J. Fluid Mech. (1975), *vol.* 70, *part* 3, *pp.* 543–559
Printed in Great Britain

Wind-tunnel simulation of the atmospheric boundary layer: a report on Euromech 50

By J. C. R. HUNT

Department of Applied Mathematics and Theoretical Physics and Department of Engineering, University of Cambridge

AND H. FERNHOLZ

Institut für Thermo- und Fluiddynamik, Technische Universität Berlin

(Received 23 December 1974)

The 50th Euromech Colloquium, on wind-tunnel simulation of the atmospheric boundary layer, was held in Berlin from 23–25 September 1974. Thirty-eight participants from eleven countries were present. Papers were presented describing and analysing different methods of simulation of neutral, stable and unstable atmospheric conditions in various types of wind tunnel. Numerous applications of wind-tunnel simulations were described or mentioned in the papers and the discussion sessions. Some conclusions about the validity, the techniques, the limitations and future developments of wind-tunnel simulations were reached in discussion. Tables are presented in appendix A listing the institutes in Europe and the U.S.A. of actual or invited participants where wind tunnels are used for simulation work; also listed are the characteristics of the wind tunnels and relevant measurements of the simulated atmospheric boundary layers, to enable comparisons to be made between different techniques.

1. Aims of the Colloquium

This Colloquium was conceived by Professor R. Wille as an occasion to bring together the various groups in Europe and elsewhere who are using wind tunnels to simulate the atmospheric boundary layer. Tragically Professor Wille died in December 1973, but in his honour the Colloquium went ahead, and we were appointed co-chairmen.

The Colloquium had two main aims. The first was to establish what techniques are being used for simulating the atmospheric boundary layer in wind tunnels and what are the applications for which these simulated flows were designed. To achieve this papers were presented describing various wind-tunnel simulations, and also a questionnaire was sent to participants from which a table was compiled of the sizes and parameters of operational or prospective wind tunnels for simulation work. This table is included in appendix A. We believe that there is a need for more systematic comparisons first between different simulated wind-tunnel boundary layers and second between simulated boundary layers and meteorological data. Tables 1 and 2 in appendix A were compiled with this view in mind.

The second aim of the Colloquium was to discuss how the various techniques work, their relative merits, their meteorological validity and their range of application. The discussions were structured by circulating before the Colloquium lists of questions that ought to be answered in the discussion sessions (and, indeed, thought about by anyone concerned with this subject); see appendix B. Having such an agenda for discussion helped us to bring the discussions to some conclusions, much more easily than without any agenda. We recommend this procedure to other chairmen of colloquia or conferences where discussion sessions are aimed at arriving at conclusions.

2. Simulation methods without stratification

E. Plate (Karlsruhe) began the technical sessions with a review lecture. There are, he said, two main reasons for simulating the atmospheric boundary layer in a wind tunnel. One reason is to help the understanding of airflows in the atmosphere, which requires collaboration between engineers and meteorologists. The other is to help solve engineering problems such as (i) predicting the wind forces on structures, both the overall forces and the local fluctuating pressures on cladding; (ii) predicting the way in which the structures affect the wind, for example so as to disturb people walking near buildings; and (iii) studying diffusion from chimney stacks and other sources of air pollution. The modelling laws for these different applications cannot be satisfied simultaneously. (See Plate 1971.) For any given application some modelling laws are satisfied and others have to be relaxed. Plate described in detail the modelling of mean and fluctuating forces on a structure in the lowest part of the atmospheric boundary layer and controversially concluded that the only part of the spectrum of the wind that need be simulated is that over frequencies equal to and above the natural frequencies of the structure. This was challenged by a number of subsequent speakers. He surveyed the various artificial means of developing a thick boundary layer in a short distance along a wind tunnel and of simulating the temperature variations in the atmospheric boundary layer. It was suggested that a water tunnel is perhaps one appropriate way of simulating strong 'inversion' conditions. Plate concluded that modelling diffusion in the atmosphere can only be done accurately near the source, mainly because the veering of the direction of the wind with height, which is not simulated in a wind tunnel, affects diffusion a few kilometres downwind of a source. (See Snyder 1973.) He suggested that one should look into the possibility of allowing for this 'Ekman spiral' effect by numerically superposing its effect upon the measured data.

J. Gandemer (C.S.T.B., Nantes) described a new wind tunnel at the Centre Scientifique et Technique du Bâtiment at Nantes. It is similar to that at the University of Western Ontario, Canada. The working section has an adjustable roof. But there are two novel features: directional jets are positioned in the floor at the entrance to the working section to thicken the boundary layer† and to provide some low frequency oscillations in the flow to simulate the largest eddies in the atmospheric boundary layer; for the same reason the rotational

† Cermak commented that a similar device had been developed by Nagib *et al.* (1974).

speed of the tunnel fan can be oscillated by up to 30 % at frequencies of up to 1 Hz. The resulting velocity spectra showed that large eddies were produced but some participants questioned whether there was enough evidence from the measurements to conclude that these spectra were similar to those of atmospheric turbulence and whether the low frequency oscillations in one direction really simulated the large eddies in the atmosphere. Gandemer described measurements of the spectra with different degrees of floor roughness.

V. Nee (Notre Dame, U.S.A.) described another method of simulation, involving the use of multiple horizontal jets of variable strength directed at each other from either side of the wind tunnel (Nee *et al.* 1973). By varying these jets the turbulence intensity and Reynolds stresses were varied so as to generate a thick, slowly varying shear layer 70 cm thick in a relatively short distance (7 m). In this layer the velocity profile was logarithmic and both the shear stress and turbulence intensity appreciably constant. Nee claimed that there is an important difference between methods for thickening boundary layers based on passive devices such as grids, fences, vorticity generators, etc., and those based on active devices such as jets. In the former all the turbulence energy is derived from the kinetic energy of the mean flow, so that the mean velocity profile and turbulence are not independently variable, whereas with active devices these properties are to a greater extent independently variable. The disadvantage of inactive devices, Nee claimed, is that if turbulence intensities are to be realistically large, then the turbulence decays rapidly down the tunnel.

