the modelling of snowdrifting even though this implies abandoning the Froude-number similarity requirement.

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References

1 R.J. Kind, A Critical examination of the requirements for model simulation of wind-induced erosion/deposition phenomena such as snow drifting, Atmos. Environ., 10 (1976) 219—227.
2 J.D. Iversen, Drifting snow similitude — drift deposit rate correlation, Proc. 5th Int. Conf. on Wind Engineering, Fort Collins, CO, July 1979.
3 G. Strom, G.R. Kelly, E.L. Keitz and R.F. Weiss, Scale model studies on snow drifting, U.S. Army Snow, Ice and Permafrost Res. Establ., Res. Rep. 73 (1962).
4 F. Odar, Simulation of drifting snow, U.S. Army Cold Regions Res. Eng. Lab., Res. Rep. 174 (1965).
5 N. Isyumov, An approach to the prediction of snow loads, Ph.D. Thesis, University of Western Ontario, 1971.
6 K. Croce, in Snow Studies in Germany, National Research Council of Canada Tech. Memo. 20 (DBR) (May 1951).
7 D. Kobayashi, Studies of snow transport in low-level drifting snow, Inst. Low Temp. Sci., Sapporo, Japan, Rep. No. A31 (1973).
8 P.R. Owen, Saltation of uniform grains in air, J. Fluid Mech., 20 (1964) 225—242.
9 F.H. Clauser, The turbulent boundary layer, Adv. Appl. Mech., 4 (1956) 1—51.
10 A.E. Perry, W.H. Schofield and P.N. Joubert, Rough wall turbulent boundary layers, J. Fluid Mech., 37 (1969) 383—413.
11 B. Etkin, Interaction of precipitation with complex flows, Proc. 3rd Int. Conf. on Wind Effects on Buildings and Structures, Tokyo, 1971, pp. 135—143.
12 G.K. Batchelor, An Introduction to Fluid Dynamics, Cambridge University Press, 1967, pp. 541—543.
13 R. Eichhorn and S. Small, Experiments on the lift and drag of small spheres suspended in a Poiseuille flow, J. Fluid Mech., 20 (1964) 513—527.
14 R.A. Bagnold, The Physics of Blown Sand and Desert Dunes, Methuen, London, 1941.
15 W.S. Chepil, Equilibrium of soil grains at the threshold of movement by wind, Proc. Soil Sci. Soc. Am., 23 (1959) 422—428.
16 B.R. White and J.C. Schulz, Magnus effect in saltation, J. Fluid Mech., 81 (1977) 497—512.
17 J.D. Iversen, Drifting snow similitude, Proc. Am. Soc. Civ. Eng., J. Hydraul. Div., 105, HY6 (1979) 737—753.

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SOME EFFECTS DUE TO VARIATIONS IN TURBULENCE INTEGRAL LENGTH SCALES ON THE PRESSURE DISTRIBUTION ON WIND-TUNNEL MODELS OF LOW-RISE BUILDINGS

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Summary

The work described here consists of results from wind-tunnel tests on models of the Building Research Establishment's experimental building at Aylesbury. The use of several scale models of this building in uniform and in simulated atmospheric boundary-layer flows together with the results from the full-scale experiments allowed an assessment of the effect of variations in the ratio of the longitudinal-turbulence integral length scale to body dimension (L_x/D). This confirmed that the values of L_x/D have to be modelled correctly even in a non-homogeneous, non-isotropic turbulent flow in order to obtain model results that are representative of the full-scale situation. The present results also appear to confirm explanations given for similar results for homogeneous, isotropic turbulent flows.

Notation

$\overline{C_p}$ mean pressure coefficient
D characteristic body dimension
G transfer function
L_x turbulence integral length scale in longitudinal direction
n frequency
S power spectrum
Re Reynolds number

1. Introduction

The modelling of the atmospheric boundary layer in a wind tunnel require[s] shear and turbulence parameters to be scaled in order to achieve realistic mo[d] results in terms of wind loading [1—3]. Additional parameters to be consider[e] in such experiments are the model Reynolds number an[d] blockage. Generally, the effects of these parameters are negligible provided that the blockage is small and the m[o] so that separation is likely to be determined by the edge

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when dealing with bluff bodies in turbulent sheared flows it may be necessary to substantiate experimentally the claims of Reynolds-number insensitivity and negligible blockage effects, as well as assessing effects due to other parameters.

The principal difficulty involved in such experiments is to differentiate between effects due to variations in Reynolds number and those due to variations in the ratio of the longitudinal-turbulence integral length scale to characteristic body dimension (L_x/D). The results of wind-tunnel tests conducted at the Hatfield Polytechnic on models of the Building Research Establishment's experimental building at Aylesbury [6, 7] are discussed with reference to this problem.

