J. Indian Inst. Sci. 62(A), May, 1980, Pp. 89–99

Mean wind velocity profiles in an artificially thickened boundary layer

S. SIVARAMAKRISHNAN
Indian Institute of Tropical Meteorology, Pune 411 005, India.

Received on June 25, 1979 ; Revised on May 1, 1980.

Abstract

Simulation of wind flow over different terrains under adiabatic conditions of the atmospheric boundary layer has been attempted in a wind tunnel using a velocity profile generator called honeycomb-cum-flat plate (HFP). The HFP was tested in a low-speed, short test section (0·61 × 0·61 m), open-circuit wind tunnel.

Measurements of mean velocity profiles downstream of HFP, at different speeds of the tunnel, reveal that the artificially generated boundary layer is considerably thick (about 32 to 34 cm) and developed at a downstream distance of 2·6 m. The profiles produced at free stream velocities 10–12 m/sec follow closely the power law profiles characteristic of flow, under adiabatic conditions of the atmosphere, over terrain of a level country with numerous scattered obstructions.

Key words : Wind tunnel simulation, atmospheric boundary layer, honeycomb, flat plate.

1. Introduction

The production of thick boundary layer in a wind tunnel is essential for studies of simulation or modelling the chief characteristics of the lower atmosphere in the laboratory. The boundary layer in a wind tunnel can be thickened to a desired height either by allowing it to develop naturally in a long test-section wind tunnel or artificially by means of devices like grids, rods, vortex generators, etc., in a short test-section wind tunnel. Cermak[1] attempted the simulation of wind and thermal characteristics of the atmospheric boundary layer in a meteorological wind tunnel of test section 29 m long wherein a boundary layer of 0·9 m height develops naturally. Adopting a system of 'elliptic wedge' generators and a castellated barrier, Counihan[2] produced a rough wall boundary layer of desired height in a short test-section wind tunnel.

An artificially thickened boundary layer need in fact reproduces the velocity and thermal terms of the flow field if the atmospheric phenomena are to be simulated. The velocity terms include mean velocity, intensity of turbulence, scale and spectrum of turbulence.

The lapse rate of temperature or potential temperature represent the thermal characteristics of the atmosphere. In strong winds adiabatic equilibrium prevails locally in the earth's boundary layer. If the simulation experiment is confined to events occurring in strong winds which result in a well mixed atmosphere, the stable and unstable states can be ignored. This means that in such situations the wind tunnel boundary layer need not reproduce the thermal terms of the flow field. Hence the artificially, thickened boundary layer should be capable of reproducing only the velocity terms appropriate to flows over different terrain features. The devices to be used should be chosen in accordance with the requirements. Counihan[3] developed a method for the simulation of rural and urban adiabatic boundary layers in a wind tunnel and has shown that the simulated flows and full-scale boundary layer flows are similar. While outlining the various methods of producing velocity gradients in a wind tunnel, Lawson[4] opines that no conclusion as to the relative merits of each method could be reached as long as the relative importance of each parameter is not known.

The present attempt envisages to grow a thick boundary layer in a short-test section wind tunnel by resorting to a method of combining a graded honeycomb and flat plates and to realise different types of velocity profiles.

2. Mean wind variation with height in the atmospheric boundary layer

Many forms for the law governing the variation of mean wind with height have been suggested as early as 1880. Counihan[5] has extensively reviewed and analysed the meteorological literature on fully developed adiabatic atmospheric boundary layer for the period from 1880 to 1972. To quote him : "The choice appears arbitrary as to whether the mean velocity profile is represented by log-law or a power law. The lower 30–50 m of the boundary layer is better represented by a log-law, and it is clearly incorrect to try to deduce a power law index from measurements made in this height range. However, the power law seems to give a better fit to most of the data over a greater height range and for high wind conditions." Hence if we describe the wind speed variation with height by the well-known power law :

$$U/U_{max} = (Z/Z_{max})^{\alpha}$$

U_{max} then will correspond, in wind tunnel simulations, to the free stream velocity at a height Z_{max} at the top of the boundary layer. U is the velocity at any height Z in the boundary layer region. In simulation experiments we may take U_{max} and Z_{max} to correspond to the gradient wind velocity U_G at the height Z_G in the atmosphere. The power profile exponent or index α is a function of atmospheric stability and the terrain roughness. In a neutral atmosphere wherein the thermal effects are not dominant, α is a function of only the terrain geometry.

Earlier Davenport[6] and subsequently Counihan[5] on the basis of their analysis of meteorological data have summarised wide range of values for the index α. The values of α for certain typical terrain are reproduced in Table I.

