MODEL LAW AND EXPERIMENTAL TECHNIQUE FOR DETERMINATION OF WIND LOADS ON BUILDINGS

by

NIELS FRANCK
(Copenhagen, Denmark)

1. INTRODUCTION

THIS paper deals with a description of an experimental technique used at the Wind-Laboratory, the Technical University of Denmark, at model tests for determination of wind loads on buildings.

The experimental technique described has permitted to produce turbulent boundary layers in the wind tunnel. With respect to turbulence, the model tests could therefore be brought into agreement with the conditions in nature which is a condition of obtaining accordance between model tests and nature.

2. THE MODEL LAW

The condition of establishing similarity of turbulence in the wind tunnel and in nature is that of the relation between the roughness of the surfaces in the wind tunnel and in nature.

The wind in the layer near the ground is nearly always turbulent the whole way down to the surface.

The turbulence in the flow alone depends on the roughness of the surface when the atmosphere is in a neutral equilibrium, i.e. when there are no thermic contributions to the turbulence.

The velocity profile in a turbulent flow over a rough surface follows the logarithmic formula

$$\frac{v(z)}{v_*} = \frac{1}{\mathcal{K}} \log_e \frac{z + z_0}{z_0}$$

$v(z)$ is the velocity at the height z,
v_* is the friction velocity,
$\mathcal{K} = 0.4$ is Kármán's constant, and
z_0 is the roughness parameter.

The roughness parameter z_0 is a measure of the roughness of the surface concerned and, at the same time, of the turbulence in the boundary layer over the surface so that a more turbulent boundary layer corresponds to a surface of greater roughness.

Fig. 1 shows a velocity profile measured in nature. The abscissa is the relative velocity, the velocity at a height of 100 m being fixed at 1.0. The ordinate is the height above the level of the ground marked out on a logarithmic scale.

In this way the velocity profile becomes a straight line. If the line is extended to intersect the ordinate axis, the value of z_0 is obtained. The profile in *fig. 1* was measured over a cultivated field, and the roughness parameter is $z_0 = 0.95$ cm.

The condition of obtaining similarity between the phenomena in the model tests and the corresponding phenomena in nature is that the roughness parameter for the tunnel bottom, z_0, must be to scale to the roughness parameter in nature, Z_0.

$$\frac{z_0}{Z_0} = \frac{d}{D}$$

where d and D are corresponding dimensions of the object in the tunnel, respectively of that in nature.

Obviously, the model must be entirely immersed in the turbulent boundary layer of the tunnel bottom.

The model law for phenomena in natural wind has been practised at the Wind Laboratory since 1948, where its validity has been demonstrated by experiments for phenomena depending upon the wind velocity, such as shelter effect, as well as for phenomena depending upon the velocity pressure.

The model law was first published by Martin Jensen: Shelter Effect, Copenhagen, 1954.

The satisfaction of the model law necessitates a number of special requirements of the laboratory equipment used.

In the following, an explanation will be given regarding the principles to be observed for the construction of apparatus and experimental technique at model experiments with houses in a turbulent boundary layer.

3. APPARATUS

3.1 Wind Tunnel

The experimental section of the wind tunnel must be closed, and of such length that it is possible to produce a turbulent boundary layer of sufficient thickness over the tunnel bottom.

At the Wind Laboratory tests were made in a wind tunnel of the type with enclosed working section and open return flow. The tunnel which is shown in *fig. 2* is 60 x 60 cm in cross section and its total length is 10 m. The insertion of a 2 m long extra section between sections 1 and 2 permits, however, the length of the tunnel to be increased to 12 m, which was done at the experiments described in this paper.

The experimental section of the tunnel consists of a framework with hatches which together with the frame form the inside of the tunnel. It is provided with honeycombs at each end.

Maximum wind velocity in the tunnel is 32 m/s.

3.2 Tunnel Coatings.

In model tests, to reproduce the situation in nature, it must be possible to establish velocity profiles in the wind tunnel with such roughness parameters as are to scale to those in nature. This has been practised by various coatings of the tunnel bottom.

Below, five tunnel coatings are described as have been applied at our model tests of wind loads on houses.

In all cases the coating extended from the honeycomb at the inlet end of the tunnel to the 4th experimental section (see *fig. 2*). The coating covered the entire width of the tunnel.

The thickness of the turbulent boundary layer corresponding to the tunnel coating evidently increases with the distance from the inlet end of the tunnel.