2. Equipment and instrumentation

The main test facility employed during the present experiments was an open-return-type wind tunnel having a working section of dimensions 1.2 m × 1.5 m and in which a maximum velocity of 25 m s^{-1} could be achieved. The models used for the experiments were four scale models of the Aylesbury experimental building. The scale of the models covered a range from 1/50 to 1/200. Modelling of the atmospheric boundary layer was achieved by the use of a barrier/roughness combination [8, 9]. The simulation could be adjusted

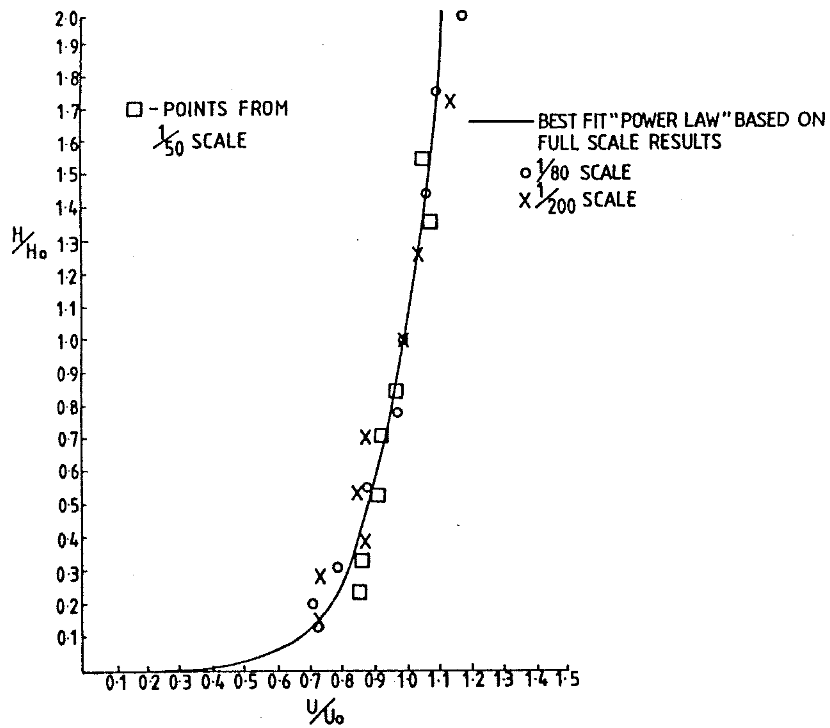


Fig. 1. Comparison between model and full-scale shear profiles.

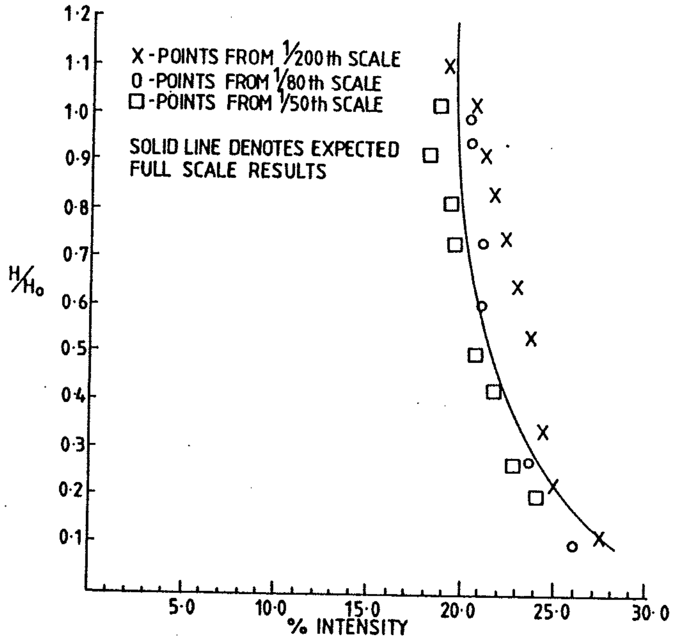


Fig. 2. Comparison between model and full-scale intensity profiles.

to keep the shear and turbulence intensity profiles largely constant for the complete model range, as shown in Figs. 1 and 2.

The instrumentation for measurements of the flow characteristics consisted of pitot—static tubes and standard hot-wire anemometry capable of accommodating both single- and cross-wire probes for measurements of fluctuating velocities. Pressure transducers placed inside pressure scanners were used for measurements of fluctuating and mean pressures. The outputs from the hot wires were linearised ensuring a linear frequency response from 0 to 20 kHz, whilst the plastic tubing from the pressure scanner to the pressure tappings, as well as the pressure scanner itself, severly restricted the linear frequency range of transducer operation. Calibration of the tubes and pressure scanner was carried out, and the results are shown in Fig. 3. The frequency response of the transducers was linear from 0 to 10 kHz, but when they were used with tubing and inside the pressure scanners corrections were carried out according to the formula

$$S_1(n) = |G(n)|^2\, S_2(n)$$

where $G(n)$ is the transfer function of the tubing system and pressure scanner as displayed in Fig. 3. $S(n)$ is the power spectrum, and n is the frequency.

Outputs from the anemometers and transducers were digitised and processed by the use of either a D.E.C. PDP 8/E or D.E.C. PDP 11/03 on-line facility. The latter was programmed to determine statistical quantities such as power and cross spectra, as well as correlation functions [9].