Table I

Type of terrain	Source	Value of a	Z_G
1. Rural terrain	Counihan	0·143–0·167	600 meters
2. Suburban areas	Counihan	0·21 –0·23	
3. Urban areas	Counihan	0·28	
4. Level surfaces with only low surface obstructions, *e.g.*, praire grassland, desert	Davenport	0·133	275 m
5. Level or slightly rolling surfaces with slightly larger surface obstructions, *e.g.*, farmland with very scattered trees and buildings	Davenport	0·154	305 m
6. Gently rolling, or level country with low obstructions and barriers : *e.g.*, open fields with walls and hedges, scattered trees and buildings	Davenport	0·1818	335 m
7. Rolling or level surface broken by more numerous obstructions of various sizes, *e.g.*, farmland, with small fields and dense hedges or barriers, scattered wind breaks of trees, scattered two-storey buildings	Davenport	0·222	366 m
8. Rolling or level surface uniformly covered with numerous large obstructions : *e.g.*, forest, scrub trees, parkland	Davenport	0·286	412 m
9. Very broken surfaces with large obstructions : *e.g.*, towns, suburbs, outskirts of large cities, farmland with numerous woods and copses and large wind breaks of tall trees	Davenport	0·333	457 m
10. Surface broken by extremely large obstructions : *e.g.*, centre of large city	Davenport	0·40–0·66	550 m

In Table I we see that the gradient height Z_G as given by Counihan and Davenport are different. According to Counihan, in choosing what may be considered as a practical and typical boundary layer height, some compromises must be made; *e.g.*, the height is clearly a function of both the gradient wind speed and the surface roughness. On the basis of reviewed data for high wind speeds (speeds greater than 5–7 ms^{-1} at anemometer level) Counihan recommends a value of 600 m as representing the average height of both rural and urban boundary layers. However, Davenport suggests that this height is a function of terrain type and proposes a value of 274 m for rural terrain and 518 m for urban terrain.

3. Basic approach

An artificially thickened turbulent boundary layer can be produced in a wind tunnel by any kind of obstruction on the tunnel floor. For instance, the shear flow in the atmosphere can be simulated by means of grids and the turbulence intensities by grids or coarse screens. In a neutral atmosphere, the laboratory simulation envisages simultaneous reproduction of velocity and turbulence intensity profiles, characteristic of flows over different types of terrain.

Gauzes, honeycombs and rods are some of the devices used for the production fo velocity and turbulence profiles by wake action, in wind tunnels. The scale and decay of turbulence downstream of grids or honeycombs in relation to the mesh size was described by Taylor[7] in his work on statistical theory of turbulence. Baines[8] (*see* Lawson[4]) used a honeycomb graded so that the cell length decreased with height and showed it was a practical proposition for the production of velocity profiles. By plugging the cells of honeycomb laboriously, by trial and error, Starr[9] (*see* Lawson[4]) produced the required velocity profiles. These lead to an understanding that a graded honeycomb will produce a sheared turbulent flow. But with a honeycomb in which the cell dimensions were once fixed, further modification to vary the profiles of velocity and turbulence at will will be cumbersome. This difficulty may be overcome to a certain extent by resorting to another system of barriers that could be used side by side with the honeycomb so that the resulting profiles could be varied. It is thought that the system of barriers could be a grid of flat plates, the differential spacing of which produces the desired velocity profiles by boundary layer action. Lloyd[10] had attempted the production of shear flow in wind tunnel by using an array of flat plates. For the production of turbulent shear flow he employed a method of placing upon the flat plates, turbulence or vortex generators, but the resultant scale of turbulence produced was small. One of the notable features in Lloyd's work was that for a given surface roughness and grid arrangement, a non-developing boundary layer, which is essential for studies on the dispersal of pollutants in the atmosphere, could be produced. This serves as an impetus to the adoption of flat plates for use along with graded honeycomb. The combination of honeycomb and flat plate generates the velocity profiles. The design of this honeycomb-cum-fla pltate (HFP) is described in section 4.

