

AN EXPERIMENTAL INVESTIGATION OF BOUNDARY LAYER WITH ADVERSE PRESSURE GRADIENT*

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ABSTRACT

A test chamber was manufactured having rectangular cross section with a shutter covering having controllable opening. Two slots in the side walls allow continuous detections along the whole "floor." Measures of turbulent intensity and of intermittence factor are reported. Between the free stream and the turbulent boundary layer, each with its own level of turbulence, there is an intermittence layer, not revealed by the Pitot tube.

WIND TUNNEL

A working section was made suitable to many research fields, particularly for studying the boundary layer along a surface either flat or curved, with or without pressure gradient, at a temperature equal to or different from the ambient temperature.

Through the suggestion of the Prof. C. Ferrari, director of the Institute of Aerodynamics, in order to obtain an adverse pressure gradient on the wall, the Clauser method¹ was used. The ceiling of the working section is formed with shutters, the opening of which is adjustable (Fig. 1).

The cross section of the working section is 0.56×0.66 m, and its useful length is 5 m. The fan of a small wind tunnel with closed circuit, already existing in the laboratory, was used and fitted for this purpose; it can be seen at the bottom of Fig. 2.

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The connection between the wind tunnel and the test chamber occurs by means of

(a) a rubber joint to avoid mechanical vibrations (another mechanical insulation has been obtained by placing some rubber layers between the frames and the working section),

(b) a diffuser, and

(c) a double effuser. A double two-dimensional effuser has been used, because it does not exist in theory a good three-dimensional effuser having rectangular

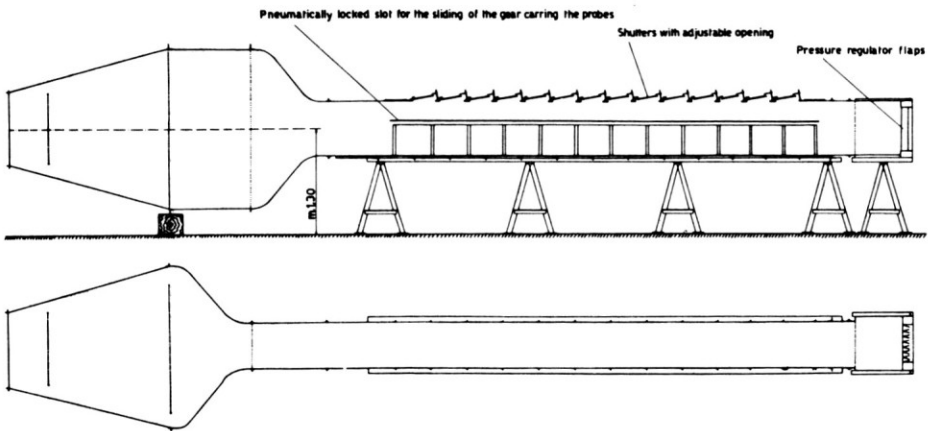


Fig. 1.

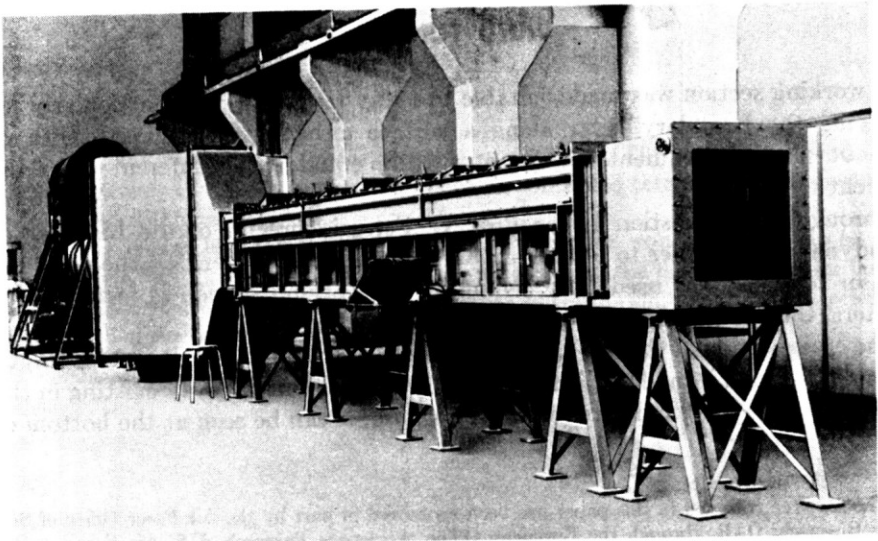


Fig. 2.

cross section; furthermore, the double two-dimensional effuser is of simple design and controls the flow after the first effuser. Between the two effusers a gauze screen was placed having very high mesh.

