels in England and the United States have been built after this pattern, some with 4 foot square in section, some with 7 foot square in section. One particularly large tunnel at Teddington, was 7 by 14 foot section, with two propellers mounted side by side (fig. 19). (See reference 13.) With its two 200 hp. motors, its top speed was 30 m/s. (98.4 ft./sec.).

One particular feature of this design is the cellular wall (of brick masonry), which divides the building in two rooms. The air upon passing this honeycomb wall, is further damped down and thus reaches the suction cone in much steadier attitude. There is also a honeycomb ahead of the propellers which should enhance the time uniformity.

A new version of the 7-foot tunnel is illustrated in figure 20 (reference 14). The exit cone is larger and the trunk has been removed, evidently, since the honeycomb wall insures sufficient quiescence. The wind tunnels are built of wood and iron and presumably represent the cheapest construction of this kind.

Similar tunnels to figure 20 have been built elsewhere to a considerable extent, some of round section. Of course, the square section has the advantage of allowing greater freedom of movement of the personnel when the floor is level and the walls vertical. On the other hand, the round section offers less frictional surface. Representative of this type are the wind tunnels at the Saint Cyr Aerotechnical Institute (reference 15), at Rome, (reference 16) and various American universities.

4. The Aerodynamic Institute of the Technical University, Vienna

This wind tunnel (reference 17) is also of the open-jet type but employs pusher propellers and a dome-like system of deflecting vanes instead of entrance cone and honeycomb (fig. 22), thus converting the radial inflow into a unidirectional stream. In contradistinction to all others the air stream is vertically downward (fig. 21). The open jet, indicated by arrows, is in the cellar and under atmospheric pressure. The air passes through the diffuser and the exit-cone flare in the cellar, whence four helical fans at the four corners with connected diffusers carry it to the attic, which is under negative pressure, and from there, after the flow has become somewhat quiescent, through the large opening to the roof-shaped system of guide vanes. The octagonal entrance-cone section is about 2.5 m^2 (26.9 sq.ft.), its over-all length = 2.0 m (6.56 ft.), and its maximum width = 1.4 m (4.59 ft.). The maximum speed is 22 m/s (72.18 ft./sec.), with a power plant of 4 by 7.5 hp.

5. The Second Göttingen Wind Tunnel, Erected 1916-17

The first tunnel was, to begin with, only a temporary makeshift, and the design of a new, larger wind tunnel was soon under way. This project underwent many modifications as time went on, although the principle was retained. The circular, closed arrangement of the first tunnel was very satisfactory and without a doubt, superior to the method of drawing air from a room and returning it to it, on account of the enhanced uniformity of flow. On the other hand, to avoid the great resistances manifested in the first tunnel, the return flow, the deflection around the corners and the spatial comparability through honeycomb, etc., had to be effected with lower speed; that is, larger section which, of course, involved higher construction costs. The transition from this larger section to the working section next to the experiment chamber led, moreover, to the advantages cited in section II, as far as local uniformity was concerned. Preliminary experiments had proved the superiority of the open- over the closed jet (reference 18). Since the air was to flow in a closed passage while passing from propeller to entrance cone, no negative pressure chamber of Eiffel's type was necessary; on the contrary, the open jet could be allowed to pass into the open hall as in the installation at Vienna. The return flow, then, was, of course, under negative pressure. The circulation was first projected on a horizontal plane (lateral return next to the experiment chamber). But at the suggestion of my then coworker, H. Thoma, we decided to dispose the circulation in a vertical plane so as to bring the return vertically beneath the working chamber. The necessary height of the whole structure was taken care of by building the parts under positive pressure of reinforced concrete. The return passage was about 2 meters below the ground. The vertical arrangement made the working portion very accessible from all sides. The test equipment is mounted on rails with turntable (fig. 23). The jet section is 4 m^2

(43.05 sq.ft.) (~~diameter of~~ inscribed circle of the 16-cornered bell mouth is 2.24 m (7.35 ft.)). The section in the closed tunnel increases consistently in the flow direction up to the entrance cone, reaches 7 m^2 (75.35 sq.ft.) at the propeller and 20.25 m^2 (217.97 sq.ft.) 4.5 by 4.5 m (14.76 by 14.76 ft. square) in the maximum section at the honeycomb. It is very important that the open jet be exactly level when effecting the measurements. With this in mind the entrance D was made rotatable through a few degrees. The deflecting vanes are of airfoil design with round leading, and sharp trailing edge. They were made of reinforced concrete (the same way as cement pipes are made). The honeycomb consisted of smooth and corrugated metal strip as shown in figure 2c. The speed is 58 m/s (190.29 ft./sec.) with 300 hp. A description of the wind tunnel is given in Report I of Ergb. Aero. Vers., p. 8f.