4. Design of honeycomb–cum–flat plate HF(P)

The distribution of velocity and turbulence downstream of any profile generator will depend mainly on the geometry of the device adopted and its position in the stream of air flow. In the case of honeycombs the geometry of the cells and its size (mesh length) determine the type of flow downstream. Studies of Taylor[7] reveal that when the turbulence of a definite scale is produced in a stream of air by a honeycomb, the size of the eddies which is defined by the scale of turbulence is a definite fraction of the mesh length provided the turbulence is not very small. Further the length of the cells of honeycomb in the stream direction gives an increased directive effect (*see* Pankhurst

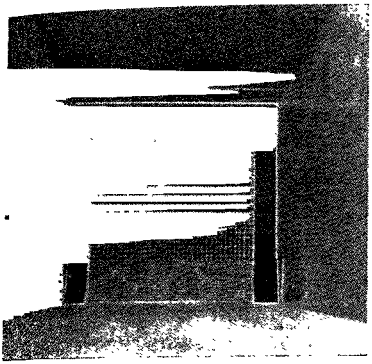

FIG. 1. Honeycomb-flat plate flush mounted at the entrance of test section inside the wind tunnel.

and Holder[11]), *i.e.*, the transverse components of the velocity fluctuations are diminished to a greater extent. The wakes of the cells introduce disturbance and turbulence into the flow. With a view to produce different eddy sizes, therefore, two different cell sizes 6·35 mm (¼″) mesh and 12·7 mm (½″) mesh were chosen with a cell length (depth of honeycomb) equal to 76·2 mm (3″). A perspex frame 457 mm × 457 mm (18″ × 18″) square in cross-section and 76·2 mm (3″) in width was prepared from 6·35 mm (¼″) thick perspex sheet and a graded honeycomb was built in it. The honeycomb extends to a height of 235 mm (9¼″) from the bottom of the frame, the first 115 mm (4½″) containing an array of 6·35 mm cells and the rest 12·7 mm cells. The remaining portion of the frame contains an array of flat plates above the honeycomb. Such an arrangement will produce different types of profiles of velocity and turbulence.

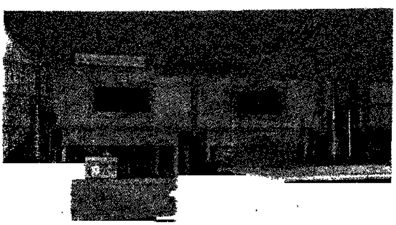

FIG. 2. Test section of the wind tunnel with the traverse arrangement placed at its top.

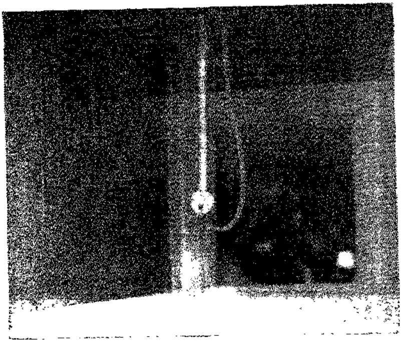

FIG. 3. Pitot tube inside the test section fitted to a traversing rod.

The cells of the honeycomb were made of 0·3 mm aluminium sheets and the flat plates of 1·65 mm aluminium sheets. The relative positions of the flat plates above the honeycomb are 20, 45, 70, 95 mm respectively. The choice of these positions is arbitrary and that by investigating the profiles downstream the position of the plates could be altered to a desired type of flow.

5. Experimental arrangement

The honeycomb-cum-flat plate was mounted inside the test section (dimensions: 0·61 × 0·61 m cross-section; 3 m length) of a low-speed wind tunnel, at the Central Water and Power Research Station (CWPRS), Khadakwasla, Pune. The tunnel develops a wall boundary layer of height that is quite small for boundary layer studies. Hence an attempt was made to thicken the boundary layer by artificial means. The HFP was flush mounted on the floor of the tunnel at the entrance of test section. The mounting was done as shown in Fig. 1; the base of HFP rests on the tunnel floor, the sides are about 70 mm away from tunnel side walls and there is a clearance space of about 274 mm between the tunnel top and the topmost of flat plates.

Figure 2 shows a three dimensional traverse positioned at the top of the test section and the Betz manometers used for measurement of pressures. The HFP can also be seen in the picture. The total head was measured using a pitot tube (Fig. 3). The static head was taken from the test section walls. The static head measured from the wall of test section was found to be nearly constant in the test section and equal to that measured using a standard static tube when measurements were made with HFP for a given speed of the tunnel. The pitot tube was traversed vertically (Z) starting from a distance Z_0 when the tube touches the wall, to several hundred millimeters above the

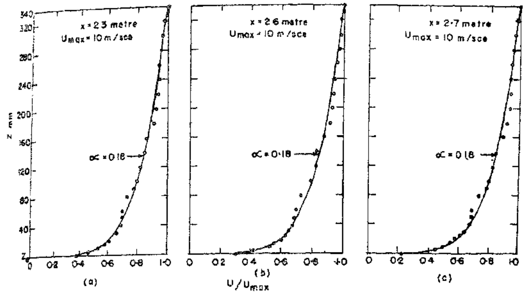

FIG. 4. Mean velocity profiles downstream of honeycomb-cum-flat plate inside wind tunnel for U_{max}=10 m/sec.

wall. The profiles were measured at several downstream (*X*) distances from HFP corresponding to the centre of the cross stream direction (*Y*), *i.e.*, the mid-width of the test section. The tests were conducted at low speeds of the tunnel starting from about 3·6 m/sec to about 12 m/sec. The scope of the present investigation is to ascertain the efficiency of HFP arrangement in producing velocity profiles comparable to that observed in the atmosphere.