Owing to space, the diffuser which serves also to change the circular section into a square one, has a high angle of divergence (30°); to avoid the flow separation two gauze screens have been set up inside, one at the inlet and another at the outlet. The gauze screens do not fill the whole cross section but leave the path free along their perimeter. Some openings were also left in the four terminal edges of the diffuser, closed by thin foam-rubber layers, which permit slow drainage of the stagnating fluid.

WORKING SECTION

In order to make the flow two-dimensional insofar as possible, the shutters of the ceiling are provided with side flaps (Fig. 3) in such a manner that when these are opened the flow exhausting is maintained parallel to the wind-tunnel axis. In order to maintain as far as possible the symmetry of the flow, the whole wind tunnel is symmetric with respect to the vertical plane.

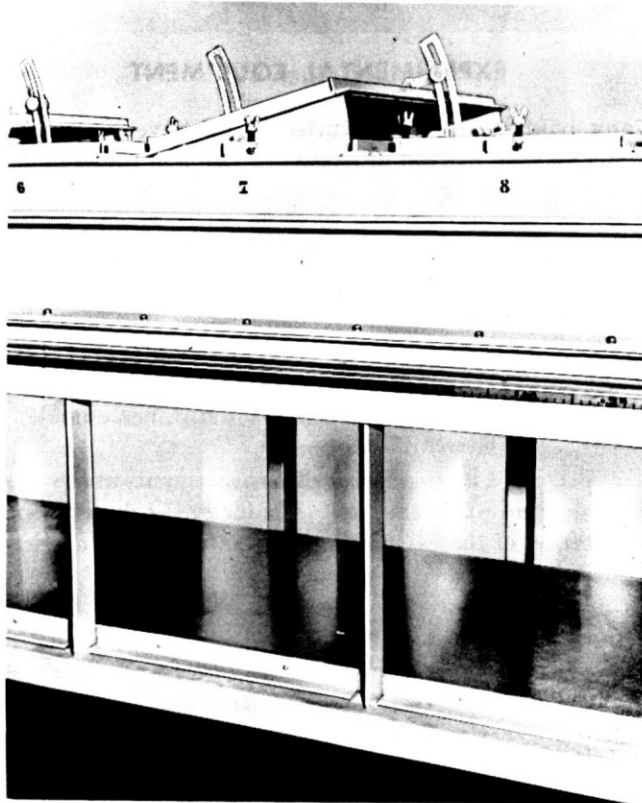


Fig. 3.

The shutters are made with a double frame, so that when they are lowered and tightened by means of restraining screws the inside of the wind-tunnel ceiling is smooth and without recesses or projecting surfaces.

The side walls of the working section are made in two portions, separated from each other by an 8-mm slot (Fig. 3) which permits the probe-supporting gear to slide so that a continuous analysis of the boundary layer is possible.

The slot shutting occurs rapidly by pneumatic means, by inflating at constant pressure (0.8 kg/cm^2) a rubber pipe contained in a channel.

The lower region of the side walls is made by transparent Plexiglas plates (Fig. 3).

The floor of the working section is formed with a smooth flexible masonite sheet; the bolts fixing the plate are long enough to permit, if desired, a slight bending of the plate. The upper portion of the plate is a divided panel, which can be easily replaced.

At the end of the working section there is a pressure regulator which is formed by a chamber closed by two sets of orientated flaps controlled by a wheel. In order to obtain a very precise pressure regulation, the flaps are turned by couples, one against the other. If the effuser with flat walls were a perfect effuser the regulator would be a perfect pressure regulator—that is, it would give a uniform pressure adjustable with great accuracy.

EXPERIMENTAL EQUIPMENT

To avoid any boundary-layer disturbance we have preferred to bring the probe down from the top instead of passing it through the boundary-layer wall. The device has guide arms that move in the slot of the side walls, and carries a hot-wire probe, a Pitot tube, and a thin bar (Fig. 4). The latter serves to measure the distance of the hot wire and of the Pitot from the wall. When the bar comes in touch with the plate it actuates a microswitch which lights a lamp; the probe, however, is still free to move, since a mechanism prevents the bar from traveling too low. The device is calibrated outside of the wind tunnel so that when the lamp is switched on, the exact distance of the wire from the wall is known. A driving-gear readout arrangement transmits the distance outside, which is read on two dials, with an accuracy of 0.2 mm.