C. G. Bray (Bristol) gave an account of the wind-tunnel simulation at Bristol University (Cook 1973), which was primarily designed for studying wind loads on buildings in urban areas. Only the lower third of the atmospheric boundary layer was simulated, the methods of artificial thickening being a large grid (mesh size 0·3 m), a fence and roughness elements. Comparisons were made between wind-tunnel and full-scale measurements of mean velocity profiles, turbulence intensities and spectra. Unlike any other wind tunnel, comparisons were also made of the peak '3 s gust' in a 1 h period (the times being scaled down for the wind tunnel), since it is this parameter of the turbulent wind that is used in structural calculations. The differences between model and full-scale results seemed to be less than the variation in the meteorological measurements.

A. G. Robins (Marchwood, U.K.) presented a detailed investigation of the development of an unusually deep (2 m) simulated boundary layer in the C.E.G.B. Marchwood wind tunnel, primarily for the study of chimney emissions into a neutrally stable flow (Robins 1975). Thus, unlike many velocity measurements of simulated boundary layers which are taken in one plane across the tunnel, these results gave a better understanding of the mechanics of the turbulence and a better evaluation of the appropriateness of the simulation. By artificially thickening the boundary layer with a combination of a fence, vorticity generators (as developed by Counihan 1969) and a rough surface Robins found that the turbulence in the boundary layer reached an equilibrium state about $7\frac{1}{2}$ boundary-layer thicknesses downwind. This conclusion could be made because the production and dissipation of turbulence had been measured, unfortunately an all too rare measurement. The intermittency in the turbulence had also been measured and found to be the same as that of a naturally grown boundary layer over a flat plate. It had not been compared with intermittency in the atmospheric boundary layer.

R. C. F. Dye (Manchester) showed how a short (1·5 m long) wind tunnel can be used for demonstrating wind flow round buildings. To simulate mean ground-level winds round tall buildings it is important to simulate the velocity profile of the natural wind even if the turbulence is not well modelled (Wise 1971). In this case a shear grid was used (one with variable pitch). A particular investigation of wind flow around the buildings of Manchester University at $\frac{1}{250}$ scale was described.

J. A. B. Wills (Teddington, U.K.) described an investigation of a naturally grown equilibrium boundary layer with an adverse pressure gradient in a wind tunnel at the National Physical Laboratory. The object was to determine whether imposing an adverse pressure gradient, by shaping the walls of the wind tunnel appropriately, was a suitable way of producing a thick boundary layer similar to the atmospheric boundary layer within a short distance along the wind tunnel. It was found that the mean velocity profile and the intensity and scale of the turbulence were adequately simulated but that the vertical shear-stress profile contained a strong maximum, quite unlike that in the atmospheric boundary layer. Since the shear stress affects turbulent diffusion, Wills concluded that this was not a promising method of simulation for turbulent diffusion work, but might be suitable for other applications.

E. M. Laws & J. L. Livesey (Salford) described their calculations of flows in two-dimensional and axisymmetric ducts where velocity variations are produced by shaped gauzes. The theory of Elder (1959) was extended and compared with experimental measurements in a pipe of diameter 10 cm. For even the most curved profiles the agreement between theory and experiment was satisfactory. Laws & Livesey concluded that gauzes can be used to create most types of mean velocity profile that might occur in atmospheric shear flows, but that the turbulence cannot be simulated using gauzes.

N. Frossling & R. Karlsson's (Göteborg) paper was concerned with the measurement of the wall shear stress τ_0 in simulated boundary layers. They remarked that in artificially thickened boundary layers there may not be an equilibrium layer near the wall, in which case fitting a log law to the measured mean velocity profile can lead to large errors in estimating τ_0. Using a Preston tube must therefore lead to errors. Experimental hot-wire measurements of the shear stress in the viscous sublayer and in the buffer layer were described. But they were shown to be somewhat unreliable because the proximity of the wall increased the heat transfer and corrections for this effect are uncertain. The authors concluded, and were supported in this by other participants, that a 'floating' element balance in the wall is the best method of measuring wall shear stress in this kind of flow.

J. C. R. Hunt (Cambridge) showed how theoretical principles can be used to examine the validity of different techniques of wind-tunnel simulation. Only neutral conditions were considered. The similarity and differences between the shear-stress distributions in a constant-pressure turbulent boundary layer and the idealized atmospheric (or Ekman) boundary layer were considered. Thence it was argued that there is no theoretical reason (and no meteorological evidence) for the constant-stress distributions found in artificially thickened boundary layers over very rough surfaces (Counihan 1973; Cook 1973; Sundaram, Ludwig & Skinner 1972). Using the turbulent energy equation it was shown that the turbulence in some simulated boundary layers is rapidly decaying and is not in equilibrium with the mean flow, which must imply incorrect simulation of turbulence spectra. The effect of not attempting to simulate the upper part of the boundary layer was examined. It was suggested that recent work on turbulent boundary layers by Willmarth & Yang (1970), Townsend (1975) and Hunt (1975) showed how the large eddies in the upper part influence the low frequency turbulence near the ground, which is of importance in wind loads and diffusion. Also, when airflow over hills is modelled, the mean flow in the upper layer strongly influences peak velocities near the ground (Jackson & Hunt 1975). The turning of the wind direction in an Ekman layer also affects ground-level winds when roughness changes or airflow over hills are modelled. Finally a film was shown of recent wind-tunnel experiments on the effects of wind on people. It has been shown how much people are affected by variations of the mean wind speed over 1 m and gustiness, relative to uniform steady winds (Hunt, Poulton & Mumford 1975). In this case there could be no scaling: the actual mean wind speed, variations in wind speed near a building and one or two frequencies of gustiness (< 2 Hz) had to be reproduced. A large wind tunnel at the National Physical Laboratory was used.