The thickness, t, of the boundary layer in the 4th section of the tunnel is noted for each of the five tunnel coatings.

Velocity profiles over the tunnel bottom measured in the 4th section have been plotted for each coating on *fig. 3*.

The abscissa is the relative velocity, the velocity at 100 cm level being fixed at 1.0. The ordinate is the logarithm of the height above the surface.

The different tunnel coatings are shown in *figs. 4, 5, 6, 7* and *8*.

Smooth masonite, *fig. 4*. 0.3 cm thick sheets of hard masonite were screwed to the bottom of the tunnel. $z_0 = 1.8 \times 10^{-3}$ cm, t = 12 cm.

Sandpaper, *fig. 5*, was glued to the tunnel bottom. $z_0 = 1.85 \times 10^{-3}$ cm, t = 15 cm.

Corrugated paper, *fig. 6*, was fixed to the tunnel bottom. $z_0 = 0.047$ cm, t = 18 cm.

Broken stones, *fig. 7*. Cubical stones of sizes between 1.5 and 2 cm were distributed over the tunnel bottom. $z_o = 0.21$ cm, $t = 20$ cm.

2.5 x 2 cm fillets. *fig. 8*. Wooden fillets, 2.5 cm in height and 2 cm in width, were fastened to the bottom. The fillets were placed transversely to the tunnel, forming angles varying between 90° and 70° to the longitudinal axis of the tunnel. The mutual distance was varied fortuitously between 15 cm and 25 cm. The velocity profile in *fig. 3* corresponds to $z_o = 0.6$ cm, the thickness of the boundary layer in the 4th section is $t = 28$ cm.

3.3 Pitot-static Tube

The velocity profile of the wind in the tunnel is measured by means of pitot-static tubes and manometer.

Measurements of the velocity profiles in the different boundary layers in the tunnel necessitate the use of a pitot-static tube of such size as to permit measuring of velocities near the surface of the tunnel coating without disturbance of the movements of the air within the area of measurement.

At the Wind Laboratory the pitot-static tube shown in *fig. 9* was used for measurements of velocity profiles.

The two branches are tubes of external diameter 0.1 cm. The short branch is open at the end so that the pressure will there be the sum of the dynamic and static pressures.

The larger branch protrudes 0.3 cm in front of the short branch and is closed at the end but provided with two lateral holes, $d = 0.009$ cm, abreast of the point of the short branch. From these holes the static pressure is taken.

The velocity pressure will thus be registered by a manometer, the two sides of which are connected with the two branches of the pitot-static tube.

The pitot-static tube was mounted in the manner shown in *fig. 10* allowing it to be moved in the vertical symmetry plane of the wind tunnel and adjusted with an accuracy of 0.01 cm.

3.4 Models of Houses

The size of the models placed in the tunnel must be chosen so that the narrowing of the cross-section of the tunnel, due to the placing of the model, will not cause any systematic error in the measurement.

The models of the houses are placed at the bottom of the tunnel, which, in fact, substitute the surface of the ground, and they must be completely immersed into the turbulent boundary layer.

The models used at the Wind Laboratory were made of brass sheets with smooth and plane surfaces. All models were hollow.

The roofs and walls of the models were provided with measuring holes at such a number as to permit the obtaining of a picture in detail of the distribution of the wind load.

The points of measurement in the roofs of the models were located in the greatest number near the corners where experience shows that the largest suction values and the greatest gradients occur.

At the points of measurements thin steel tubes, bore 0.1 cm, were placed normal to the surface of the model. *Fig. 11* shows a section of one of the house models used and a detail of a point of measurement.

To the free end of the steel tube a rubber hose was attached to transmit the pressure to a manometer.

3.5 Turntable

The models of the houses placed in the wind tunnel must be revolved in a convenient way in relation to the direction of the wind.

For this purpose we used a turntable which was placed on the same level as the bottom of the tunnel in the 4th section of the wind tunnel. The turntable has a diameter of 21 cm, and on a graduated scale engraved along the edge, the angle between the direction of the wind and the model could be measured.

The rubber hoses were led from the points of measurement through a tube at the centre of the disk and out of the tunnel to the multimanometer described below.

3.6 Multimanometer

For the sake of survey it is most expedient that the conditions of pressure at several of the holes of measurement of the model could be registered simultaneously. In this way the variation of the load on the surfaces of the model could more easily be surveyed. Hence, a multimanometer is a necessity.