The described design has been variously copied, at times with horizontal, at others with vertical, return passage. One of the first of these, that of the Zeppelin Works at Friedrichshafen, of 2.90 m (9.51 ft.) entrance-cone diameter (M. Munk, designer) (reference 19), is of the double-return flow type (return passage on either side of the test chamber). The same arrangement is found in the large wind tunnel of the National Advisory Committee for Aeronautics at Langley Field (fig. 24), which also was designed by M. Munk. Other wind tunnels, which were closely patterned after the so-called Göttingen type are found in Japan, as described in Report No. 15, of the Aeronautical Research Institute (Tokio, 1926), and in the California Institute of Technology, at Pasadena (reference 20).

6. Various Recent Designs

The trend of modern wind-tunnel practice is in two directions, namely, large size and change from air under normal conditions to air at high pressure. The first makes it possible to make aerodynamic tests with laboratory accuracy on full-scale fuselages, engine cowlings, tail surfaces, and other airplane parts; and on model wings of large size, which is of the utmost importance for the study of engines and propellers under actual working conditions, as well as for the the measurement of lift and drag. The second (reference 21) makes it possible to obtain with small models the Reynolds Number of large-scale objects, since in compressed air the density rises but not the viscosity and consequently, the kinematic viscosity varies inversely proportional to the density. The product of velocity times length may be considered as equivalent to 1/20 of the same product for full scale when working with air of 20 atmospheres.

Representative of the first are:

a) The 20-foot propeller research wind tunnel of the National Advisory Committee for Aeronautics, at Langley Field (fig. 24). The air-stream diameter is 6.10 m (20.0 ft.) Its power is 2,000 hp., and the maximum speed is approximately 50 m/s (164 ft./sec.). It is driven by two Diesel engines. In the meantime, another tunnel of still larger size has been built at Langley Field, in which a full-scale airplane may be tested. The oval section is 30 by 60 ft. (9.15 by 18.3 m). An alleged speed of 51 m/s (167.32 ft./sec.) is reached with an 8,000 hp. power plant.

b) Figure 25, the wind tunnel of the Moscow Aero-Hydrodynamical Institute is a peculiar combination of a 3 m (9.84 ft.) and a 6 m (19.68 ft.) tunnel (reference 22). The circulation is closed. The movable section (shaded portion) can be swung aside. In the shaded position the tunnel is closed and ready for operation with the 3 m diameter. The shift of the section into the position indicated by dashes permits the air to pass in the 6 m section direct for experimentation. With the 3 m section a speed of 104 m/s (341.21 ft./sec.) has been reached with 820 hp. minus honeycomb, and 78 m/s (255.90 ft./sec.) with honeycomb, and 30 m/s (98.42 ft./sec.) in the 6 m section. As may be expected, the velocity distribution in the 6 m (19.68 ft.) section is not very good.

c) The only variable density wind tunnel in operation is that of the N.A.C.A. at Langley Field.* The wind tunnel proper is housed within a 54 mm (2-1/8 in.) steel tank 4.57 m (15 ft.) in diameter, and 10.52 m (34.5 ft.) long. It was originally built according to the closed-jet type, but recently redesigned for open jet (fig. 26).** The max-

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*A second tunnel of this kind is being built in England; air-stream diameter 1.80 m (5.90 ft.), inside diameter 5.20 m (17.06 ft.), length 15.50 m (50.85 ft.), wall thickness 63.5 mm (2.50 in.), maximum pressure 25 atm., anticipated speed, 25 m/s (82.02 ft./sec.), according to Engineering, 1930, p. 806.

**Figure 26 shows the tunnel with open jet. The data for this photograph was obtained through the kindness of Dr. G. W. Lewis, Director of Aeronautical Research of the N.A.C.A.

imum pressure is 20 atmospheres, the tank is filled by 300 hp. air compressors. The driving motor is of 250 horsepower, the air stream has a diameter of 1.52 m (5 ft.), and the maximum speed at 20 atmospheres, is 24 m/s (78.74 ft./sec.). All experimental equipment must be automatic, that is, be with remote control. ~~But in spite~~ of this complicity, the tunnel has produced some very valuable results. A description may be found in N.A.C.A. Technical Report No. 227 (reference 23).