3. Simulation methods involving thermal stratification

R. S. Scorer (Imperial College, London) began by showing a film of the surface of a reservoir on the downwind side of a wall along the top of the dam. A marked pattern of 'cat's paws' was seen where advancing wind discontinuities (increases) ruffled the surface. It showed the merit of looking at nature as well as motion in wind tunnels. Scorer advanced the unusual idea that motions in the cats' paws were similar to those caused by fronts of cold air moving into warm air. Richards (1965) had already shown by detailed measurements that the motion in a puff with no density anomalies is very close to that in a thermal, where it is all buoyancy driven, and it is likely that the incursions of large velocity fluid from outside into a boundary layer are similar to the advance of density currents. The point of interest is that buoyancy-driven motions are much easier to study because they can be scaled down and controlled at lower speeds. Simpson (1969) has demonstrated a close similarity between small laboratory models and haboobs. Wind discontinuities cannot be properly represented in a spectral analysis and ought to be studied (and modelled, if models are used) individually because they are so important in the atmosphere.

J. E. Cermak (Fort Collins, Colorado) described the three tunnels used at Colorado State University. In one 30 m long different lengths of the floor can be heated up to 200 °C or cooled to simulate airflows over water and land. In another tunnel 'dry ice' is used to simulate cold airflow over mountains at scales of $\frac{1}{14000}$. Artificial methods for thickening the boundary layer are sometimes used. The scaling laws that are satisfied are those for surface temperature, roughness, Richardson number, but not, of course, Reynolds number, since velocities have to be very low ($\sim 0{\cdot}2$ m/s) to produce the same Richardson number as in a stratified atmosphere (Cermak 1971, 1975). Nevertheless the wind-tunnel boundary layer simulates the spectra and intensities of turbulence and the log–linear laws for mean temperature and mean velocity in the atmospheric surface layer. Some of the practical applications were described, such as the onset of 'fumigation', mixing of air pollution in a city below an inversion and comparison of full-scale and model-scale measurements of dispersion from a source upwind of a city (Fort Wayne, Indiana). Radiation from the ground and the effects of cloud cover could not be simulated. For the smallest-scale investigations of diffusion over hillsides the flow may be laminar; yet Cermak suggested that if the flow pattern is correctly modelled and the turbulent eddy diffusivity is roughly scaled on molecular diffusivity, then the wind-tunnel predictions are approximately correct. In discussion this reasoning was supported by Hunt on the basis of a detailed theoretical comparison between turbulent and molecular diffusion in flow round a bluff obstacle (Hunt & Mulhearn 1973).

P. Bonmarin (Marseille) began by explaining that a large facility is needed to simulate the interaction between the ocean and the atmosphere. This is why the combined wind tunnel and wave tank at the Institut de Mécanique Statistique de la Turbulence is 3·2 m wide and 40 m long. Since energy transfer is to be studied the temperature of the water and the temperature and humidity of the air are controlled. Measurements that have been undertaken so far are of the turbulence structure, heat and moisture transfer, and statistics of the waves (maximum height 20 cm).

J. Schon's (Lyon) wind tunnel has only been used to simulate neutral and unstable conditions over the lower part of the atmospheric boundary layer (Schon 1974; Schon & Mery 1971). The boundary layer develops naturally over the heated floor of the tunnel at a temperature $\leqslant 100$ °C, the top wall of the tunnel being at less than 20 °C. Detailed measurements were made of velocity and temperature gradients as functions of the wall shear stress and wall heat flux, i.e. the Richardson number Ri as a function of z/L, where z is the distance above the surface and L is the Monin–Oboukhov length. In the experiments $0 > Ri > -0{\cdot}2$. The turbulence and the velocity temperature correlations were measured, and the energy budget calculated. All the measurements were compared with the Kansas meteorological data and found to agree not only in the surface layer but up to about 40 % of the boundary-layer thickness. This experiment showed how a wind tunnel can be used to simulate the velocity and temperature field in the lower part of the atmospheric boundary layer in unstable conditions, when it may be particularly important to model turbulent diffusion. Schon also remarked that such a tunnel is a useful way of testing mathematical theories of unstable conditions in the atmospheric boundary layer.

W. Debler (Ann Arbor, Michigan) described how a constant stable temperature gradient was set up in a wind tunnel by means of heated honeycomb strips upwind. There is a problem of avoiding a thermally driven circulation which limits the size of the temperature gradient. Some interesting calibration problems for X-wire anemometers occur in such wind tunnels. The results showed that a stable temperature gradient in a turbulent flow attenuates vertical velocity fluctuations but does not have much effect on horizontal motions. Spectra were also measured. The temperature fluctuations increased downwind.

4. Applications of simulation methods

R. Bouquet (Poitiers) showed how a wind tunnel could be a very useful tool for investigating the effects of a wind with velocity V on exhaust gases leaving a chimney stack with velocity W and on the dispersion throughout the surrounding area. Bouquet was particularly concerned with the plume rise as a function of the ratio W/V, the buoyancy of the plume and the height of the stack. The wind-tunnel simulations showed up the effects of turbulence and local topography on dispersion, modelled on a scale of $\frac{1}{2000}$. When the buoyancy of the plume is correctly modelled by a densimetric Froude number, the velocity of the tunnel has to be very slow. Then Reynolds number modelling is seriously in error. The solution may be to use larger wind tunnels.

J. S. Ostrowski (Warsaw) suggested in his paper that flows round buildings could be changed by the suitable placing of obstructions such as fences, hedges, etc., upwind of the building: an obvious point but one which is often overlooked. The placing of these flow control obstacles is most easily investigated in a wind-tunnel simulation. Ostrowski was concerned with two long low parallel buildings (500 m long) on flat ground. Using smoke bombs near the actual buildings he found that the separated flow extended thirteen building heights downwind. The ground was covered with snow; so the airflow was probably stably stratified. Such a long bubble had not been observed full scale before, though it had in some previous wind-tunnel studies, and was not observed in the rather simple wind-tunnel simulation Ostrowski used. The wind-tunnel studies showed how this separated region could be reduced in length by a factor of four using obstacles upwind. This would have the desirable effect of lessening the entrainment of exhaust gases from the chimney above the building back into the wake. At the Technological University in Warsaw they have recently constructed a pulsed-flow wind tunnel. It is a 0·3 m square blower tunnel with a combination of bleed and throttle shutters, mechanically operated, giving velocities of 0–30 m/s at 10 Hz.