At the Wind Laboratory a multimanometer with 15 tubes was used. The manometer liquid was alcohol of specific gravity 0.80, and the manometer tubes were mounted with an inclination corresponding to a factor of 0.4 of the hydraulic head in mm.

4. EXPERIMENTAL TECHNIQUE

The experimental technique applied at our model tests for determination of the wind load on a model of a house is described in detail in this section.

(a) The turntable is mounted at the bottom of the tunnel in the 4th section and a suitable coating is placed across the whole bottom.

(b) Under the ceiling of the 3rd section of the wind tunnel and above the turbulent boundary layer a Prandtl pitot-static tube is mounted, with

which, in connection with an ordinary FUESS manometer, the velocity of the air flow above the boundary layer is measured.

(c) The velocity profile in the 4th section is determined by means of the pitot-static tube described in section 3.3.

Furthermore, the usually small difference between the static pressure in the turbulent boundary layer at the location of the model, and that at the location of the Prandtl pitot-static tube above the boundary layer is determined.

(d) The model is fastened to the turntable, and 15 points of measurement, distributed for instance over a wall, are connected with the upper ends of the manometer tubes by means of rubber hoses.

(e) The static pressure of the Prandtl pitot-static tube is connected with the top side of the reservoir of the multimanometer.

(f) Preceding measurements proper, a survey of the variations of pressure and suction at the 15 points of measurement is made by observation of the manometer while the model is turned in relation to the direction of the wind.

In this way it is possible to find the points of particular interest with regard to wind load, and also the distribution of the wind load could be determined in the main.

(g) The load at each of the points of measurement is determined as the mean of the loads at different wind velocities.

The loads (pressure or suction) found by the tests are made dimensionless by division with a specific velocity pressure. At all our measurings we have used the velocity pressure which occurs in the turbulent boundary layer at the level of the ridge.

This results in the shape factors for each of the points of measurement.

The velocity pressure at the level of the roof of the model is arrived at as the velocity pressure at the Prandtl pitot-static tube in the 3rd section multiplied with a factor that is determined as the ratio between the velocity pressure at the level of the roof without model in the tunnel and that at the Prandtl pitot-static tube, measured simultaneously.

The computation of the c-values must be corrected for the difference that may occur between the static pressure at the Prandtl pitot-static tube and the static pressure at the model, since it is really the latter that should be applied to the top side of the reservoir of the multimanometer.

Obviously, it would have facilitated the measurings if the pitot-static tube of reference could simply be placed in the actual boundary layer at the level of the roof of the model. The tunnel used at the Wind Laboratory is, however, too narrow for such placing of the pitot-static tube of reference to permit entirely correct results.

5. EXAMPLE OF DETERMINATION OF WIND LOAD

In this section, as an example, test results for a model of a house with desk roof will be brought, comprising investigations in boundary layers with small as well as great turbulence.

The length of the model is 140 mm, the width 70 mm, and the height to the lower eave 70 mm. The inclination of the roof is 1 ÷ 10.

In *figs. 12, 13, 14* and *15* measuring results of wind loads on the top surface of the roof of this model are given. 45 points of measurement were spread over the area of the roof.

The results shown in *figs. 12* and *13* are measured for the model placed in a boundary layer with small turbulence, smooth masonite sheets at the tunnel bottom.

The results shown in *figs. 14* and *15* apply to the model placed in a boundary layer with great turbulence, 2.5 x 2 cm fillets at the bottom of the tunnel.

The shape factors given in the figures are $c = \frac{p}{q} \times 100$, where p is pressure or suction at the point of measurement concerned, and q is the velocity pressure in the turbulent boundary layer, measured at the level of the upper line of the roof.

Curves have been traced through points indicating equal c-values, end extreme point values are stated. Areas signifying suction corresponding to c greater than 40 are hatched with variated shades.

In the figures the shape factors are shown for the positions of the model which are the most interesting in respect of wind loads.

For certain positions of the model, the load on a part of the roof only is given, viz the part for which the load assumes extreme values while for the rest of the roof the load is trivial.

The very great suction values which occur at the corners of the roof for the wind approaching the corner at an angle of about 45° to the walls should be noted. Particularly large suction values will occur when the high corner of the roof is directed towards the wind. Suction values corresponding to c = 420 in small turbulence were measured here.