d) In view of the requirements incidental to propeller experiments, the inverse principle of the variable density wind tunnel was employed in a more recent Göttingen tunnel which, on the whole, is similar to the large Göttingen tunnel, but in which the open experiment section can be hermetically sealed by means of a detachable cylindrical section. The remaining parts of the tunnel being of sufficient strength as well as air tight, the tunnel can be evacuated to about 1/4 atmosphere, so that an air stream of lower density can be produced. With propellers the blade tips quite often work at or near the velocity of sound, in which case the compressibility of the air becomes very significant. In order to be able to follow the then occurring phenomena on a model, it is necessary to apply the same relative velocities as in a full-scale test. But that involves a fairly high output for the blower as well as for driving the propeller model, wherein the propeller drive in particular, presents experimental difficulties. These objectionable features can be eliminated by lowering the pressure to 1/4 atmosphere, so that the performances also drop 1/4. The wind tunnel can be used with a variety of entrance cones. At air under normal conditions, a 225 hp. output gives a speed of around 57 m/s (187 ft./sec.) for a 1.5 m (4.92 ft.) entrance-cone diameter, and 77 m/s (252.62 ft./sec.) for a 1 m (3.28 ft.) air-stream diameter, at 1/4 atmosphere pressure, a speed of approximately 120 m/s (393.70 ft./sec.) can be obtained with the 1 m entrance cone. These data are provisory because the tunnel has only been put into operation quite recently and its definite structural form has not been decided.

VII. SURVEY ON THE ENERGY CONSUMPTION OF WIND TUNNELS

The useful performance of a wind tunnel consists in bringing a stated air mass to the velocity w required at the experiment chamber. The mass per second is $\rho F w$, the performance per unit mass is $= w^2/2$, hence the performance (work per second) is $\rho \frac{F w^3}{2}$. Now the question is, What other performance is to be produced by the propeller?

In wind tunnels with closed circulation, only the losses need to be covered, and in those with air stream returning in a hall, the speed before the exit through a diffuser (gradual enlargement of the passage) is likewise moderated, so that, as a rule, the required driving power is less than the effective power of the air in the working section. The best conditions for the "efficiency" (effective power in the experiment chamber - absorbed power) are obtained with wind tunnels which, by means of suitably flared entrance cone, draw the air from a hall and return it to the same room after proper enlargement aft of the experiment chamber. Inclusive of that of the fan, efficiencies as high as 3 are normally obtained. (Under particularly favorable circumstances an efficiency of 8 or more is, moreover, possible.) Figuring with the "air power" alone, an efficiency of around 4 (up to 10) is obtained with an 0.75 fan efficiency. This holds true for wind tunnels of the closed-jet type; provided the parallel piece is not too long, the diffuser is very satisfactory, and the energy consumption of the honeycomb is low. The open-jet type, whether of the so-called Eiffel or Göttingen type, produces additional losses as a result of the coalescence of the open jet with the surrounding air, which become so much greater as the open air stream is longer with respect to its diameter.* The

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*According to unpublished Göttingen measurements on a model wind tunnel of the Göttingen type, there is an approximately linear drop of energy in the open jet. Aft of the entrance-cone flare, at a distance equivalent to the entrance-cone diameter, an energy drop of 8 percent was recorded. Added to this are yet other losses in the diffuser whose functioning is so much more imperfect as the velocity in its entrance section is unevenly distributed.

loss in the honeycombs and in the deflecting vanes of the Göttingen system are relatively low when care is taken to insure a low speed at these points. The pressure losses are from 0.30 to 0.50 of the local dynamic pressure, provided the honeycombs are not too narrow, and of from 0.15 to 0.20 of the dynamic pressure for the vanes when the air stream to be deflected is very homogeneous. With severe inhomogeneities the vane losses can become very much greater, as a result of secondary flows. The losses which occur directly before and behind the fan due to abrupt sectional changes can be minimized by fairing the propeller hub.* The efficiency of open-jet wind tunnels ranges in general, between 1.5 and 2.2, and as high as 3.5 in especially propitious cases.

According to the foregoing, it appears tempting to build wind tunnels for high power with possible high efficiency. But this higher efficiency has also considerable drawbacks. As soon as a nominal part of the power is absorbed in the form of resistance energy by a model in the wind stream, the velocity of the air stream drops, and indeed, so much more as the losses of the bare wind tunnel are smaller; that is, as the efficiency is higher. Contrariwise, wind tunnels with lower efficiency are less sensitive against additional resistances. This occurs in the following manner: The efficiency of the diffusor is, especially if it is near to the limit of the permitted angle of enlargement, different in the accelerating and in the decelerating period when the velocity fluctuates, that is, the efficiency is better in the acceleration and poorer in the deceleration.** This obviously may cause the deceleration to become greater with decelerations because of increased resistance, whereas conversely, the

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*The use of the propeller fairing (shown in dotted lines in fig. 23) in the large Göttingen tunnel resulted in a 32 percent higher efficiency. The data for the Göttingen tunnel in this report pertain to the attitude with faired hub.