The need for effecting a large number of measurements at low wind speeds has resulted in some design improvements to the inclined-tube manometer that will help avoid elaboration of the experimental data. The manometer is described in a paper which will be published in *l'Aerotecnica*.*

For the turbulence measurement we used an HWB2 hot-wire anemometer made by the Flow Corporation, Arlington, Mass., which is fed by a stabilizer Sorensen 1000 S and connected with an oscilloscope Tektronix Type 502 (Fig. 5). The measurements of the intermittence factor were made by means of an apparatus executed by SICAR of Turin,² fed by a Nobatron Feeder and connected with a Hewlett-Packard 523B electronic counter. The oscilloscope recording was obtained by a Hewlett-Packard oscilloscope camera Model 196A with Polaroid Land film Type 47.

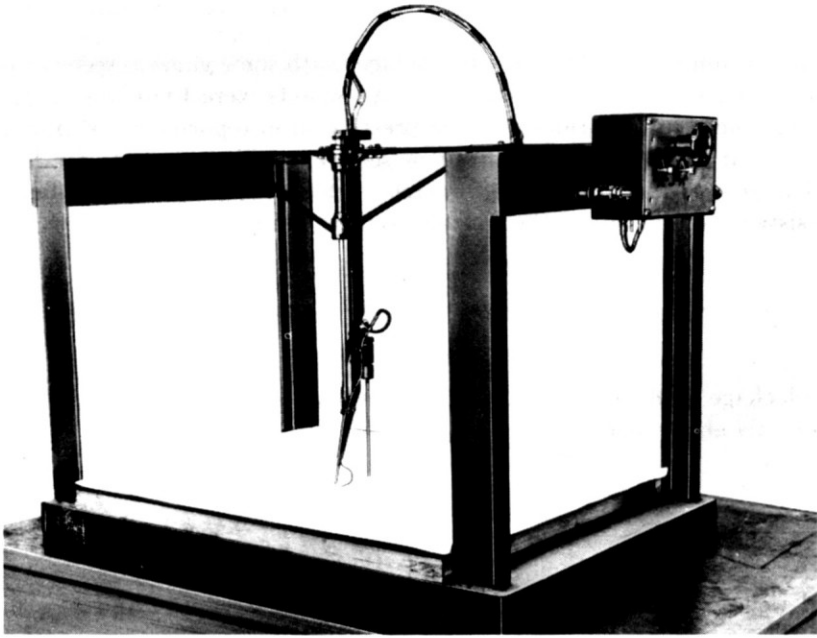


Fig. 4.

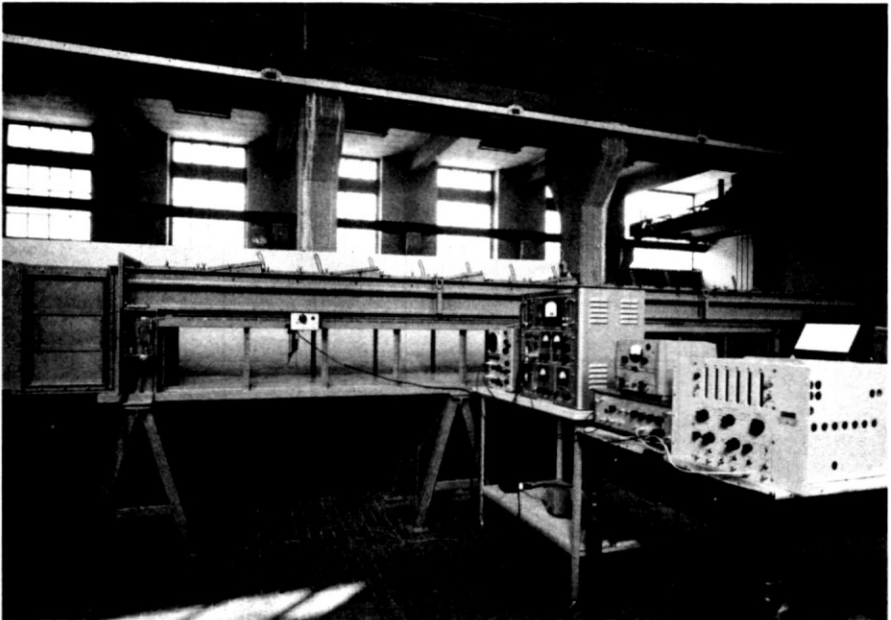


Fig. 5.