O. Christensen (Copenhagen) is involved in measuring wind pressures with transducers built into a 130 m tall chimney stack on the coast of Denmark. The velocity and temperature distribution are being measured on a 40 m mast close to the stack. The measurements are all recorded on magnetic tape and are available for analysis by other research groups: a useful idea which might be more widely adopted. The data are still being analysed and may be compared with wind-tunnel simulations. Christensen pointed out that, in the very stable atmospheric conditions sometimes prevailing on the coastline, there was sometimes no appreciable turbulence at wind speeds up to 15 m/s. This must be borne in mind in any simulation. In discussion it was pointed out that Christensen's study was similar to that of Tunstall (1974), where the wind on an instrumented chimney had been compared with locally measured wind speeds. The results had been compared with wind-tunnel tests, with some success.

R. Royles & P. K. Das (Edinburgh) applied their boundary-layer wind tunnel to determine the dynamic response of cantilever structures. The boundary layer was thickened by means of the vorticity generators developed by Counihan (1969). Turbulent velocity spectra were measured, and found not to simulate the spectra of the atmospheric natural wind as satisfactorily as in some other wind tunnels,† although the mean velocity and turbulence intensity profiles were satisfactory. The mean and r.m.s. bending moments were measured as functions of wind velocity and the natural frequencies and damping of the structures.

5. Discussions

Measurement techniques

Various methods were mentioned for measuring the high turbulence intensities found in boundary-layer flows over rough surfaces and near model buildings. Robins recommended the pulsed-wire anemometer (Bradbury & Castro 1971), which could be used in reversing flows. Frossling commented that the laser-Doppler anemometer was suitable but corrections might be needed close to a surface. Schon (Schon & Baille 1974) referred to a three-wire anemometer; Cermak uses a single wire rotated through a number of directions, and a five-wire probe was mentioned by Fiedler. There was some uncertainty as to whether these types of hot-wire anemometer could be used in flows where the velocity reverses or where the turbulence intensity is very high.

Meteorological data

Cermak described the new Wind Engineering Programme in the U.S.A., in which wind measurements are to be made at a large number of sites using sonic anemometers. It was pointed out that Counihan (1974) had recently carried out a comprehensive review of wind measurements in the atmospheric boundary layer. Scorer suggested that some thought should be given to considering how detailed the wind measurements should be before they are made. He wondered whether too much is already being found out.

The mechanics of simulation techniques and their limitations

Nee commented that it is important to investigate how a simulated boundary layer develops, and that detailed turbulence measurements are needed. But Gandemer, whose tunnel incorporated some unusual flow devices, emphasized that tunnels are there to do a job of work and there may not be time to study the details of flow development. With regard to simulating the stratification of the atmospheric boundary layer, Cermak and Schon commented that many situations could not be simulated, e.g. the strongest heating and cooling of the

† Dr Royles has subsequently pointed out to us that the instrumentation was at fault. In fact the spectra are similar to those of other investigators.

air by the ground, or the diurnal variation of ground temperature. The reason for the first defect is that the temperature difference between the ground surfaces in the wind tunnel and the air have to be much larger than in the atmosphere to simulate the correct Richardson number, and that there are limits to the magnitude of these wind-tunnel surface temperatures (Schon 1974). The reason for the second defect is that the thermal capacities of most wind-tunnel heating or cooling systems are too large to allow for the rapid changes in temperature required by the scaling laws. Hunt noted that some of the most stable airflows in the atmosphere (particularly flows round hills and various types of unsteady flow) are quite easily modelled in a small flume filled with a salt solution with a high concentration of salt at the bottom and a weak concentration at the top (Odell & Kovasznay 1971). There are also stable airflows which cannot be simulated this way. For simulating neutral conditions in the atmosphere large water tunnels have been used, in order to obtain higher Reynolds numbers. Furthermore flow visualization is often simpler in water.

Applications of wind-tunnel simulation methods

D. J. Hall (Stevenage, U.K.) mentioned how the wind tunnel at Warren Spring Laboratory had been used for modelling air pollution by particulate matter, and for modelling the accidental releases of dense gases such as propane and butane. He commented that the relatively large roughness elements used in simulating boundary layers affected in an unrealistic way the flow of dense gases. He believes that for this application correct modelling of the roughness height and shear near the ground is not as important as modelling the boundary layer above about 3 roughness heights. Cermak had also been modelling dispersion of particulate matter but had encountered considerable difficulties. His wind tunnel had been used to simulate snow drifting, using polystyrene particles $\frac{1}{2}$ mm in diameter; the blowing about of debris and waste paper in city centres near tall buildings; the dispersion of silver iodide in the atmosphere, which is used to induce rain; and lee waves behind mountains, particularly with a view to predicting the high ground-level winds they induce, which can pose severe wind loading problems; and to choose the optimum sites on hills for wind power generators. Hunt mentioned another type of application, that of investigating the aerodynamic noise created by oscillatory flows around buildings (Berhault & Davies 1974). In this case it is often more practical to examine the simulated flow and attempt to eliminate the oscillations in it rather than measure the sound generated by the wind-tunnel model. Frossling commented that the techniques developed for artificially thickening simulated atmospheric boundary layers could also be applied to simulating the thick boundary layers along ships' hulls.

The design of wind tunnels for simulating the atmospheric boundary layer

Plate attempted to define the optimum design for this kind of wind tunnel. Its test section should be about 10 m long and $2 \times 1{\cdot}5$ m in cross-section, as a bigger tunnel is too clumsy to use. The maximum wind speed should be 10 m/s, the side-wall boundary layers sucked off and the ceiling adjustable. An overpressure in the working section is desirable, but a recirculating tunnel is not necessary because low turbulence levels are not particularly important. Robins endorsed Plate's conclusion that a very large tunnel is undesirable as it takes too long to change models and to conduct experiments, but he thought that if buoyant plumes are to be simulated $\frac{1}{500}$ is the minimum scale possible. Cermak thought that there was no need for tunnels any larger than the largest being used at Fort Collins, Colorado, or Marchwood, U.K. He disagreed with Plate as to the optimum size, favouring a test section 20 m long and at least 3 m wide, the additional width being necessary to avoid any effects of the walls on the separated flows around model buildings. A number of other participants reiterated this point about the width. Wills thought that a tunnel should have a higher wind speed than 10 m/s for pressure fluctuation measurements. Fernholz asked the meeting their views on a suggestion that there was a need for a monster European industrial aerodynamics tunnel. The meeting was unanimous in saying no!