Also, it should be noted that there are considerable differences between the c-values in the two different turbulent boundary layers, which may serve as an illustration of the significance of the turbulence with regard to the wind loads.

For wind directed towards the high edge of the roof at 45° to the wall it will be noticed that the greatest suction will occur when the model is located in small turbulence.

For wind directions lengthwise or crosswise to the model, the greatest suction will, however occur at the windward edge of the roof when the model is placed in great turbulence.

From this it will appear that maximum loads may occur for the model located in small as well as in great turbulence.

(A complete report of wind load tests will be published at the end of 1963, entitled Martin Jensen and Niels Franck: Model Tests in Turbulent Wind, Part II).

REFERENCES

JENSEN, Martin, Shelter Effect, Copenhagen, 1954.

JENSEN, Martin, The Model Law for Phenomena in Natural Wind. - *Ingeniøren, International Edition*, 1958, 2, 4.

JENSEN, Martin and FRANCK, Niels, Model Tests in Turbulent Wind, Part I, Copenhagen, 1963 and Part II (under preparation).

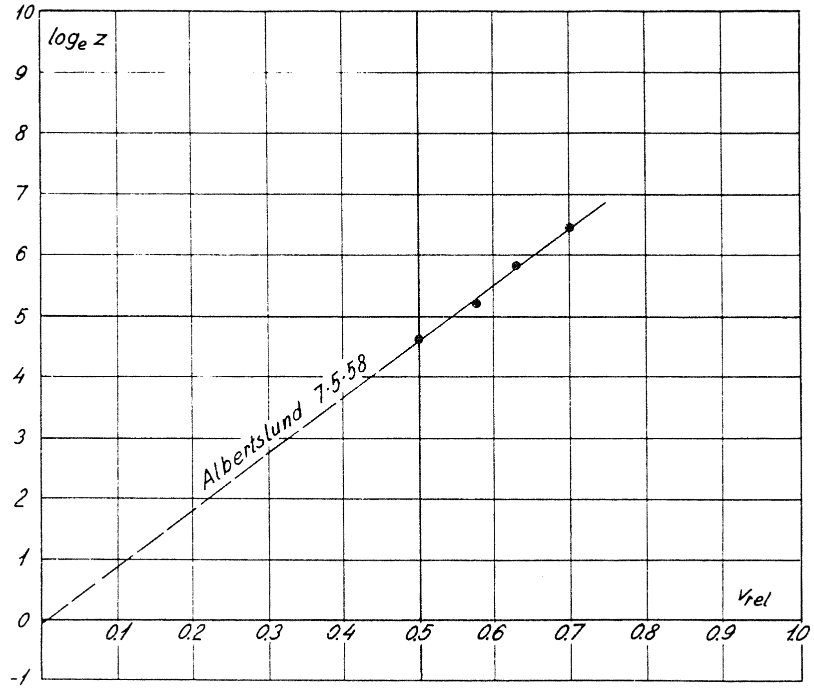


Fig.1. Velocity profile measured in nature.

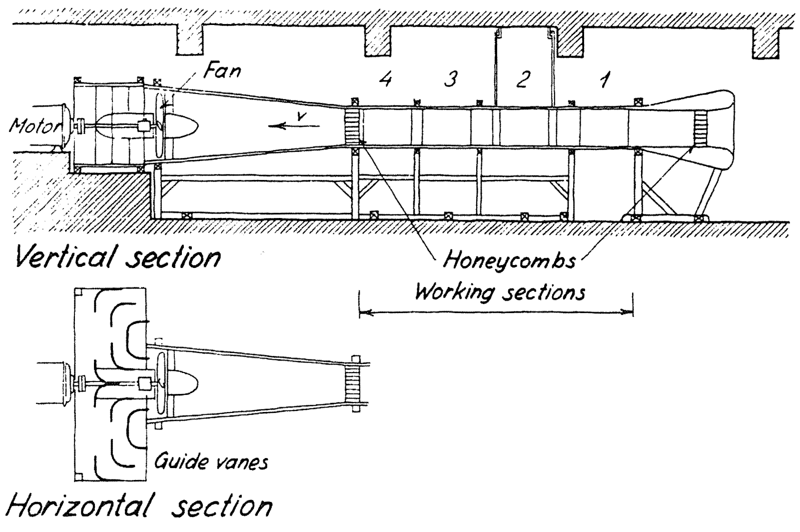


Fig.2. 60 x 60 cm wind tunnel.