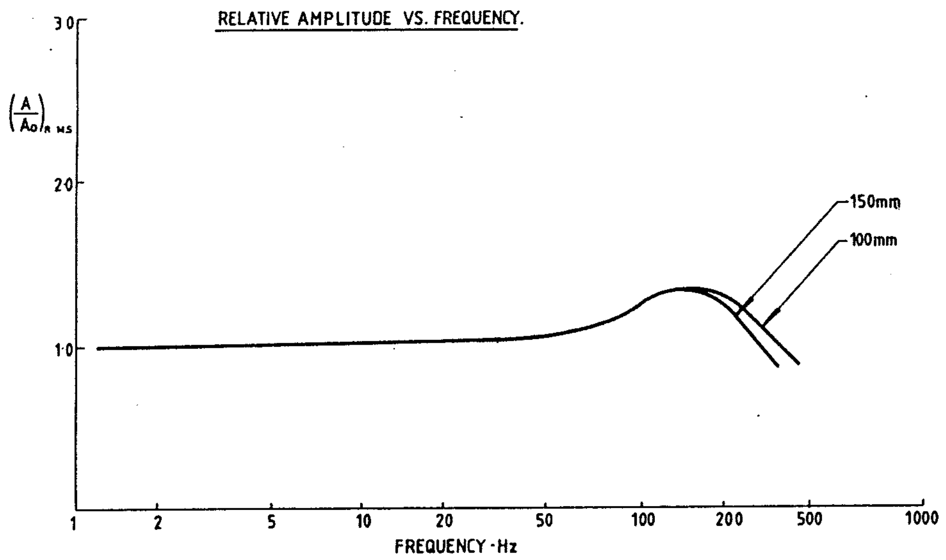


Fig. 3. Transfer functions for 10 mm and 150 mm tubes.

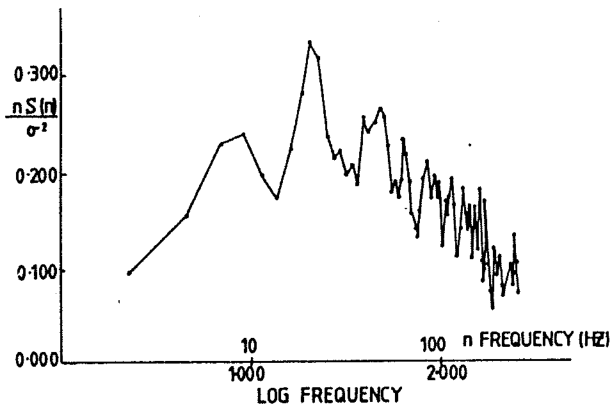


Fig. 4. Uniform flow: *U* component of freestream power spectrum at maximum flow through wind tunnel.

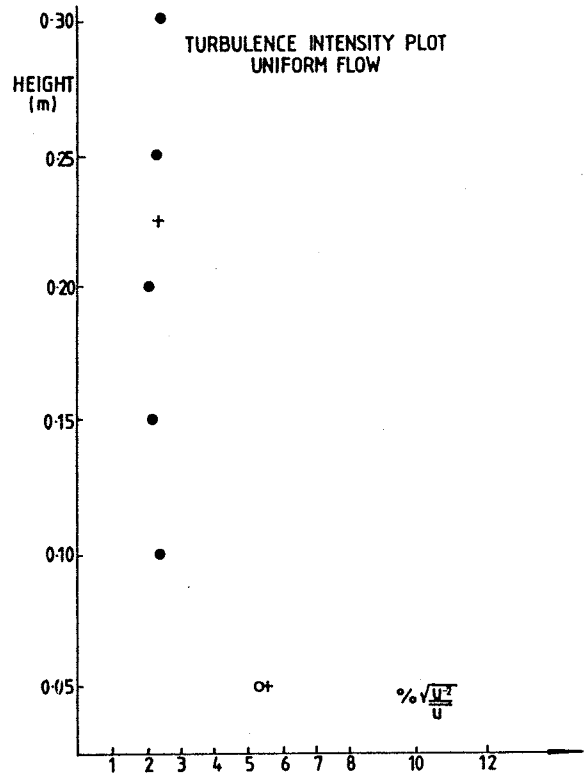


Fig. 5. Typical variation of turbulence intensity with height in nominally uniform flow.

3. Results

The first part of the investigation was concerned with possible blockage and Reynolds-number effects. Blockage effects were investigated by testing the complete model size range at constant model Reynolds number, achieved by varying the wind-tunnel speed accordingly, whilst effects due to model Reynolds-number variations were investigated by changing the model scale and keeping the wind-tunnel speed constant. These experiments were carried out in a nominally low-turbulence, uniform wind-tunnel flow without any flow-simulating devices. Details of this flow are shown in Figs. 4 and 5.

To avoid immersion in the wind-tunnel floor boundary layer the models were mounted on a false floor raised above the floor boundary layer. The boundary layer on this floor was found to be sufficiently thin at both maximum and minimum wind-tunnel speed to achieve negligible masking of the present results [8, 9].