Appendix A

Table 1 lists some wind-tunnel simulation systems. It includes only wind tunnels at institutes which were invited to send or sent delegates to the Colloquium. There are some well-known wind tunnels used for simulation work in Canada, the U.S.A., the U.S.S.R., Japan and elsewhere which are not included in this list. However, it probably includes a good proportion of the major European systems. The data are as supplied by the institutes; there has been no external check. Universities are referred to by their towns, other institutes by initials. For reference purposes typical values of some of the parameters for the atmospheric boundary layer are also given, taken from Panofsky (1969). A few institutes supplied data on velocity spectra in neutral conditions, and these are shown in table 2 along with atmospheric data, from Busch & Panofsky (1968).

Key to table 1

Columns

(1) O, operational; P, planned.

(2) b, breadth; h, height; l, length of working section.

(3) Working sections: O, open jet; C, closed jet. Return: O, open; C, closed.

(4) F, fence; GG, graded or shear grids; J, jets; P, pulsation; R, roughness; S, step; Sc, screen; T, thermal stratification; UG, uniform grid; V, vortex or vorticity generators.

(6) *a.b.l.*, atmospheric boundary layer.

(7) δ, thickness of simulated wind-tunnel boundary layer.

(8) ν, kinematic viscosity; U_∞, free-stream velocity above the boundary layer.

(9) z, distance above surface; L, Monin–Oboukhov length.

All the subsequent data are for a neutral atmosphere.

(10) Development length is the length along the wind tunnel from the entrance of the working section to the region where the boundary layer simulates the *a.b.l.* in multiples of boundary-layer thickness δ.

(11) Length of the *a.b.l.* which is believed to be simulated, in multiples of δ.

(12) If the velocity profile is described by $U/U_\infty = (z/\delta)^\alpha$, then α is the power-law exponent.

(13) $U_* = (\tau_0/\rho)^{\frac{1}{2}}$, where τ_0 is the surface shear stress and ρ is the density of air.

(14) U_{30}, velocity in the tunnel at a height equivalent to 30 m above the ground in the atmosphere. (The usual meteorological height of 10 m was regarded as too close to the ground to be modelled satisfactorily.)

(15) z_0, roughness length.

(16) $(\overline{u^2})^{\frac{1}{2}}$, r.m.s. turbulent velocity parallel to the mean wind and the ground.

(17) $(\overline{v^2})^{\frac{1}{2}}$, r.m.s. turbulent velocity parallel to the ground and perpendicular to the mean wind.

(18) $(\overline{w^2})^{\frac{1}{2}}$, r.m.s. vertical turbulent velocity.

(19) L_x, approximate integral scale.

Rows: institutes

Austria

(1) Vienna

Denmark

(2) Lyngby

Germany

(3) Aachen
(4) Bochum
(5) Berlin
(6) Hannover
(7) Stuttgart

France

(8) Marseille
(9) Nantes (C.S.T.B.)
(10) Lyon
(11) Poitiers

Netherlands

(12) Amsterdam (N.L.R.)
(13) Eindhoven

Norway

(14) Trondheim

Sweden

(15) Göteborg

Switzerland

(16) Zurich (E.T.H.)

United Kingdom

(17) Bristol
(18) Watford (B.R.S.)
(19) Leatherhead (C.E.G.B.)
(20) Manchester
(21) Edinburgh
(22) Oxford
(23) Salford
(24) Southampton (Marchwood, C.E.G.B.)
(25) Stevenage (Warren Spring Laboratory)
(26) Teddington (N.P.L.)

U.S.A.

(27) Fort Collins, Colorado
(28) Notre Dame, Indiana

Row (29). Typical values in atmospheric boundary layer (neutral). ($U_\infty = 10\,\mathrm{m/s}$.)