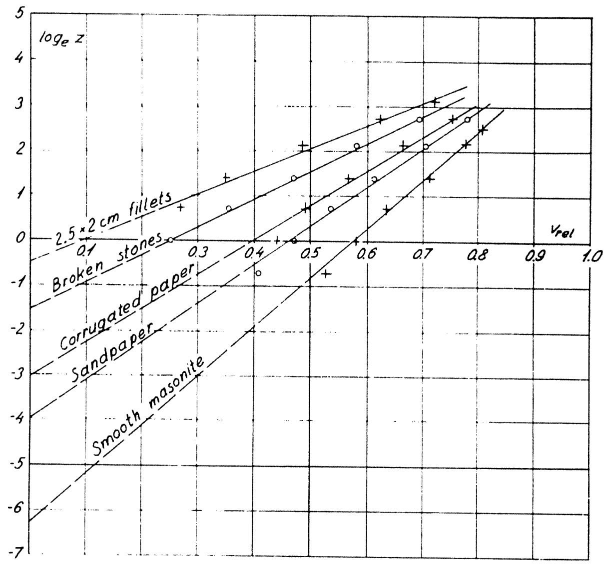


Fig.3. Velocity profiles over five tunnel coatings.

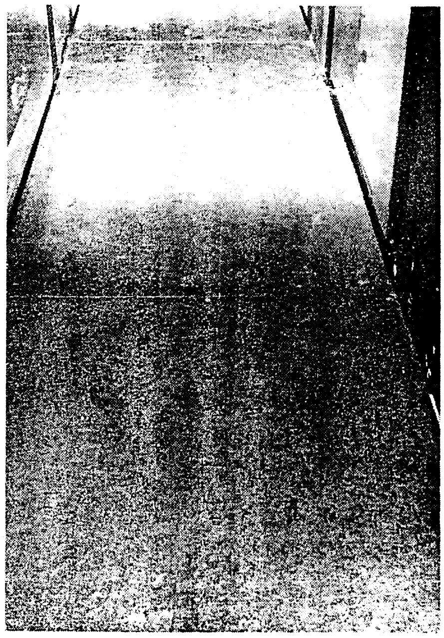


Fig.4. Smooth masonite.

Fig.5. Sandpaper.

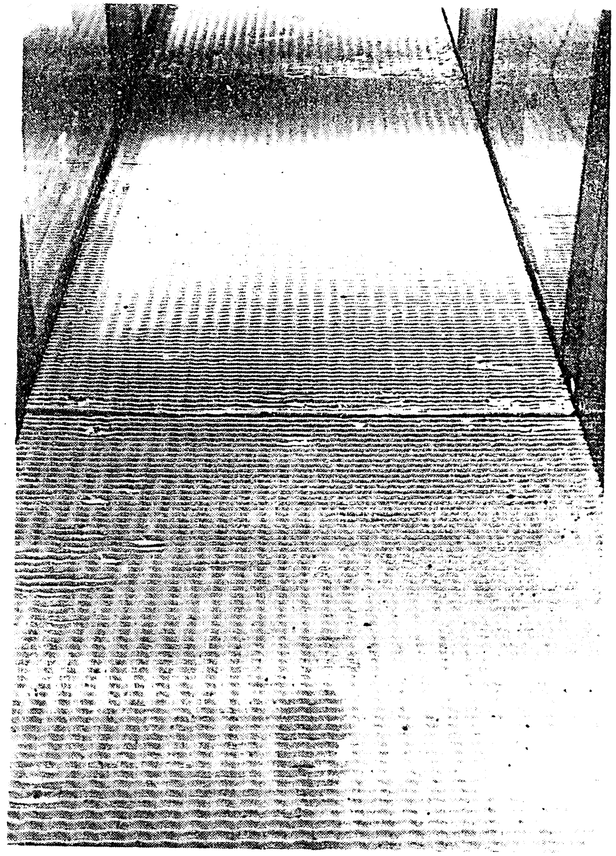


Fig.6. Corrugated paper.