No effects in terms of mean surface pressure distribution were found when the wind-tunnel blockage was varied from 1.5% to 7.0% at constant model Reynolds number (i.e., from 1/200 to 1/50 scale model). However, reverse effects were found when the model Reynolds number was changed. These results are shown in Figs. 6—8 as averages $\overline{C_p}$ for each surface with varying direction of flow. The effects are most noticeable on the longest surfaces (roof and wall) at flow directions from 0° (normal to surface) to 45° and from 90° to 180°. In these regions $\overline{C_p}$ is changed by a factor of up to 2 for a Reynolds-number change of 4. These results could also be thought to be

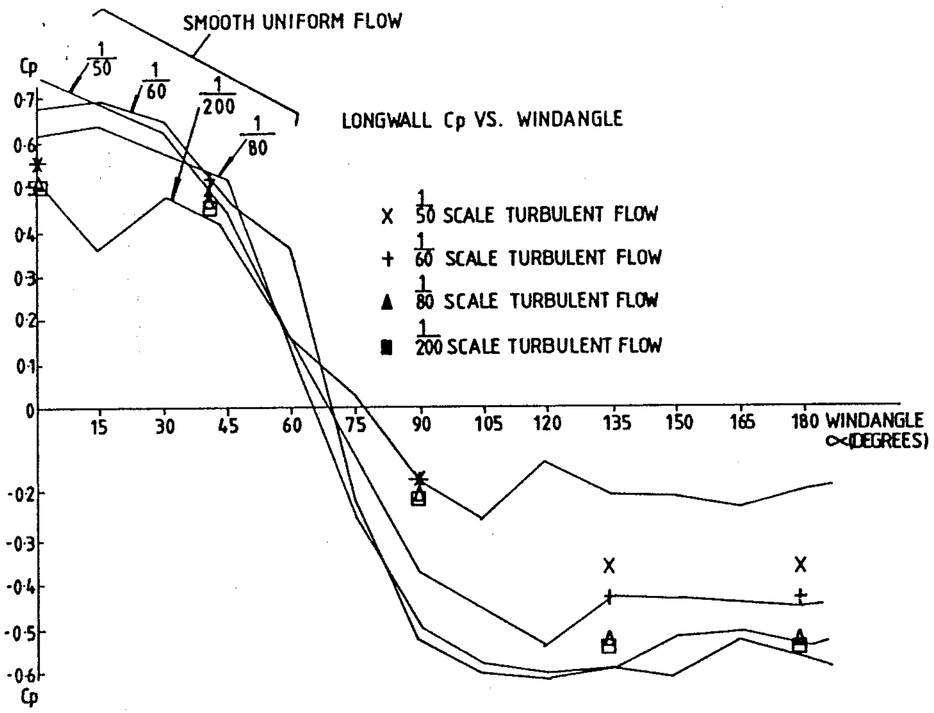


Fig. 6. Comparison between results for uniform flow and for turbulent/sheared flow (long wall): solid lines denote results for uniform flow. Reynolds number was varied by model scale.

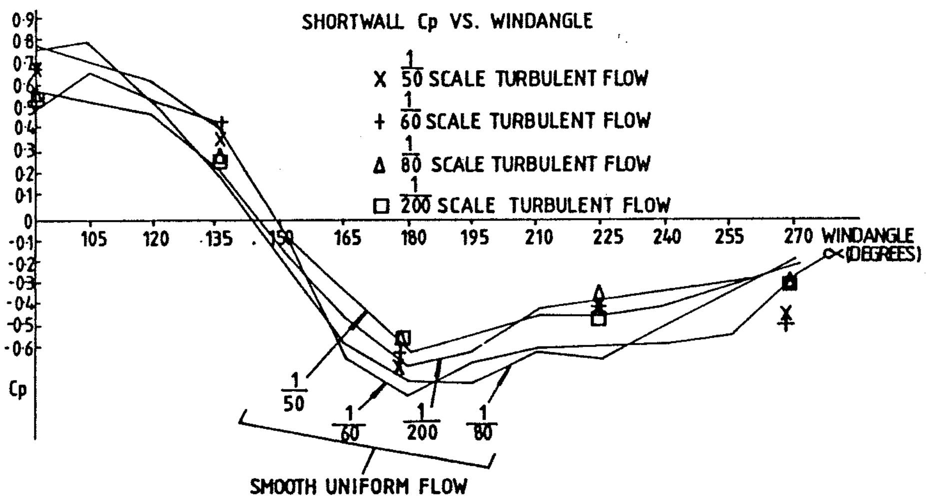


Fig. 7. Comparison between results for uniform flow and for turbulent/sheared flow (short wall): solid lines denote results for uniform flow. Reynolds number was varied by model scale.