	(1)	(2)			(3)		(4)	(5)	(6)	(7)	(8)	(9)
		Wind-tunnel dimensions (m)			Wind tunnel							
	Operational state	b	h	l	Working section	Return	Simulation method	Model scale / Full scale	Proportion of *a.b.l.* thickness simulated (%)	δ (m)	$(U_\infty'\delta/\nu)\times 10^{-5}$	Stratification parameter, z/L
(1)	*O*	1·7	1·2	10	*C*	*O*	*F*, *R*	1/200	80	0·6	20	0
(2*a*)*	*O*	1·1	1·1	13	*C*	*O*	*GG*, *R*	1/100–1/500	⩽40	0·6	5	0
(2*b*)*	*O*	1·0	0·7	2·6	*C* or *O*	*C*			—	0·35	20	0
(3)	*P*	1·5	1·2	3·0	*O*	*C*	*V*, *R*	1/200–1/400	—	—	50	0
(4)	*O*	2·1	2·1	4·3	*C*	*O*	*F*, *V*, *R*	1/500	100	0·84	—	0
(5)§	*P*	0·3	0·3	—	*C*	*O*	*S*	1/1000	100	0·2	3	0
(6)	*P*	2·4	2·4	24	*C*	*O*	*R*	1/300	40	0·8	10	0
(7)‡	*O*	1·4	1·4	2·8	*O*	*C*	*F*, *GG*, *P*	1/300	70	1·5	40	0
(8)*	*O*	3·2	1·5	40	*C*	*C*	*R*, *T*	1/20	—	0·75	40	−1·0 to +1·0
(9*a*)	*O*	2·0	2·0	13	*C*	*O*	*S*, *F*, *J*, *V*, *R*, *P*	1/400	100 or	1·0	—	0
(9*b*)	—	—	—	—	—	—	—	or 1/75	25	—	—	—
(10)§	*O*	1·0	1·2	10	*C*	*O*	*F*, *J*, *T*	1/500–1/1000	10	0·25	1·2	−0·3 to 0
(11)§	*O*	5·5	5·3	26	*C*	*C*	*GG*, *R T*	1/2000	100	2·5	3	—
(12)	*O*	2	1·2	4	*O*	*C*	*GG*, *R*	—	—	0·75	8	0
(13)	*P*	0·7	1·0	8·5	*C*	*C*	*F*, *R*, *T*	1/2000	15	0·03	2	−2·0 to 0
(14)	*P*	1·4	1·1	5·5	*C*	*C*	*GG*, *Sc*, *R*	—	—	—	—	0
(15)§	*P*	1·8	1·2	2·8	*C*	*C*	*F*, *V*, *R*	—	—	0·25	10	0
(16)	*O*	3	2·1	9	*C*	*C*	*GG*	1/200–1/1000	—	0·45	20	0
(17)†	*O*	1·0	1·0	12	*C*	*C*	*UG*, *S*, *R*	1/150–1/1000	20–50	1·5	—	0
(18)†§	*O*	2·0	1·0	8·0	*O*	*O*	*UG* or *V*, *F*, *R*	1/200–1/1000	30–100	1·5–0·9	20	0
(19*a*)§ (19*b*)†	*O*	4·6	1·5	11	*C*	*O*	*F*, *V*, *R*	1/500	100	1·2	20	0
(20)†	*O*	1·0	0·7	1·5	*C*	*O*	*F*, *GG*, *R*	1/250	25	2·4	60	0
(21)†	*O*	1·5	0·9	9	*O*	*O*	*V*, *Sc*, *R*	1/350–1/900	100	0·7	4	0
(22)§	*P*	4·0	2·0	14	*C*	*O*	*F*, *V*, *R*	1/200	100	2	20	—
							or *UG*, *F*, *R*	1/75	33	6	90	—
(23)	*O*	0·5	0·5	1·0	*C*	*O*	*UG*, *GG*, *Sc*	—	—	0·4	10	0
(24)‡	*O*	9·1	2·7	21	*C*	*O*	*F*, *V*, *R*	1/300	100	2	20	0
(25)§	*O*	4·3	1·5	22	*C*	*O*	*F*, *V*, *R*	1/50–1/800	30–50	1·0	6	0
(26)†	*O*	2·7	2·1	3·7	*C*	*C*	*GG*, *R*	1/240	—	1·5	20	0
(27*a*)	*O*	1·9	1·9	28	*C*	*C*	*F*, *V*, *R*, *T*	1/50–	100			
(27*b*)	*O*	1·9	1·9	19	*C*	*C*	*F*, *V*, *R*, *T*	1/15000	(neutral)	0·5–1·3	15	−0·2 to +0·2
(27*c*)	*O*	3·9	2·6	17	*C*	*O*	*F*, *V*, *R*		20 (stable)			
(28)	*O*	1·5	1·5	14	*C*	*O*	*J*, *R*	1/100	15	1·0	4	0
(29)	—	—	—	—	Rural Urban		—	—	—	500–600	400	0

Table 1. Simulation systems. Terrain simulated: †, urban; ‡, suburban; §, rural; *, sea surface

	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	
										Equivalent full scale	
	Development length/δ	Length of *b.l.* simulated/δ	Power-law exponent, α	$\frac{U_*}{U_\infty}$	$\frac{U_*}{U_{30}}$	$\frac{U_* z_0}{\nu}$	$\frac{(\overline{u^2})^{\frac{1}{2}}}{U_*}$	$\frac{(\overline{v^2})^{\frac{1}{2}}}{U_*}$	$\frac{(\overline{w^2})^{\frac{1}{2}}}{U_*}$	z_0 (m)	L_x (m)
(1)	13	5	—	—	—	—	—	—	—	—	—
(2a)*	10	5	—	0·03–0·04	—	1	1–2·5	0·75–1·9	0·75–1·9	0·08	60
(2b)*	5	2	—	0·04–0·05	—	300					
(3)	3	—	—	—	—	—	—	—	—	—	—
(4)	3	1	—	—	—	—	—	—	—	—	—
(5)§	8	8	—	—	—	—	—	—	—	—	—
(6)	28	—	—	—	—	—	—	—	—	—	—
(7)‡	0·5	0·5	0·24	0·06	0·13	—	2·5	—	—	—	—
(8)*	50	50	—	0·045	0·06	10	2·0	—	—	—	—
(9a)§	10	2·5	0·16	0·04	0·064	14–150	2·5	—	—	0·11	56
(9b)†	—	—	0·4	0·05	0·16	—	3·0	—	—	1·6	—
(10)§	34	—	—	0·03–0·04	—	—	1·5–2	1·5	1·3	—	—
(11)§	—	—	—	—	—	—	—	—	—	—	—
(12)	2·8	1·5	—	—	—	—	—	—	—	—	—
(13)	30–50	5–10	—	—	—	—	—	—	—	—	—
(14)	—	—	—	—	—	—	—	—	—	—	—
(15)§	7	2	—	0·03	—	40	3·3	—	—	—	—
(16)	2·5	3	—	0·05	0·1	—	3·2	2·4	—	—	—
(17)†	2·7	—	0·3	—	0·13	—	2·7	2·0	1·8	1·0	75
(18)†	—	—	—	—	—	—	—	—	—	—	—
(19a)§	3	20	—	0·046	0·070	3·8	2·6	1·7	1·3	0·1	100
(19b)†				0·053	0·14	172	2·3	1·0	1·0	2·2	45
(20)†	0·4	0·4	—	—	—	—	—	—	—	—	—
(21)†	4	2	0·36	0·05	0·14	80	1·8	—	—	1·9	—
(22)§	7	—	—	—	—	—	—	—	—	—	—
	2	—	—	—	—	—	—	—	—	—	—
(23)	1	2–4	—	—	—	—	—	—	—	—	—
(24)‡	4	4–5	—	0·065	0·144	250	2·6	2·0	1·4	1·3	126
(25)§	5–10	10	—	0·055	0·081	11	2·5	—	1·7	0·2	—
(26)†	—	—	—	0·07	0·14	905	2·2	—	2·2	2·6	40
(27a)§	12–30	12–30 (neutral)	—	0·03	0·045	4	1·8	1·9	1·3	0·2	70
(27b)	12–30 (neutral)	5–15	—	—	—	—	—	—	—	—	—
(27c)	—	10 (stratified)	—	—	—	—	—	—	—	—	—
(28)	6	5	—	0·044	0·08	—	3·1	—	—	—	—
(29)	Rural		0·16	0·03	0·05	6×10^2	2·6	2·0	1·3	0·03	100
	Urban		0·4	0·05	0·12	3×10^4		Approx. same		1·0	—