PRELIMINARY RESEARCHES ON THE USE OF GAUZE SCREENS

As we had planned to build a pressure reducer with some gauze screens at the end of the working chamber, preliminary experiments were therefore made in order to see whether the formula for the pressure drop reported by Pankhurst and Holder³ for speeds higher than 10 m/sec were still acceptable for lower speeds. The answer was affirmative for high values of the blockage coefficient.

The resistance coefficient of the gauze screens is defined by

$$c_r = \frac{p_1 - p_2}{\frac{1}{2}\rho U^2}$$

and the blockage coefficient β is the ratio of empty to full surface.

The formula above mentioned

$$c_r = \frac{1 - \beta}{\beta^2} \quad (1)$$

appeared well approximated for gauze screens having $\beta = 0.72$ and $\beta = 0.36$ (Fig. 6). The experimental points shown in the figure are the average of the three measurements made at different speeds (between 3 and 8 m/sec.).

On the contrary, for a gauze screen having $\beta = 0.16$, Eq. (1) gives values that are quite excessive.

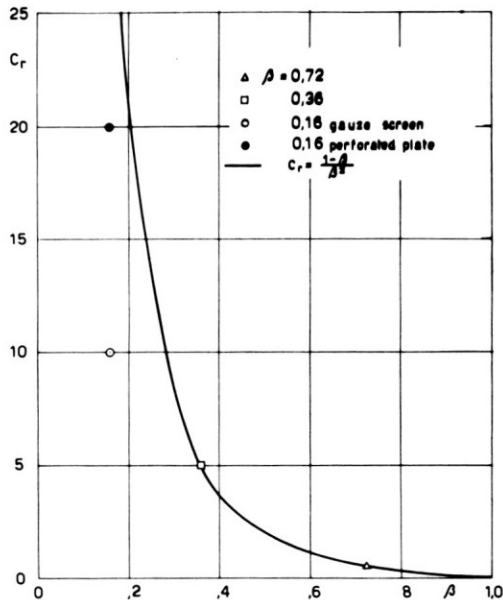


Fig. 6.

The fourth experimental point in Fig. 8 show the fall of pressure through a perforated plate with hole having a diameter of 1 mm, center distance of 2.2 mm, and $\beta = 0.16$. It has therefore the same blockage coefficient as the last gauze screen, but produces almost twice the pressure drop of the latter. This shows that the parameter β is no doubt the main parameter that influences the drop of pressure when the gauze screens are compared with one another, but if different gauze screens are used, the hole shape also becomes important.

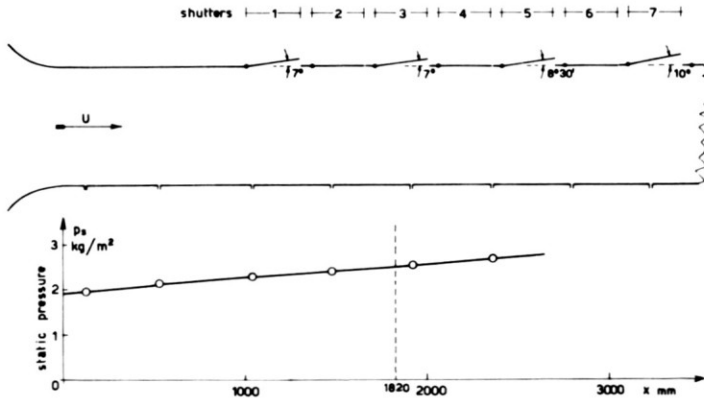


Fig. 7.

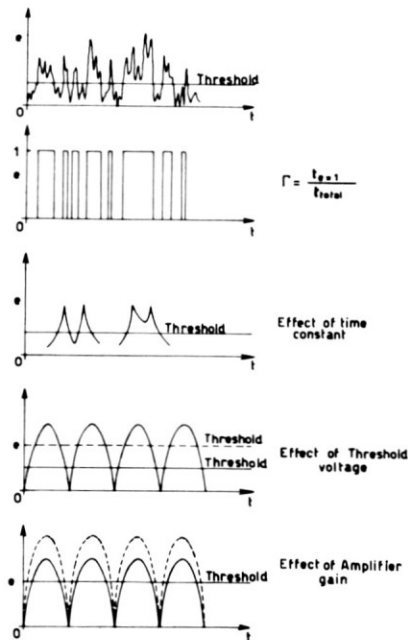


Fig. 8.