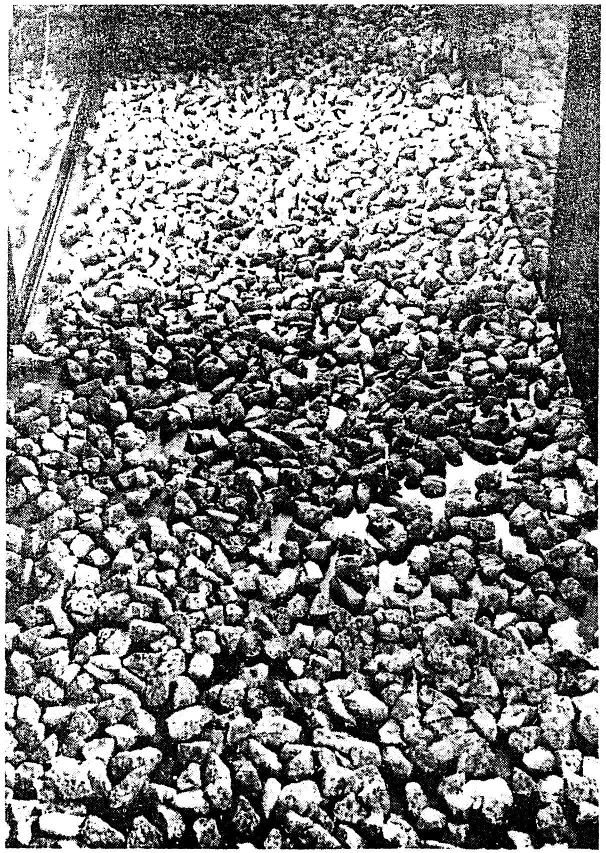


Fig.7. Broken stones.

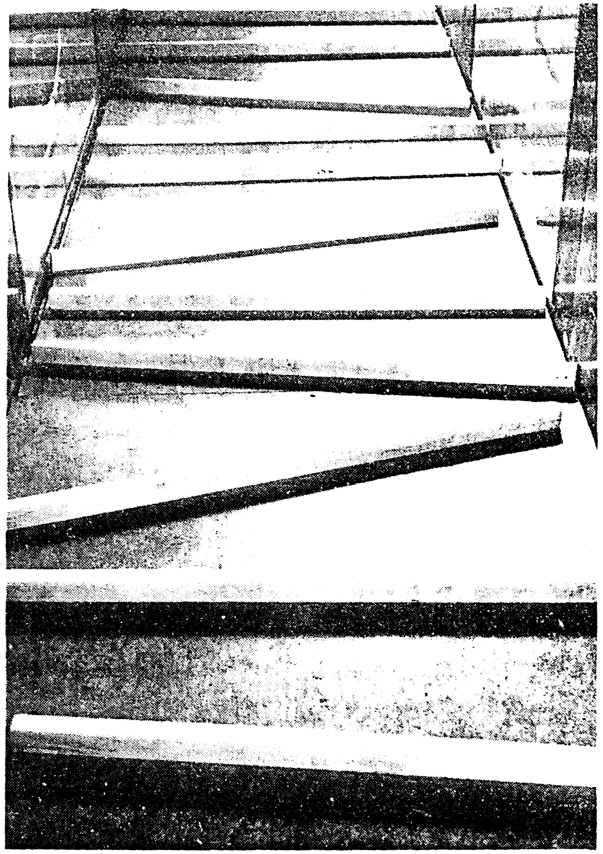


Fig.8. 2.5 x 2 cm fillets.

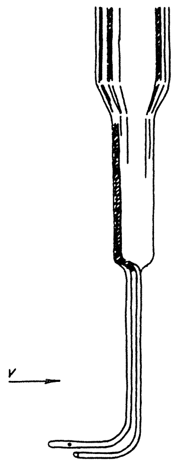


Fig.9. Pitot-static tube for precision measurements. Length of the longer horizontal branch is 1.2 cm.

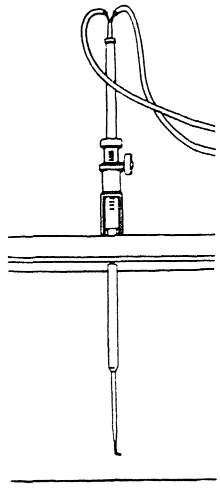


Fig.10. Holder for the pitot-static tube in Fig.9. By means of the holder the pitot-static tube may be placed at any point of the vertical symmetrical plane of the tunnel.