TABLE 1 (*cont.*)

$nz/U(z)$ at $z = 30$ m	Lyon	Fort Collins (Colorado)	Bristol	Leatherhead (C.E.G.B.)†	Marchwood (C.E.G.B.)	Teddington (N.P.L.) (at $z = 120$ m equivalent height)	Nantes (C.S.T.B.) ($z = 60$ m)	Met. measurement
				Values of $nS_u(n)/U_*^2$				
0·005	0·4	—	0·6	0·2	0·78	—	0·4	0·3–1·2
0·01	1·0	0·12	1·1	2·0	1·18	0·01	0·6	0·8–1·2
0·03	—	—	1·8	2·8	—	—	1·6	—
0·1	1·0	0·96	1·3	1·3	1·18	0·13	1·7	0·8–1·0
1·0	0·2	0·39	0·4	0·3	0·43	0·22	0·4	0·4–0·5
10·0	0·02	0·06	—	—	0·08	0·11	—	0·05–0·07
100·0	—	0·00	—	—	—	0·025	—	—
	Rural	Smooth surface	Urban	Urban	Suburban	Urban	Urban	Rural and sea surface
				Values of $nS_w(n)/U_*^2$				
$nz/U(z)$ at $z = 30$ m								
0·005	0·08	—	—	—	0·03	—	—	0·02–0·05
0·01	0·2	—	0·08	0·4	0·06	0·003	—	0·06–0·10
0·1	0·4	—	0·65	2·3	0·33	0·04	—	0·3–0·4
0·3	—	—	0·75	2·2	—	—	—	0·4–0·5
1·0	0·4	—	0·25	—	0·36	0·29	—	0·3–0·4
10·0	0·004	—	—	—	0·08	0·12	—	0·1
100·0	—	—	—	—	—	0·04	—	—
	Rural		Urban	Urban	Suburban	Urban	Urban	Rural and sea surface

† Multiplied by an arbitrary constant.

TABLE 2. Comparison of spectra

Appendix B

Here is a list of the questions sent to participants before the meeting. The discussion sessions did not by any means answer all the questions.†

Techniques and meteorological validity of different simulation methods

(1) How do the various simulation techniques work? (For example, grids, vortex generators, jets.)

(2) How are thermally stratified flows best simulated?

(3) Measurement techniques, in particular at high turbulence levels near the ground or near obstacles.

(4) Choice of appropriate meteorological data for comparison with wind-tunnel results.

(5) How do the data of the different simulation methods (cf. results of the questionnaire) compare with meteorological data?

(6) Which methods simulate which characteristics most satisfactorily?

(7) Is it possible to simulate the atmospheric boundary layer over only a small proportion of its depth or only over a limited distance in the downwind direction?

Application and relative merits of simulation methods

(1) What are current and future areas of application of simulated boundary layers in wind tunnels? (For example, wind loads on structures, wind environment of buildings, air pollution: what else?)

(2) Which flow characteristics of the atmospheric boundary layer (e.g. mean velocity profiles, variances, spectra and probability distributions of turbulent velocity components, thermal stratification) most need to be simulated for which type of application?

(3) What proportion of the depth of the atmospheric boundary layer need be simulated and over what downwind distance for different applications? (For example, diffusion tests have different requirements to wind loading tests.)

(4) How should the results of model-scale tests in simulated boundary layers be compared with those of full-scale tests?

(5) When comparisons have been made do the results suggest that the simulated boundary layers in wind tunnels now in operation are satisfactory, or do they need to be significantly improved?

(6) Are present wind tunnels adequate or are larger tunnels needed?

(7) What further comparisons need to be made between model-scale measurements in simulated boundary layers and full-scale measurements?

† At least one participant thought these questions were 'hopelessly naive and misleading'. So they are somewhat controversial!

REFERENCES

(An asterisk by a name indicates a lecture given at the Colloquium)

BERHAULT, J. P. A. & DAVIES, P. O. A. L. 1974 Wind noise in buildings. *Symp. on Full Scale Measurements of Wind Effects on Tall Buildings, University of Western Ontario.*

BONMARIN, P.* Exposé sur la grande soufflerie de simulation des interactions océan/atmosphère de l'IMST.

BOUQUET, R.* Simulation en soufflerie de l'évolution thermoconvective de gaz polluant dans l'environment d'une cheminée cylindrique.

BRADBURY, L. J. S. & CASTRO, I. P. 1971 A pulsed-wire technique for velocity measurements in highly turbulent flows. *J. Fluid Mech.* **49**, 657.

BRAY, C. G.* A family of wind-tunnel simulations.

BUSCH, N. & PANOFSKY, H. 1968 Recent spectra of atmospheric turbulence. *Quart. J. Roy. Met. Soc.* **94**, 132.

CERMAK, J. E. 1971 Laboratory simulation of the atmospheric boundary layer. *A.I.A.A. J.* **9**, 1746.

CERMAK, J. E. 1975 Applications of fluid mechanics to wind engineering – a Freeman scholar lecture. *J. Fluid Engng, A.S.M.E.* **97**, 9.

CERMAK, J. E.* Physical modelling of the atmospheric boundary layer in wind tunnels.