**The reason is that during the accelerating phase, the resultant deceleration in the diffuser is reduced, but increased during the decelerating phase, as a result of which the diffuser with respect to separation of flow, acts one time as a narrower, the other time as a much steeper diffuser.

acceleration may rise during acceleration as a result of the lowered resistances, or in other words, fluctuations from minor causes may be abnormally increased when the characteristic case prevails, and this is then followed by very poor time uniformity, which may develop considerable oscillations. To avoid such interferences, the enlargements aft of the experiment chamber in the Göttingen wind tunnels were intentionally fitted with a step rather than with gradual enlargement, with no regard for efficiency, and in fact, the time uniformity is relatively very good with these wind tunnels.

Translation by J. Vanier,
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COMPARISON OF THE MOST PROMINENT MODERN WIND TUNNELS*

Country	Location (designer)	Built	Dimensions of experimental air stream diameter** (D) m	area (F) m²	Maximum speed of air stream in experiment chamber m/s	Rated horse-power of motor (N)	Efficiency of wind tunnel***	Remarks
Austria	Vienna (Knoller)	1911-12		2.50	22	4x7.5	0.74	Longitudinal section octagonal (figs. 21 and 22)
France	Auteuil (Eiffel)	1911	2.0	3.14	32	61.5	1.40	Figure 17
	Issy les Moulineaux	1923	3.0	7.07	80	1,000	3.02	Figure 18
Germany	Göttingen (Prandtl)	1916-17	2.24	4.00	58	300	2.18	Section 16-cornered (fig. 23)
England	Teddington (NPL)	ca 1920		8.82 2.1x4.2 m (7x14 ft.)	30	2x200	0.50	Figure 19
Russia	Moscow (Central Aero-Hydrodyn. Inst.)	1926	3.0 6.0	7.50 30.00	{104 78 30	} 820	8.5 3.6 0.81	Without honeycomb With honeycomb " } Octagonal section Figure 25
America	Langley Field (NACA)	1926	1.52	1.82	24	253.5	0.74	Variable density wind tunnel maximum pressure, 21 atm. (fig. 26)
	"	1927	6.10	29.25	50	2,000	1.52	Propeller research tunnel (fig. 24)
	Pasadena	1929	3.05	7.30	{77 87}	760	3.6 5.3	Open-jet Closed-jet } Göttingen type
Italy	Rome (Istituto Sperimentale Aeronautico)	1929	1.60	2.01	80	360	2.38	Tunnel No. 2 (NPL type with closed, divided return passage)

* A survey of the older wind tunnels is found at the end of Flachsbart's "History of Experimental Hydro- and Aerodynamics."

** Where the section of the air stream is a regular polygon, hereinafter the diameter of the inscribed circle is given.

*** Definition:

$$\text{Efficiency} = \frac{\text{air power in experimental chamber}}{\text{rated output of motor}} = \frac{\frac{\rho}{2} v^3 F}{75\ N} = \text{average } \frac{v^3 F}{1200\ N}, \quad \text{where } \rho = \text{air density, mean } 1/8 \text{ kg s}^2 \text{ m}^{-4}.$$

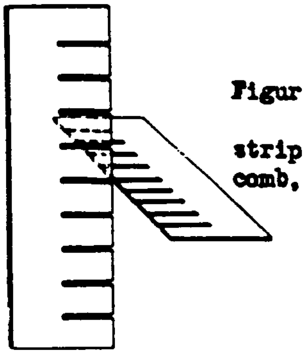


Figure 3.- Crossed metal strip for honeycomb, Fig. 2a

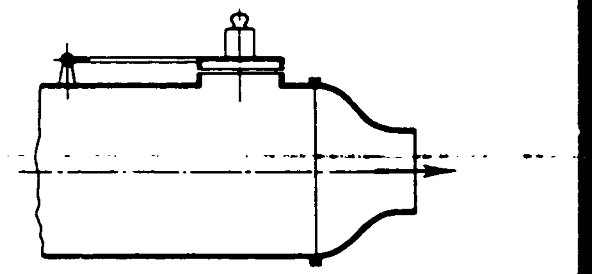


Figure 1.

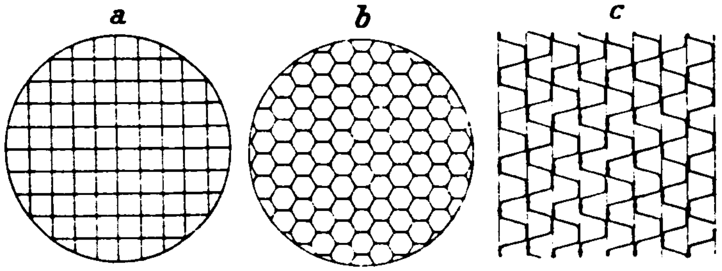


Figure 2.- Various types of honeycombs.

