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On simulating the varying fraction of the lower part of the adiabatic boundary layer

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ABSTRACT. Results of a theoretical study on the feasibility and techniques of simulating the varying fraction of the lower part of the natural boundary layer in a wind tunnel are presented. It is shown that from the mean velocity profile point of view the entire simulated boundary layer may correspond to the lowest fraction of the atmospheric boundary layer desired, within reason. However, the turbulence intensity characteristics may impose certain restrictions on the height of the simulated boundary layer that may correspond to any desired fraction of the lower part of the natural boundary layer, while simulating the lower 30 to 100 m of the atmosphere. Alternatively, while simulating the lower 100 to 300 m of the atmosphere(natural boundary layer thickness$\simeq$700m) the turbulence intensity characteristics may impose certain limits on the extent of the atmospheric boundary layer, the simulated boundary layer may correspond to. As long as the power spectra in the simulated boundary layer do not show any significant change with height and show good agreement with the von Karman model spectrum, the simulated boundary layer may be taken to correspond to lowest desired fraction of the atmospheric boundary layer, within reason; but adequate inertial frequency range should be generated in the simulated turbulent boundary layer. The atmospheric boundary layer height of at least two to three times the structure height should be simulated. Further, proper simulation of the turbulence characteristics should be of primary importance and correct simulation of the shear profile should be of secondary importance.

Introduction

Recent studies have shown that the natural adiabatic boundary layer height over a city varies between 500 to 1000 m with a rounded average of say 700 m. The maximum boundary layer height that can be generated in a wind tunnel is about 1m. This gives a model scale of 1 : 700, since according to present practice the model scale is given by the ratio of the wind tunnel boundary layer height to the natural boundary layer height. For a typical high-rise building of 50 m height, this gives a model height of 0·07 m which is too small to reproduce any minor details of secondary importance in the model.

The present trend is to simulate the entire boundary layer height in a wind tunnel with exception of Cook (1973) who has recently tried to simulate the lower third of the atmospheric boundary layer in a wind tunnel. We are not aware of any investigations as to the need of simulating the upper part of the boundary layer. For some purposes, it may be adequate to simulate only the lower portion of the boundary layer, say 2 to 3 times the height of a building. If this conjecture is true it should be possible to use much bigger models. For example, if we need to simulate only a fraction of the boundary layer, say 3 times the height of a building 50m high, the model scale can be increased upto 1 : 150, allowing models 0·33 m high to be used instead of 0·07 m for the same wind tunnel facility.

With this in mind an attempt was made to generate a varying fraction of the lower part of the atmospheric boundary layer in a wind tunnel. After considerable unsuccessful efforts it was realised that there was no unique way of defining the varying fraction of the atmospheric boundary layer. The reason is that the natural boundary layer thickness varies with terrain, atmospheric stability, wind velocity etc and further the magnitude and direction of the wind speed at the edge of the boundary layer can vary considerably within a short time. Thus, one is left with neither a reference velocity† nor a reference height to define fraction of the boundary layer. The only alternative left was to start on a fundamentally new venture to investigate as to what are the similarities and the distinguishing features of the various layers of the neutrally stable atmospheric boundary layer.

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†Friction velocity is valid only in the lower 30m of the natural boundary layer and therefore cannot be used as a reference velocity for defining fraction of the boundary layer outside the range of 30 m.

It is believed that results of this investigation should be of interest to researchers from various fields including building aerodynamics, micrometeorology, environmental sciences, agriculture, biology etc and are therefore reported briefly here.

2. Characteristics of the Atmospheric Boundary Layer

The flow characteristics of the atmospheric boundary layer may be studied in terms of its shear and turbulence. The shear of the atmosphere may be characterised by the shape of the mean velocity profile. The characteristics of the atmospheric turbulence of primary importance in building aerodynamical investigations are believed to be :

(*a*) Turbulence intensity distribution in the vertical direction
(*b*) Turbulence energy spectrum
(*c*) Turbulence length scales.

Turbulence length scales are generally derived from either the power-spectral density measurements or auto-correlation measurements. Thus correct simulation of the turbulence energy spectrum implies proper simulation of the length scales. However, turbulence length scales may also be determined from space correlation measurements (this is how the concept of length scales was originally introduced).

Of the three components of turbulence fluctuations, the most important for building aerodynamics investigations, as per general practice, is the longitudinal component of the turbulence intensity. Besides, in the lower part of the natural boundary layer the lateral turbulence intensity is smaller than the longitudinal intensity and the vertical component is still smaller (Harris 1970). Thus, for most building aerodynamics investigations neglect of proper simulation of the lateral and the vertical components of turbulence does not introduce any significant errors. However, for certain tests involving masts and towers, *e.g.*, the lateral component of turbulence may be of importance and in investigations of bridges both the lateral and the vertical components of turbulence may be of importance.