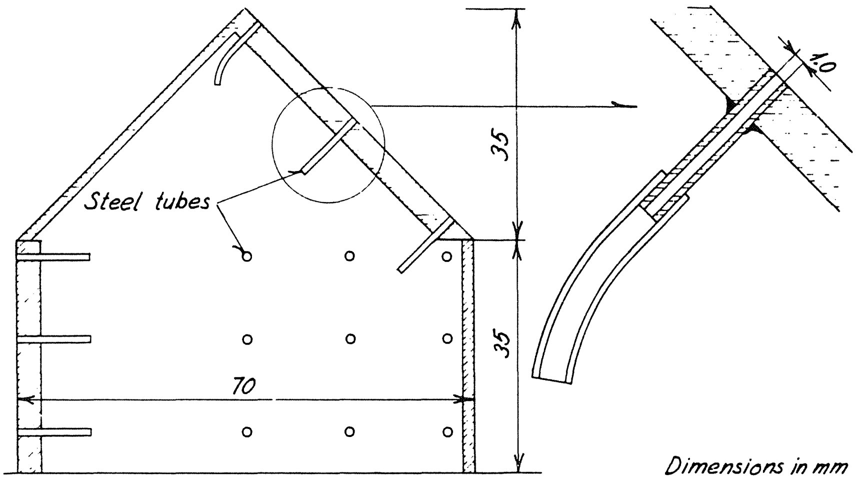
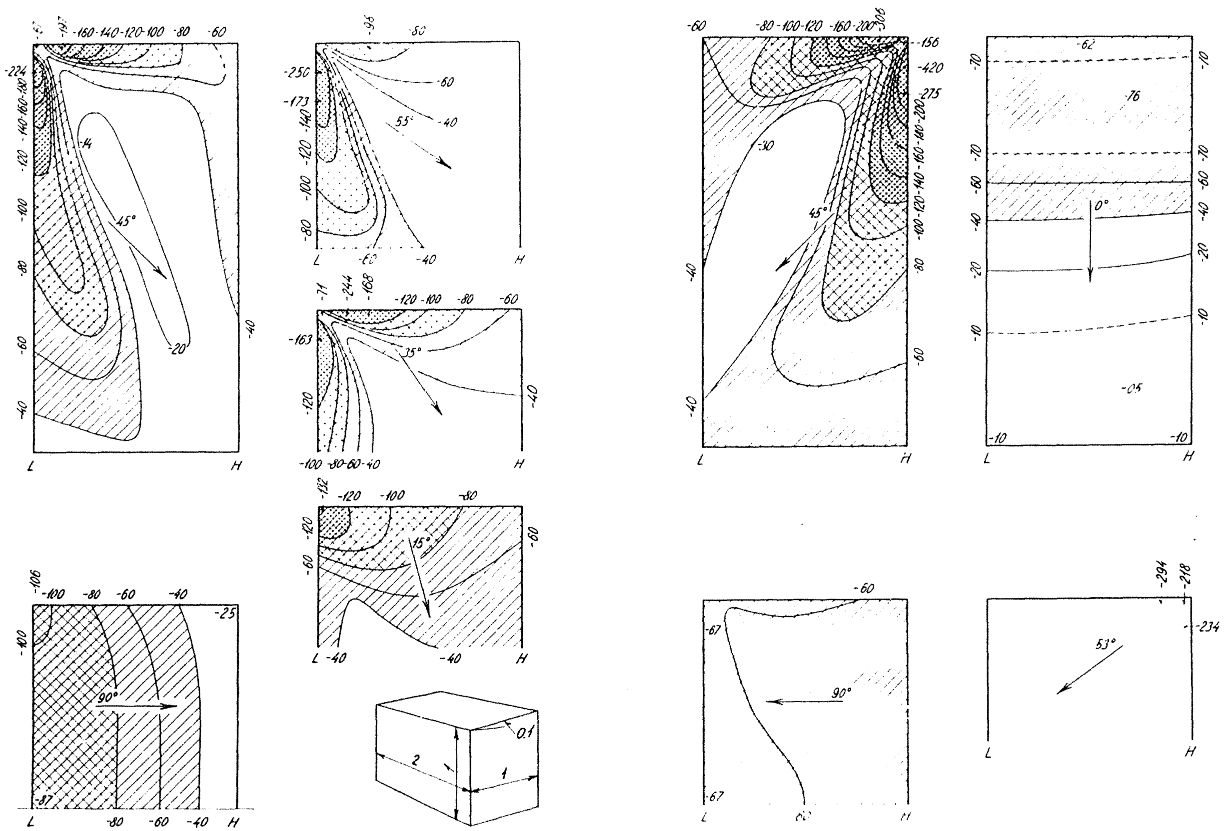


Fig.11. Model of a house used in the experiments. Detail of point of measuring.