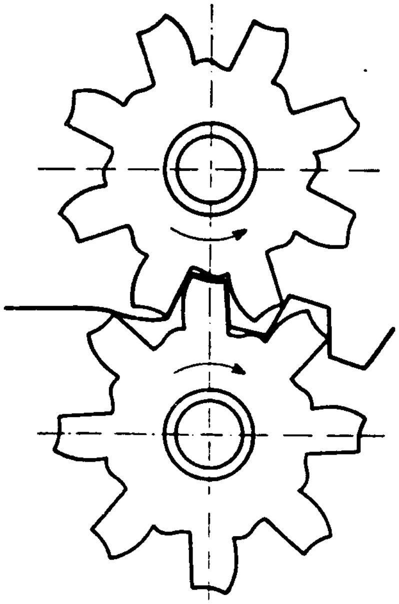


Figure 4.- Rollers for forming strip for honeycomb, Fig. 2c

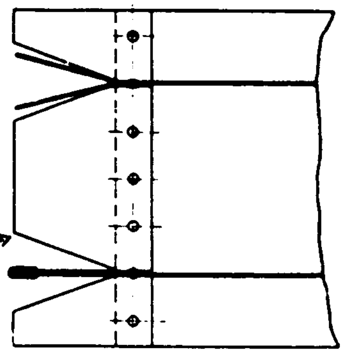


Figure 5.- Sheet-metal flaps for velocity distribution regulation

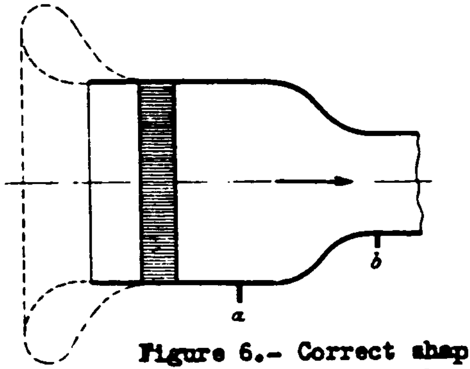


Figure 6.- Correct shape of portion ahead of experimental chamber.

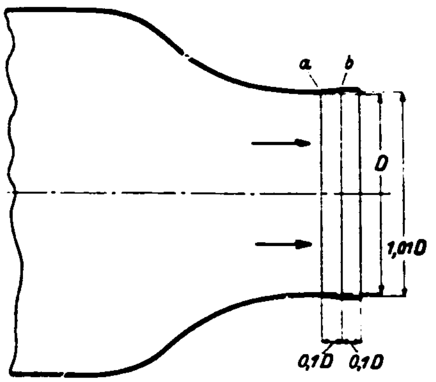


Figure 7.- Entrance cone of Göttingen propeller research wind tunnel.

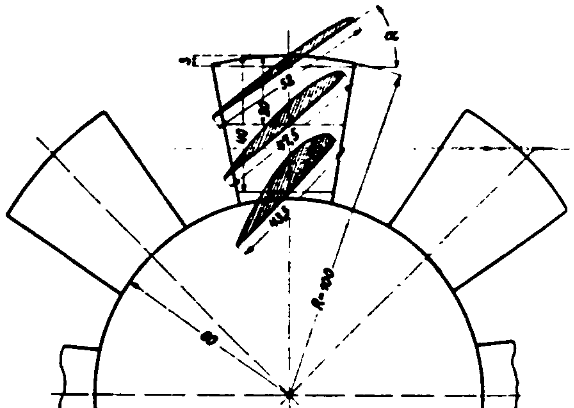


Figure 10.- Propeller-type fan with 8 wide blades for high loading (design: Betz)

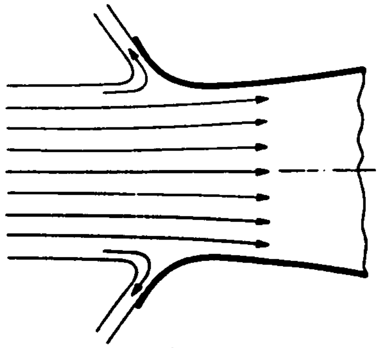


Figure 8.- Flow in the exit-cone flare of a wind tunnel.