6. Simulated profiles

Preliminary studies on the wall boundary layer thickness revealed that for a free stream velocity of 10 m/sec, the thickness of the wall boundary layer = 35 mm at 1·6 m downstream from entrance of test section in CWPRS wind tunnel. At 2·6 m the thickness is 45 mm.

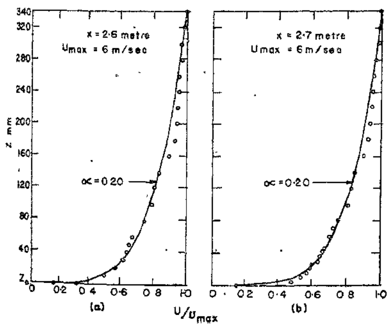

FIG. 5. Mean velocity profiles downstream of honeycomb-cum-flat plate inside wind tunnel for U_{max}=6 m/sec.

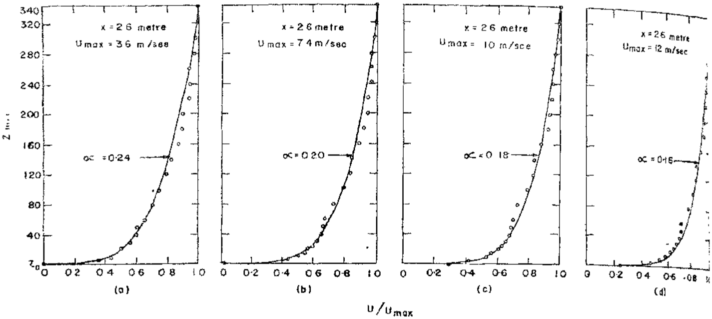

FIG. 6. Mean velocity profiles downstream of honeycomb-cum-flat plate for different wind tunnel speeds.

Earlier investigations on velocity profiles downstream of HFP were carried out in the India Meteorological Department's (IMD) wind tunnel at Pune. This low-speed wind tunnel has test section of 0·61 × 0·61 m in cross-section and 1·5 m in length. The profiles measured at 0·7 and 1·2 m downstream of HFP exhibited considerable waviness and necessitated further measurements downstream beyond these points.

The present investigation was done at the CWPRS wind tunnel. The test section dimensions of this low-speed tunnel are : 0·61 × 0·61 m cross-section; 3 m length. The profiles were measured at different speeds of the tunnel. The profiles showed signs of improvement as we traversed beyond 1·2 m downstream of HFP. The profiles got developed at 2·3 m downstream. At a free stream velocity U_{max} equal to 10 m/sec we see that the measured profiles in Fig. 4 follow closely a power law profile of power index equal to 0·18 fitted to them. In Fig. 5 we find that for U_{max}=6 m/sec, the profiles produced at 2·6 and 2·7 m downstream follow the power law index equal to 0·20. In Fig. 6 we find that the profiles at 2·6 m downstream of HFP follow different power law indices at different speeds of the tunnel.

The profiles in Figs. 4 to 6 correspond to the position of HFP mounted at the entrance of test section and the probe traversed vertically at a given distance downstream of it. The thickness of the boundary layer obtained in all these cases is found to be 320 mm.

We observe in Figs. 4, 5 and 6 that the power law index of the velocity profiles does not change with distance but changes only with wind speed. Fig. 6 reveals that at a given downstream distance, the velocity profiles follow different power law with diffe-

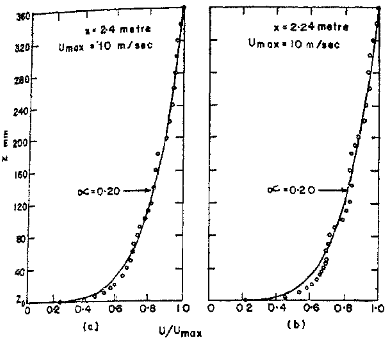

FIG. 7. Mean velocity profiles downstream of honeycomb-cum-flat plate by moving HFP towards the probe.

rent speeds. Qualitatively the shape of the profiles resembles the velocity distribution characteristic of a turbulent boundary layer flow. The changes in the profiles with speed are marked in the lower regions. This could be due to the grading of the honeycomb which produces varying blockage to the air stream. The mesh size of the honeycomb being different, the flow is retarded differently and the resulting velocity distribution is different at different speeds. Hence the velocity distribution follows velocity profiles of different power law index at different speeds.