CHRISTENSEN, O.* Dynamic wind loading: a full-scale experiment.

COOK, N. 1973 On simulating the lower third of the urban adiabatic boundary layer in a wind tunnel. *Atmos. Environ.* **7**, 691.

COUNIHAN, J. 1969 An improved method of simulating an atmospheric boundary layer in a wind tunnel. *Atmos. Environ.* **3**, 197.

COUNIHAN, J. 1973 Simulation of an adiabatic urban boundary layer in a wind tunnel. *Atmos. Environ.* **7**, 673.

COUNIHAN, J. 1974 Structure and simulation of adiabatic atmospheric boundary layers. Ph.D. dissertation, City University. (To appear in *Atmos. Environ.* **9**.)

DEBLER, W.* Wind-tunnel measurements of turbulence decay in a stratified fluid.

DYE, R. C. F.* Investigation of profile simulation in short lengths by its effect on model results.

ELDER, J. W. 1959 Steady flow through non-uniform gauzes of arbitrary shape. *J. Fluid Mech.* **5**, 355.

FROSSLING, N. & KARLSSON, R.* Measurement of the wall shear stress in simulated boundary layers.

GANDEMER, J.* Wind-tunnel simulation of the atmospheric boundary layer at C.S.T.B.

HUNT, J. C. R. 1975 The effect of boundary conditions on the calculation of turbulent velocities. *Southampton Conf. on Coherent Structures in Turbulence, April* 1974.

HUNT, J. C. R.* A theoretical look at the problem of wind-tunnel simulation of the atmospheric boundary layer.

HUNT, J. C. R. & MULHEARN, P. J. 1973 Turbulent dispersion from sources near two-dimensional obstacles. *J. Fluid Mech.* **51**, 245.

HUNT, J. C. R., POULTON, E. C. & MUMFORD, J. C. 1975 The effects of wind on people; new criteria based on wind tunnel experiments. Submitted to *Building Sci.*

JACKSON, P. S. & HUNT, J. C. R. 1975 Turbulent wind flow over low hills. *Quart. J. Roy. Met. Soc.* (to appear).

LAWS, E. M. & LIVESEY, J. L.* Some recent work on shaped gauze screen simulation of velocity profiles.

NAGIB, H. M., MORKOVIN, M. V., YUNG, J. T. & TAN-ATICHAT, J. 1974 On modelling of atmospheric surface layers by the counter jet technique. *A.I.A.A. 8th. Aerodynamic Testing Conf. July* 1974, paper 74–638. (To appear in *A.I.A.A. J.*)

NEE, V.* The simulation of the atmospheric surface layer in the Notre Dame atmospheric wind tunnel.

NEE, V. W., DIETRICK, C., BETCHOV, R. & SZEWCZYK, A. A. 1973 The simulation of the atmospheric surface layer with volumetric flow control. *Proc. Inst. Environ. Sci.* pp. 483–487.

ODELL, G. M. & KOVASZNAY, L. S. G. 1971 A new type of water channel with density stratification. *J. Fluid Mech.* **50**, 535.

OSTROWSKI, J. S.* Wind-tunnel study of wind flow control past an industrial plant.

PANOFSKY, H. A. 1969 The structure of atmospheric shear flows – a review. *Agard. Conf. Proc.* no. 48.

PLATE, E. 1971 Aerodynamic characteristics of atmospheric boundary layers. *U.S. Atomic Energy Commission, Office of Information Services* (T.I.D. – 25465).

PLATE, E.* Review of wind-tunnel simulation of the atmospheric boundary layer.

RICHARDS, J. M. 1965 Puff motions in unstratified surroundings. *J. Fluid Mech.* **21**, 97.

ROBINS, A. 1975 Experimental model techniques for the investigation of the dispersion of chimney plumes. *Proc. Inst. Mech. Engrs*, **189**, 44.

ROBINS, A.* A 1/300 scale simulated atmospheric boundary layer for diffusion studies.

ROYLES, R. & DAS, P. K.* Application of a boundary-layer wind tunnel in the determination of the dynamic response of cantilever structures to wind excitation.

SCHON, J. 1974 Contribution à l'étude des couches limites turbulentes stratifiées en température. Thèse Doc. des Sci., Université Claude Bernard de Lyon.

SCHON, J.* Comparison of neutral and unstable stratified boundary layers in a wind tunnel and in the atmosphere.

SCHON, J. & BAILLE, A. 1974 Méthode d'isolement des fluctuations turbulentes cinématiques et thermiques au moyen d'une sonde anémométrique à trois fils. *C. R. Acad. Sci. Paris*, **274**, 116.

SCHON, J. P. & MERY, P. 1971 A preliminary study of the simulation of neutral atmospheric boundary layer using air injection in a wind tunnel. *Atmos. Environ.* **5**, 299.

SCORER, R. S.* Problems of atmospheric stratification.

SIMPSON, J. E. 1969 A comparison between laboratory and atmospheric density currents. *Quart. J. Roy. Met. Soc.* **95**, 758.

SNYDER, W. H. 1973 Similarity criteria for the application of fluid models to the study of air pollution meteorology. *Boundary Layer Met.* **3**, 113.

SUNDARAM, J. R., LUDWIG, G. R. & SKINNER, G. T. 1972 Modelling of the turbulence structure of the atmospheric surface layer. *A.I.A.A. J.* **10**, 743.

TOWNSEND, A. A. 1975 *The Structure of Turbulent Shear Flow*, 2nd edn. Cambridge University Press.

TUNSTALL, M. J. 1974 Some measurements of the wind load on Fawley Generating Station Chimney. *Proc. Symp. on Full Scale Fluid Dyn. Meas.* Engng Dept., University of Leicester.

WILLMARTH, W. W. & YANG, C. S. 1970 Wall pressure fluctuations beneath turbulent boundary layers on a flat plate and a cylinder. *J. Fluid Mech.* **41**, 47.

WILLS, J. A. B.* A method of atmospheric boundary layer simulation.

WISE, A. F. E. 1971 Effects due to groups of buildings. *Phil. Trans.* A **269**, 469.