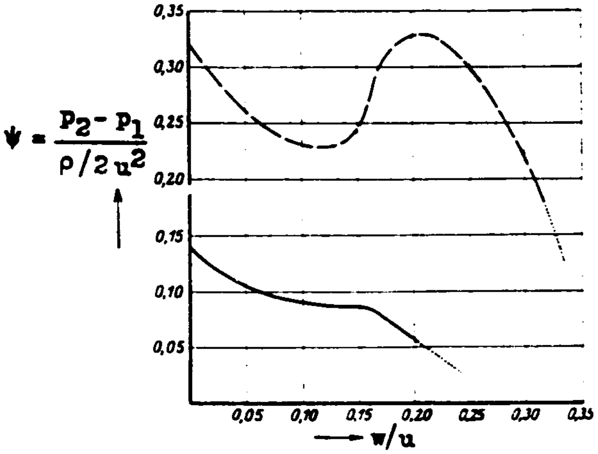
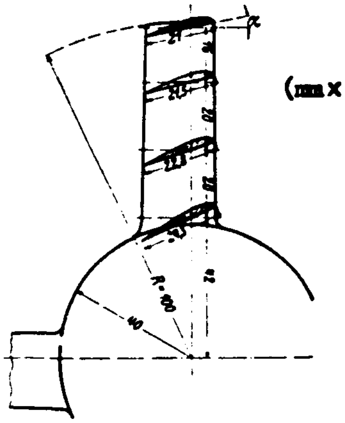


Figure 11.- Fan characteristics

——— For fan according to Fig. 9 with α = 16° (at blade tips)

- - - - - For fan according to Fig. 10 with α = 34°



(mm x .03937 = in.)

Figure 9.- Propeller-type fan with 4 small blades for low (design: Betz)

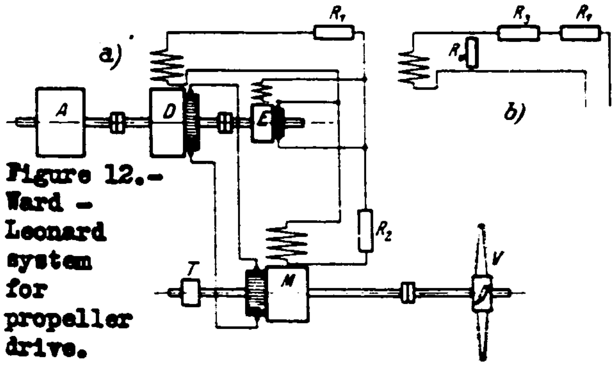


Figure 12.- Ward - Leonard system for propeller drive.

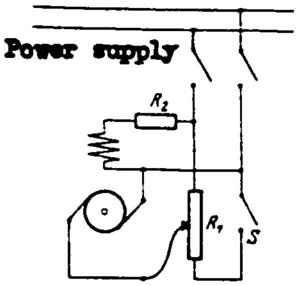


Figure 13.- Hook up for regulating propeller r.p.m. for D.C. power supply

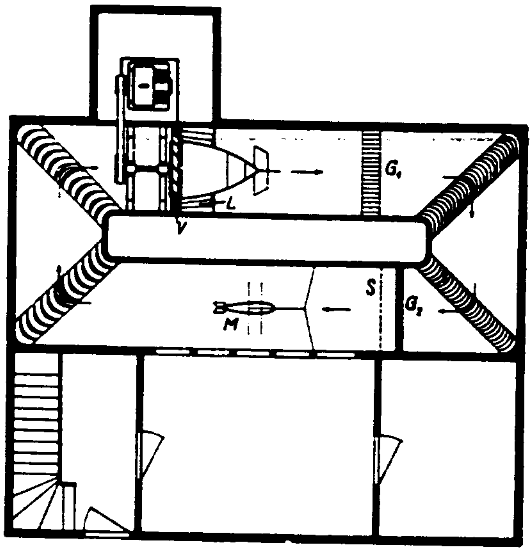


Figure 14.- First Göttingen wind tunnel.

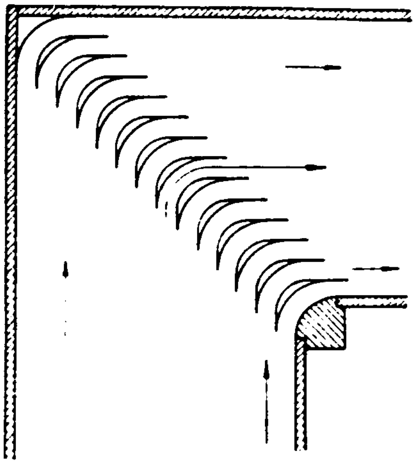


Figure 15.- Deflecting vanes

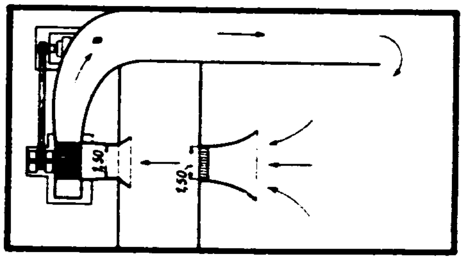


Figure 16.- Eiffel wind tunnel, Champ de Mars

(m× 3.28083= ft.)