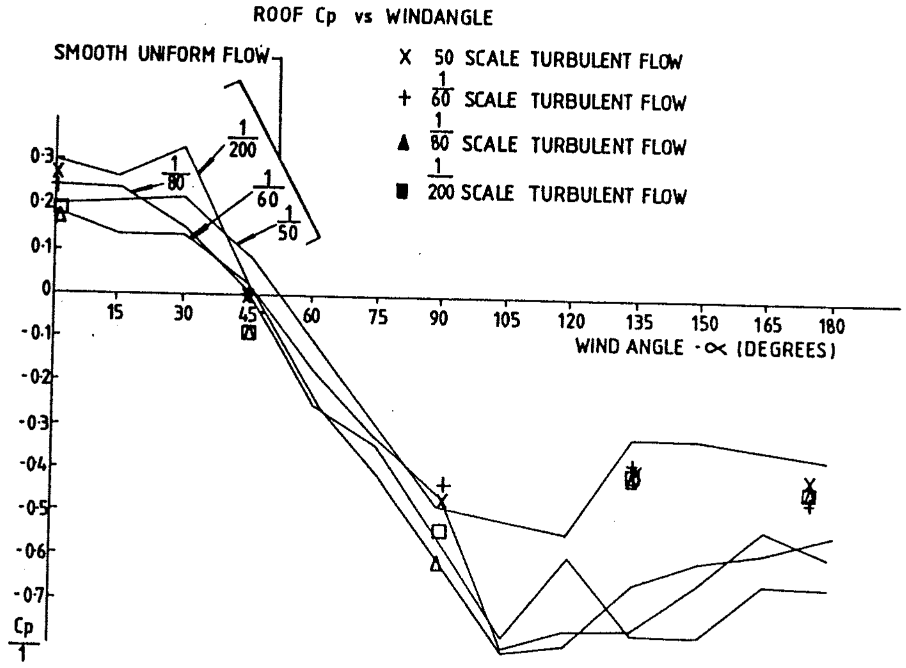


Fig. 8. Comparison between results for uniform flow and for turbulent/sheared flow (rc solid lines denote results for uniform flow. Reynolds number was varied by model scale

caused by changing L_x/D. D was the main parameter changed in the experiments and clearly both model Reynolds number and L_x/D are affected by this change.

The second part of the investigation was carried out in a simulated atmospheric boundary layer. Details of the shear and turbulence intensity profiles are given in Figs. 1 and 2; variations in any of these parameters was on average less than 2.5%. The effects of varying the model Reynolds numb and ratio L_x/D on C_p are shown as points in Figs. 6 and 7. The trends are similar to those found for the nominally uniform flow case.

Because the increase in turbulence intensity in these experiments is likely to decrease the wake blockage from the value for low-turbulence-intensity flow, where negligible blockage effects were observed, wind-tunnel blockage effects were assumed to be insignificant [10]. Furthermore, the observed effects were most pronounced when the wind-tunnel blockage was at its lowest value.

4. Comparison with full-scale results and results from other model tests

The wind directions for model and full scale do not exactly coincide, the difference being 8° for the nominally 0° case and 2° for the nominally 90° case. The comparison shows that the results for the 1/200 scale model in terms of the $\overline{C_p}$ distribution exhibit the closest match with the full-scale values. The differences are locally of the order of 0.1 in terms of the $\overline{C_p}$ value, and could well be due to the small differences in wind directions, particularly for the 0° case (Figs. 9 and 10). The difference in Reynolds number between full scale and 1/200 scale is a factor of ~200, while the normalised power spectra of the horizontal U component virtually coincide (Fig. 11), indicating a match between full and 1/200 scale in terms of the ratio L_x/D. Comparison between the 1/80 scale U component spectrum and the full-scale spectrum suggests a difference in the ratio L_x/D of 2, while the Reynolds-number difference is only a factor of 80. Differences in shear profile and turbulence intensity profile are quite small (Figs. 1 and 2). This suggests that the parameter responsible for the observed differences in the $\overline{C_p}$ distribution is the variation in the ratio of turbulence integral length scale to body cross-sectional dimension.

Comparing the results (Fig. 12) with those of Lee [11] for two-dimensional flow around square prisms, it is seen that a peak in the base pressure occurs at $L_x/D = 1.6$ for the uniform-flow results, rather than $L_x/D = 1.0$ as displayed by Lee's results. In the simulated atmospheric boundary layer this peak occurs at $L_x/D \simeq 2.8$. However, the figure of $L_x/D = 1.6$ is consistent with van der Hegge Zijnen's results [12] on scale effects on the cooling of cylinders in isotropic homogeneous turbulence.

The results displayed here are different to those referred to for comparison in several ways. The turbulence is non-isotropic, the flow in general is three-dimensional, and the model Reynolds number is not constant. Even so, it may be useful to consider the explanation of Lee's results. The theory of Hunt [13] indicates that the turbulence along the stagnation line is distorted. The nature of this distortion is dependent upon L_x/D. If L_x/D tends towards infinity the flow behaves in a quasi-static manner and the turbulence intensity decreases but when L_x/D tends to zero the intensity is amplified along the stagnation line. Laneville et al. [14] have shown that it is the turbulence along the stagnation line that is important for the development of the shear layers. The shear layers in a highly turbulent flow are thicker than in a smoother flow and this means higher entrainment of fluid in these layers and a different curvature. The shear-layer curvature is related to the surface pressures on the models and it is through this mechanism that the turbulence parameters affect the pressure distribution in the wake and separated-flow regions.

This may explain the difference in surface pressure variation with the turbulence parameters between the short and the long surfaces found in both uniform flow and the simulated atmospheric boundary layer, as illustrated in Fig. 10. When the flow direction is normal to the longer surface the change in shear-layer curvature will be large in the wake region and small where the flow has just separated. When the flow is normal to the short surface the change in curvature will affect the surface pressure on the longer surface, which is parallel to the mean approach-flow direction, and if $L_x > D$ the observed effect may be due to bulk motion of the shear layer, by large eddies, causing temporary