Figs.12 and 13. Test results for a model of a house with desk roof (inclination 1 ÷ 10).
Shape factors c are given for the top surface of the roof.
$c = \frac{p}{q} \times 100$, where p is the suction and q is the velocity pressure at the level of the upper line of the roof.
Figs.12 and 13 apply to the model placed in small turbulence.

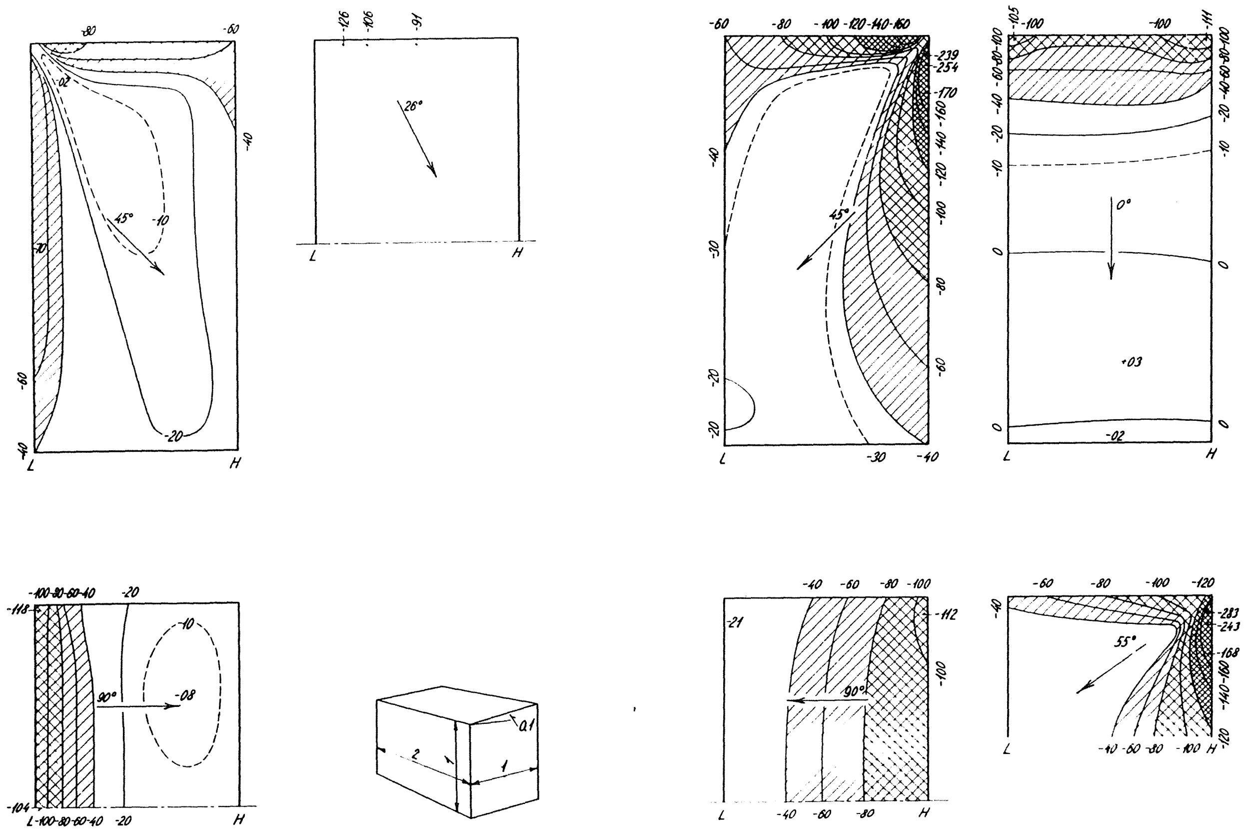


Fig.14 and 15. Test results for a model of a house with desk roof (inclination 1 ÷ 10).
Shape factors c are given for the top surface of the roof.
$c = \frac{p}{q} \times 100$, where p is the suction and q is the velocity pressure at the level of the upper line of the roof.
Figs.14 and 15 apply to the model in great turbulence.