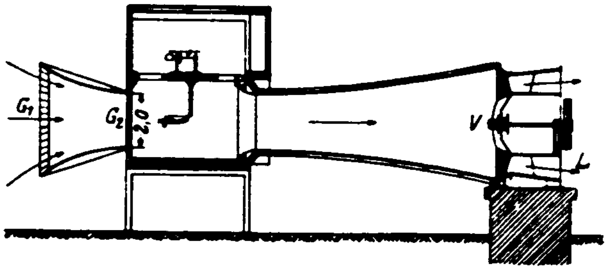


Figure 17.- Eiffel wind tunnel, at Auteuil.

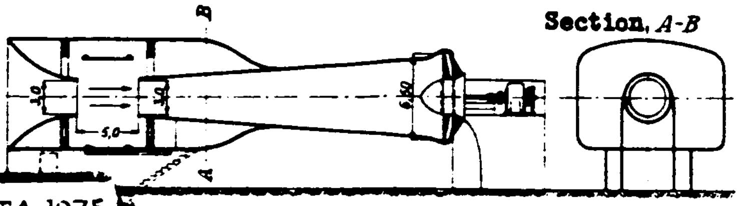


Figure 18.- Wind tunnel at Issy les Moulineaux

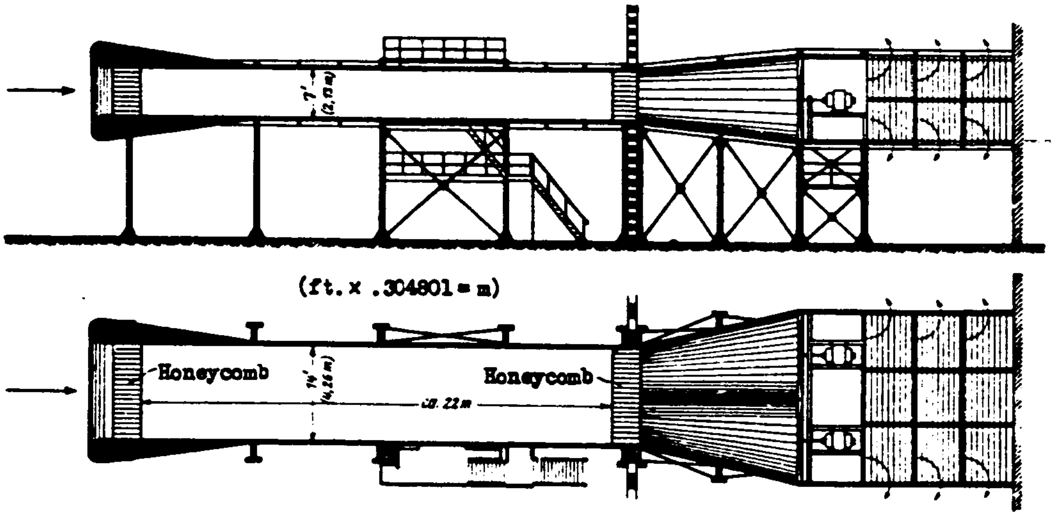


Figure 19.- The 7 x 14 foot wind tunnel of the National Physical Laboratory (N.P.L.) at Teddington

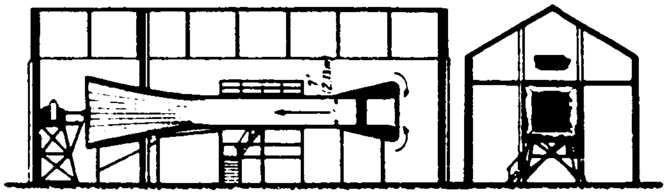
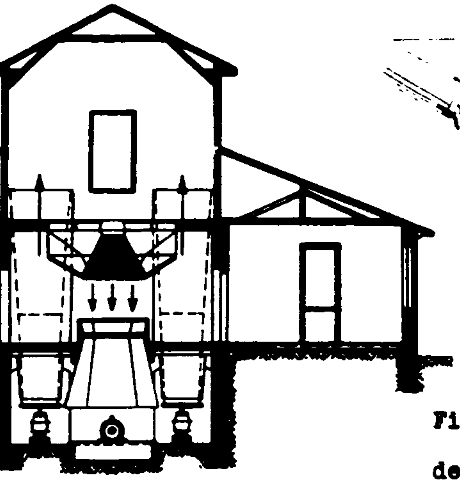


Figure 20.- New 7 x 7 foot N.P.L. wind tunnel

Figure 21.- Wind tunnel of the A.L. Wien



(m × 3.28083 = ft.)