PRESSURE GRADIENT ALONG THE PLATE

The relation between the opening angle of the shutters and the adverse pressure gradient on the plate is unknown. It is known that the openings are interdependent and therefore, as already noted by Clauser, much perseverance is needed to establish on the plate a predetermined pressure-distribution law.

Using the wind tunnel we could ascertain:

- (a) that the opening of the alternate shutter is sufficient to modify in a very precise manner the pressure on the plate. Therefore there was no need to reduce the interval between the shutters as far as possible
- (b) on the side of the shutters a scale was plotted divided in degrees to regulate the inclination; however, it was seen that even a variation of a $\frac{1}{2}$ degree brings a sensible variation on the pressure-distribution law on the plate.

In Fig. 7 are shown the openings that were used to obtain a pressure gradient substantially constant, equal to 0.32 kg/m^3 , in the first 3 m of the plate.

MEASUREMENTS OF THE INTERMITTENCE FACTOR

The instrument for the measurements of the intermittence factor is an electronic apparatus in which the signal at the output of the hot-wire anemometer, amplified and with the phase inverted, is then transformed into rectangular pulses with the value of 0 if the turbulent signal is lower than a preset threshold voltage and with the value of 1 when the turbulent signal is higher than the threshold voltage (Fig. 8).

The intermittence factor of this last signal is defined with mathematical exactness as the ratio, to a time Δt , of the fraction of the time Δt in which the voltage is 1.

However, there is not a one-to-one correspondence between the turbulent signal and the rectangular pulses signal, because the transformation is influenced by three parameters which correspond in the apparatus to three switches—the time constant of the circuit, the value of the threshold voltage, and the amplifier gain.

The three lower diagrams of Fig. 8 make evident the effect that the variation of these parameters produces on the transformation of a signal turbulent in rectangular pulses.

It seems therefore that the value of the intermittence factor may, within certain limits be varied at will. However, that the intermittence factor is a real statistical physical magnitude is shown by Fig. 9 where the factor has been measured for three different positions y of the probe, leaving constant the instrument parameters.

The measurements have been repeated five times, each measurement having a duration of 30 sec. The variation does not seem high when we consider that the motor speed was not constant.

EXPERIMENTAL RESULTS

Some experimental results obtained with the adverse pressure gradient of Fig. 7 are shown in Fig. 10; the three diagrams refer to the "velocity profile" measured with a Pitot tube, to the intermittence factor, and to the longitudinal turbulent intensity.

Analogous diagrams, with zero gradient, will be given as the main comparison parameter is determined—the stream velocity, or the boundary-layer thickness, or turbulent intensity, etc.

The intermittence factor Γ was measured choosing the parameters of the measuring apparatus so as to give $\Gamma = 0$ in the free stream and $\Gamma = 1$ in the boundary layer. *The intermittence layer, which appears in the oscilloscope as due to a casual passage of "spots," is not revealed by the Pitot tube: it ought therefore to be considered exterior to the conventional turbulent boundary layer.* In the intermittence region the turbulent intensity decreases from the value of about 10% in the proximity of the wall, to a value of about 10 times smaller in the undisturbed motion. It is therefore a question of a region of transition between two layers

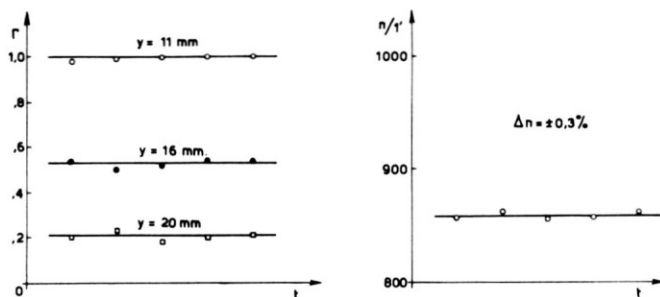


Fig. 9.