In order to probe the effect on the profiles of moving HFP towards the probe the probe was fixed at 2·7 m from entrance of test section. The profiles obtained by moving HFP to a given position towards the probe is shown in Fig. 7. The profile at $U_{max} = 10$ m/sec is found to follow the power law of index equal to 0·20 when the distance of HFP upstream of probe is 2·40 m. The same power profile more or less holds at a distance of 2·24 m also but the profile tends to show waviness. Further displacement of HFP towards the probe resulted in considerably wavy profiles.

The thickness of the boundary layer in Fig. 7 is equal to 340 mm.

The earth's atmosphere is considered to be neutrally stable when the potential temperature lapse rate is zero. During these conditions, for the thermal effects to be swamped out by mechanical turbulence the wind speeds at anemometer level (10 m) would have to be around 5 m/sec. Viewing in this light, the profiles realized in Figs. 4 to 7 have significance to the mean wind velocity profiles prevailing over different terrains of the adiabatic atmosphere only for U_{max} equal to or above 10 m/sec. The profiles realized and fitted to a power law for speeds less than this value need not represent a neutral atmospheric wind profile. And in the absence of simulation of vertical thermal gradients, nothing can be said about these profiles except the fact that they represent the nature of profiles downstream of HFP at these speeds.

Taking into account the profiles realized at $U_{max}=10$ m/sec and 12 m/sec the measured profiles, following a power law variation, represent closely the profiles over a level country with low obstructions and barriers, *e.g.*, open fields with walls and hedges, scattered trees and buildings, or level surface broken by more numerous obstructions of various sizes: *e.g.*, farmland with small fields and dense hedges of barriers; scattered wind breaks of trees, scattered two-storey buildings[6]. The profiles in this case will correspond to a mean height Z_{max} equal to about 350 m.

7. Conclusion

Relatively thick boundary layer could be obtained using a honeycomb-cum-flat plate velocity profile generator. The height of the boundary layer generated using this generator is found to be comparable to the height of the generator. A downstream fetch of about 2·3 m (nearly 7 times the height of HFP) is required to realize developed profiles. The profiles corresponding to a free stream velocity of 10 to 12 m/sec exhibit closely the power law wind profile in an adiabatic atmosphere over a level terrain having numerous scattered obstructions.

8. Acknowledgements

The author wishes to thank the Director, Central Water and Power Research Station (CWPRS), Khadakwasla, Pune, and the Director, Instruments Section, IMD, Pune for the kind permission to use their wind tunnels, and the officers of the CWPRS' wind tunnel laboratory and the IMD's meteorologists for help and co-operation. The author is grateful to the Director, Indian Institute of Tropical Meteorology, Pune, and Dr. A. K. Kamra for their interest in this work and encouragement.

References

1. CERMAK, J. E. — *AIAA 3rd Fluid and Plasma Dynamics Conference*, July 1970, Paper No. 70–751.
2. COUNIHAN, J. — *Atmos. Environment*, 1969, **3**, 197–214.
3. COUNIHAN, J. — *Symposium on External Flows*, University of Bristol, July 1972.
4. LAWSON, T. V. — *Atmos. Environment*, 1968, **2**, 73–76.
5. COUNIHAN, J. — *Atmos. Environment*, 1975, **9**, 871–905.
6. DAVENPORT, A. G. — *J. Structural Division, Proceedings of the American Society of Civil Engineers*, 1960, **86**, No. ST5, 39–66.
7. TAYLOR, G. I. — *The Scientific Papers of G.I. Taylor*, Cambridge University Press, 1960, **2**, 288–315.
8. BAINES, W. D. — *Int. Conference on Wind Effects on Buildings and Structures*, NPL HMSO, London, 1963, Paper 6.

9. STARR, M. R. *The Characteristics of Shear Flows Past Circular Cylinders*, Ph.D Thesis, Department of Civil Engineering, University of Bristol, 1966.

10. LLOYD, A. *Q.J.R. Met. Soc.*, 1967, **93**, 79–96.

11. PANKHURST, R. C. AND HOLDER, D. W. *Wind Tunnel Technique*, Sir Isaac Pitman and Sons, Ltd , London, 1952, p. 84.