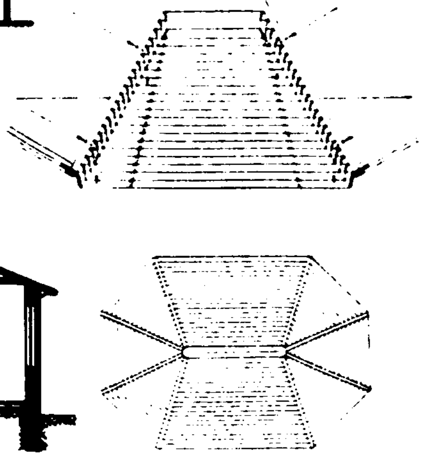


Figure 22.- Roof shaped system of deflecting vanes in wind tunnel, Fig. 21, replacing entrance cone and honeycomb

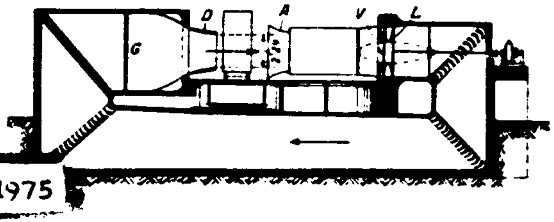
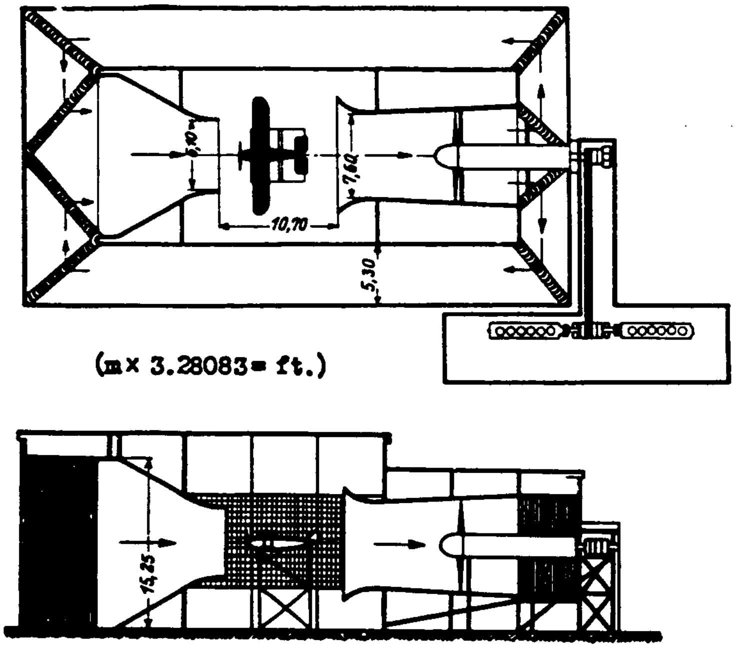


Figure 23.- Large Göttingen wind tunnel



(m× 3.28083= ft.)

Figure 24.- The 20 foot N.A.C.A. wind tunnel at Langley Field, U.S.A.

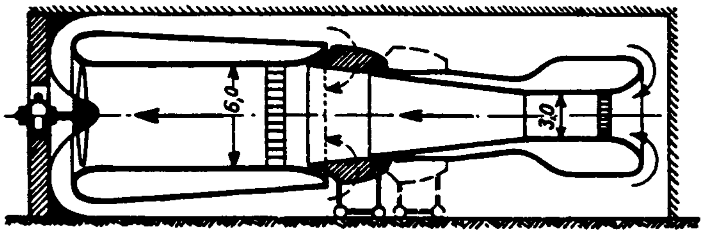


Figure 25.- Combined 3 m and 6 m wind tunnel at Moscow.

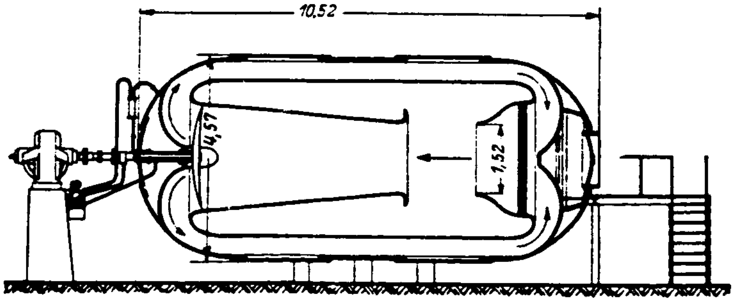


Figure 26.- Variable density wind tunnel, N.A.C.A. at Langley Field, U.S.A.