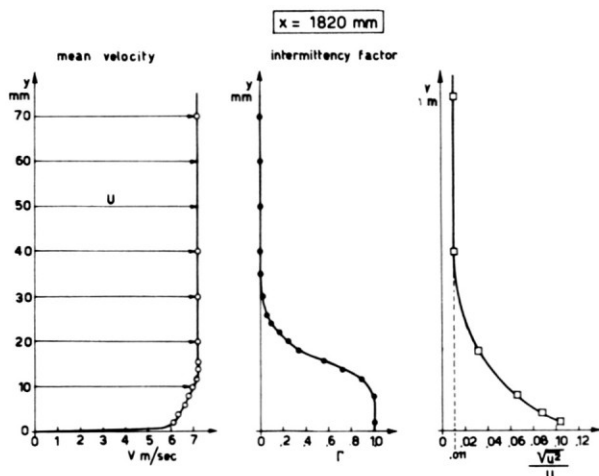


Fig. 10.

having different turbulent level. In this region the root-mean-square of the signal could be measured using the Flow Corporation's random signal Voltmeter. This equipment has a time constant of 16 sec and withstands intensity peaks from 10 to 25 times the root-mean-square.

In the photograph shown in Fig. 11, there can be seen quite clearly the three kinds of signals corresponding to the undisturbed motion, to the transition region and to the boundary layer.

In the photograph of Fig. 12, made in the same conditions of Fig. 11 but with a higher attenuation on the amplifier, the undisturbed motion appears as "laminar"; therefore in the intermittence region the peaks due to the "spots" are clearer. It is perhaps unnecessary to add that these are only two photographs chosen among the many that were made; since the light beam length was 0.5 sec, in some photographs the intermittence region appeared to be full laminar and in some others to be full turbulent.

In Figs. 13 and 14 is shown, under the signal of the hot wire taken in the intermittence region and considerably amplified, the output of the trigger, which gives the signal 0 if the turbulent voltage is lower than the threshold and the signal "1" if it is higher than the threshold. From these oscillograms it appears clear that the *intermittence layer is a region that indicates the passage between two regions having different turbulent levels.*

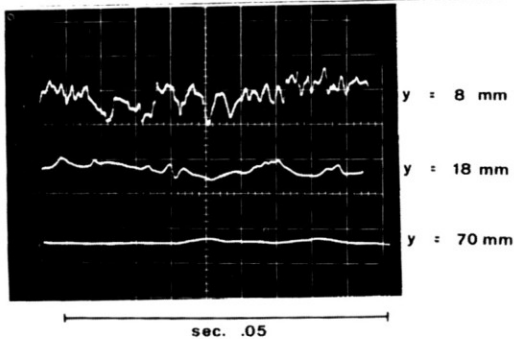


Fig. 11.

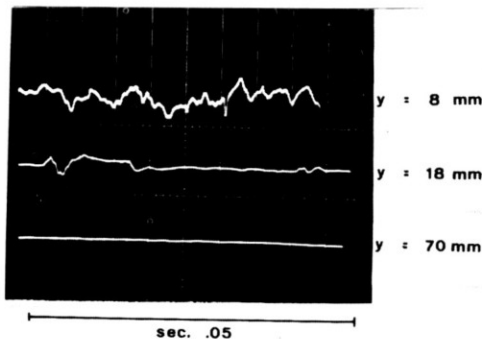


Fig. 12.

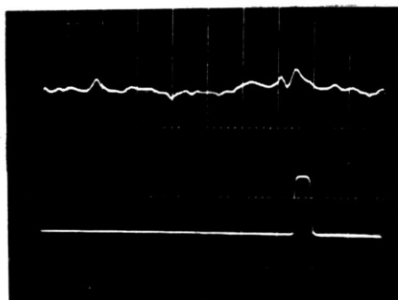


Fig. 13.

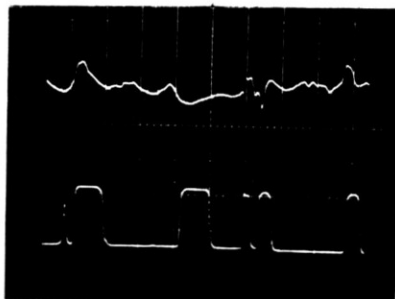


Fig. 14.

CONCLUSION

The building up the test chamber took longer than foreseen. For this reason only the results of the first measures are submitted. Other measurements must still be performed.

Corrsin and Kristler⁴ have given a picture in which the turbulent boundary layer is represented as a region with an irregular, random outline. The following picture (valid for flows with or without pressure gradient) seems to us more effective: far from the wall there is an "undisturbed motion" with its level of turbulence intensity; near the wall there is a turbulent boundary layer with its own level of turbulent intensity, not constant but much higher than that of the free stream. Between the two regions there is an intermittence layer in which the flow is "laminar" as in the free stream, but reached by "spots" of turbulence. These spots are shown by the hot wire, but do not sensibly affect the average speed value. For this reason the intermittence layer is not revealed by the Pitot tube.

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