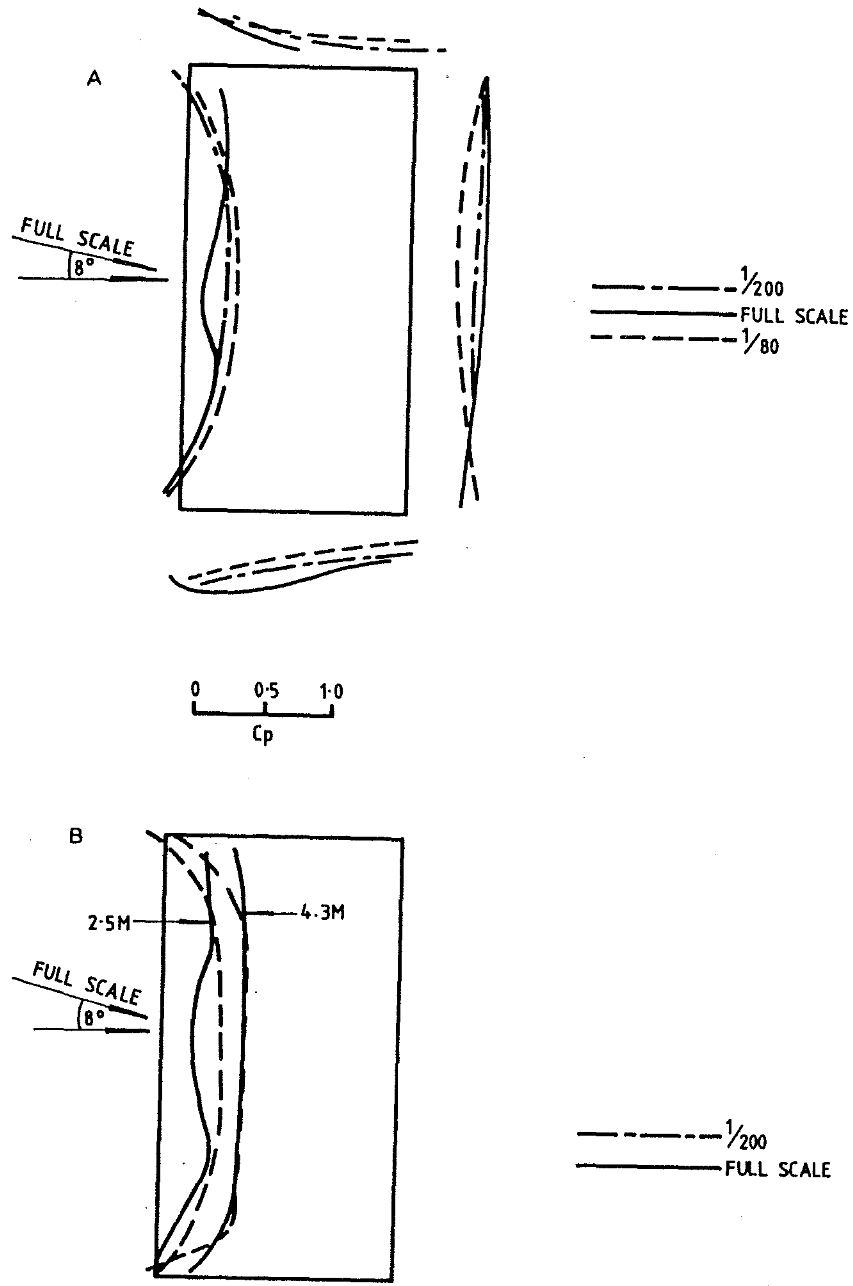
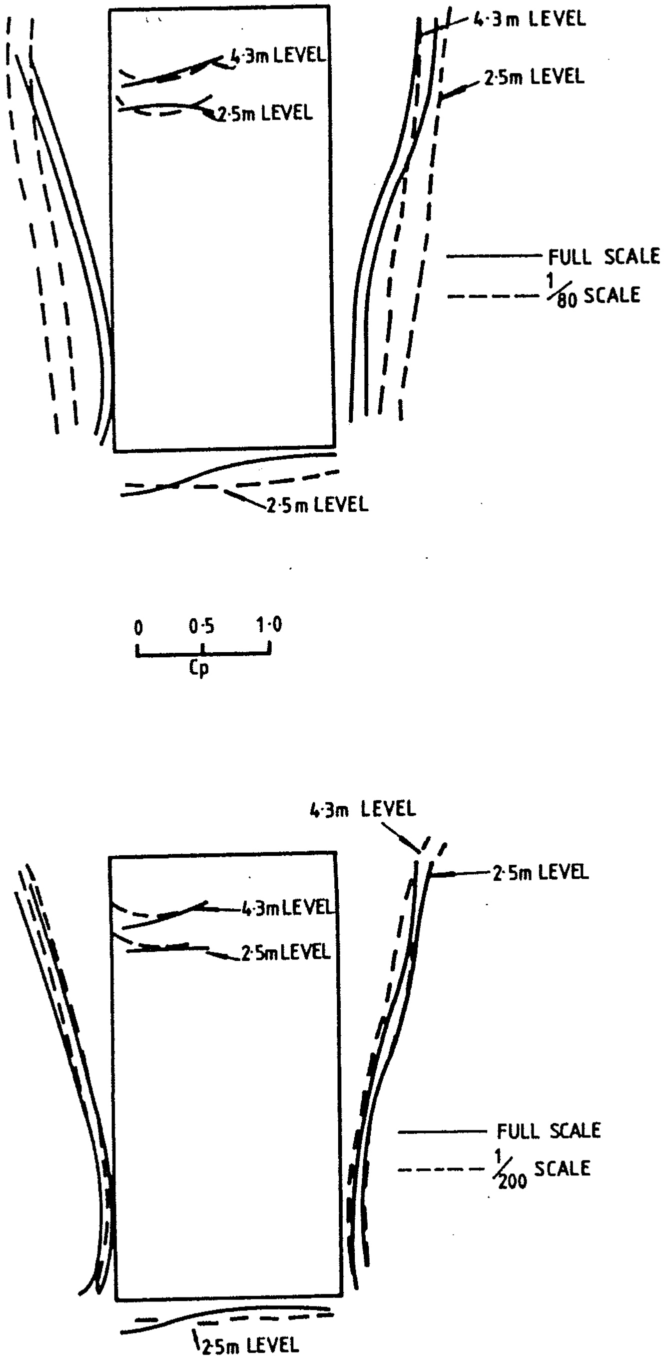


Fig. 9.(A) Comparison between full-scale and model results for $\overline{C_p}$ (at 0°). (B) Comparison between 1/200 scale and full-scale results for $\overline{C_p}$ at two levels (at 0°).



. 10.(A) Comparison between 1/80 scale and full-scale results for $\overline{C_p}$ (at 90°): solid
:s denote full-scale results. (B) Comparison between 1/200 scale and full-scale results
$\overline{C_p}$ (at 90°): solid lines denote full-scale results.

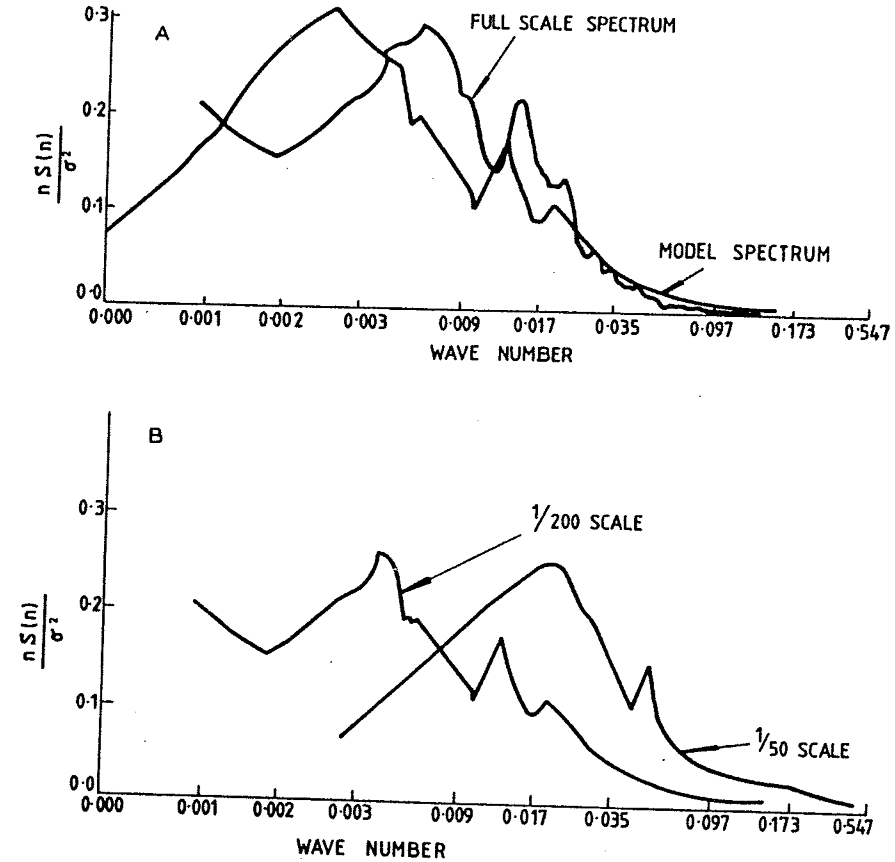


Fig. 11.(A) Comparison between full-scale and 1/200 scale spectra (model spectra details: number of estimates 128, sampling rate 450 samples s^{-1} sampled over 15 s). (B) Comparison between 1/50 scale and 1/200 scale spectra (spectral details as for Fig. 11(a)).

Since the trends in the results are common for both uniform and simulated atmospheric boundary-layer flows and these trends may be explained by other observations and theories of turbulent flows, it is suggested that the variations in the present results are due to variation in L_x/D.

In the non-homogeneous turbulence of the present experiments the integral length scale is an indication only of the magnitude of turbulence fluctuation so that even if L_x/D is much greater than unity some increases in turbulence intensity may take place along the stagnation line dependent on the distribution of length scales in the approaching flow (i.e., on the spectral distribution). This, together with inherent uncertainties in the estimation of length scales, could be the reason for the differences found between these results and those for homogeneous, isotropic turbulent flows.

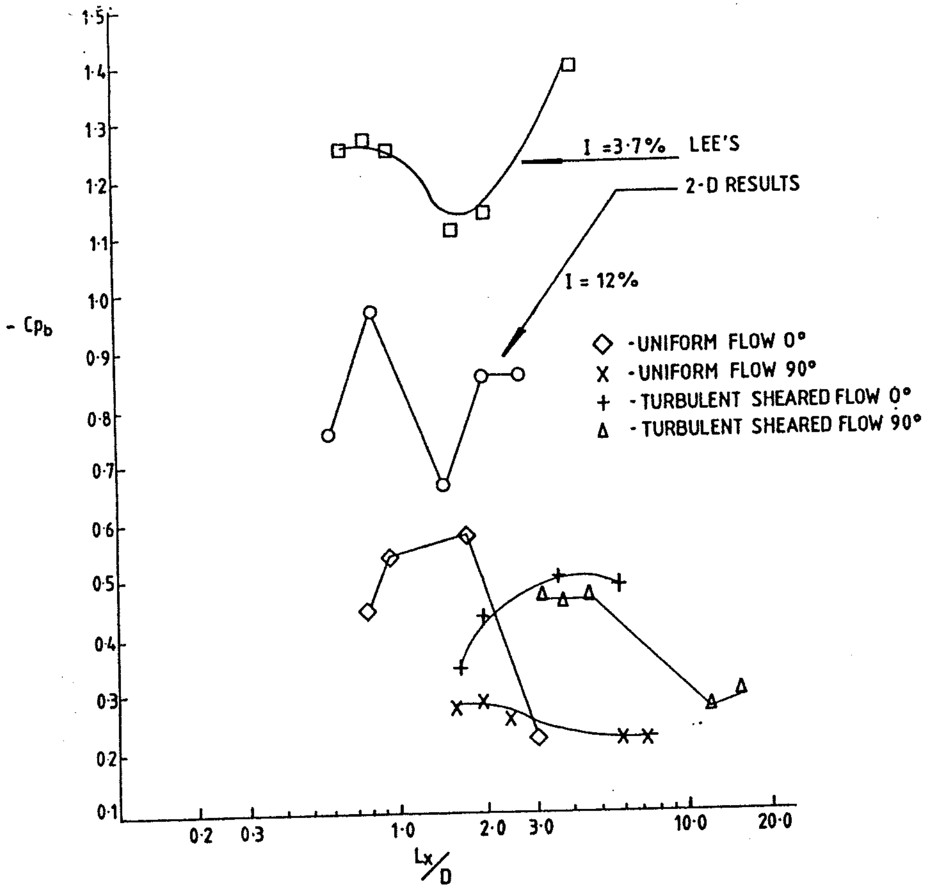


Fig. 12. Variation of base pressure with length scale parameter.

5. Conclusions

Comparison of the experimental findings with full-scale results has shown that the frequency distribution of the longitudinal velocity component is an important modelling parameter which should be matched with the full-scale frequency distribution. This parameter, expressed in terms of L_x/D, appears to be more important for bluff-body flows than is the Reynolds number in the range of turbulence intensities from 2% to 25%.

The variation of base pressure with the ratio L_x/D for bluff bodies in non-homogeneous, non-isotropic turbulence appears to be similar to that for bluff bodies in homogeneous, isotropic turbulence.

The change in base pressure with L_x/D indicates that certain ranges of this parameter are more important than others. Further work to establish these ranges would be valuable in order to assess the accuracy of this parameter required to obtain realistic results.

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References

1 M. Jensen, The Model Law for Phenomena in the Natural Wind, Part 2, Danish Tech nical Press. 1965.
2 J.E. Cermak, Laboratory simulation of the atmospheric boundary layer, AGARD Conf. Proc. No. 48, Munich, 1970.
3 J. Counihan, A method of simulating a neutral atmospheric boundary layer in a win tunnel, AGARD Conf. Proc. No. 48, Munich, 1970.
4 R.M. Aynsley, W. Melbourne and B.S. Vickery, Architectural Aerodynamics, Applie Science Publishers, 1977.
5 P. Bradshaw, Turbulence, Springer Ser. Appl. Phys. Sci., Vol. 12, 1976.
6 K.J. Eaton and J.R. Mayne, The measurement of wind pressure on two storey house at Aylesbury, Build. Res. Establ., Curr. Pap. CP 70/74 (1974).
7 K.J. Eaton, J.R. Mayne and N.J. Cook, Wind loads on low rise buildings — effects o roof geometry, Build. Res. Establ., Curr. Pap. CP 1/76 (1976).
8 A.E. Holdø, Hatfield Polytechnic, Int. Rep. THP/19/79 (1979).
9 A.E. Holdø, Ph.D. Thesis, Hatfield Polytechnic, 1979.
10 A. Pope and J. Harper, Low Speed Wind Tunnel Testing, Wiley Interscience, 1964.
11 B.E. Lee, The effect of turbulence on the surface pressure field of a square prism, J. Fluid Mech., 65 (1974) 263.
12 J.O. Hinze, Turbulence, McGraw-Hill, 1957.
13 J.C.R. Hunt, A theory of turbulent flow around two dimensional bluff bodies, J. Fl Mech., 61 (1973) 625.
14 A. Laneville, I.S. Gartshore and G.V. Parkinson, An explanation of some effects of turbulence on bluff bodies, 4th Int. Conf. on Wind Effects on Buildings and Structu Heathrow, 1975, Cambridge University Press, London, 1977, 333 pp.