Thus, the atmospheric turbulence may be characterised in terms of the variation of the longitudinal turbulence intensity in the vertical direction and the corresponding power spectral density distribution.

2·1. *Mean velocity profile shape*

The velocity profile through the depth of the boundary layer may be approximated by a power law of the form

$$\frac{U}{U_1} = \left(\frac{Z}{Z_1}\right)^{1/n}$$

where U and U_1 are the velocities at height Z and Z_1 respectively, and n is the inverse power law index. Z_1 is a reference height (which in micrometeorology is commonly taken as 10 m and in wind tunnel work as the boundary layer thickness δ) and U_1 is the corresponding reference velocity.

In wind tunnel work δ is defined as

$$\delta = (Z)_{1-\frac{U}{U\infty}=0.01}$$

whereas according to the power law representation the velocity profile is monotonically increasing and there is no unique definition of δ. Further, there is no point in the power law velocity profile where the shear profile is parallel to the height axis (or $dU/dZ=0$). However, this is a limitation one has to accept in the power law representation of the shear profile. As an alternative the other velocity profile representation form is the log-linear law (U linear with log Z) which is valid only in approximately the lower 30 m. Nevertheless, we will adopt the power law representation of the shear profile and study the various layers of the natural boundary layer with the view of simulating the varying fraction of the lower part of the atmospheric boundary layer.

Fig. 1 shows a typical atmospheric boundary layer (δ=500 m, n=5, U_1=10 m/s at 10 m) profile in a power law form. Also marked in Fig. 1 are the various layers of the atmosphere, *viz* the lower fifth ($\delta_{1/5}$) and the lower tenth ($\delta_{1/10}$) of the atmospheric boundary layer.

If the lower fifth and the lower tenth of the atmospheric boundary layer are plotted on an enlarged scale five times and ten times the original scales., respectively they compare with the full scale natural boundary layer profile for the same reference velocity (U_1=10 m/s) at the same reference height (Z_1=10m) as shown in Fig. 2.

The curve No. 2 in Fig.2 could also correspond to the complete atmospheric boundary layer with the same boundary layer thickness (δ=500 m) and the same power law index (n=5) but with a different reference flow velocity (U_1=7.25 m/s) at the same refernce height (Z_1=10m). Similarly the curve number 3 may also represent the full scale boundary layer with the same δ (=500m) and n(=5) but for different U_1 (=6.31m/s) at Z_1=10 m. Thus both the curves 2 and 3 may correspond to both fractional boundary layers (the lower fifth and the lower tenth of the complete natural boundary layor, respectively) and the complete atmospheric boundary layer with the same boundary layer thickness and power law exponent as profile 1 but different reference flow velocity at the same reference height. This becomes perhaps more obvious from Fig. 3 which shows the various layers of the atmosphere for varyind refrence flow velocities. The 500 mb thick atmospheric layer profile with a reference flow velocity of 10 m/s at a height of 10 m

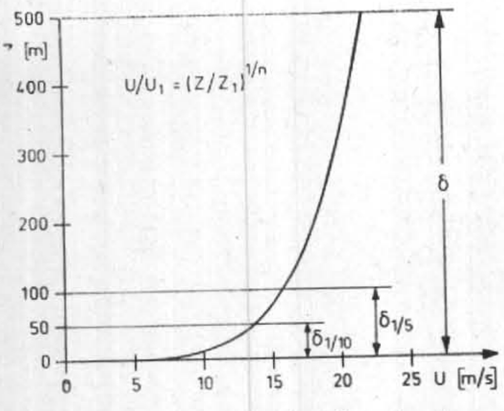

Fig. 1. A typical atmospheric boundary layer mean velocity profile ($\delta = 500$ m, $n = 5$, $U_1 = 10$ m/s at 10 m)

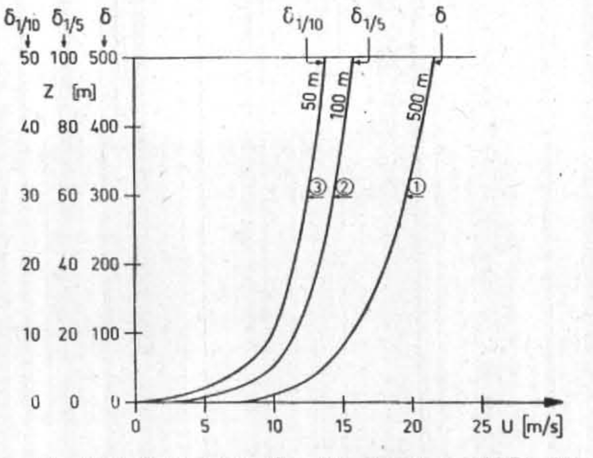

Fig. 2. Complete atmosphere boundary layer (ABL), lower fifth of the ABL and lower tenth of the ABL (all from Fig. 1) plotted together on correspondingly increasing scales

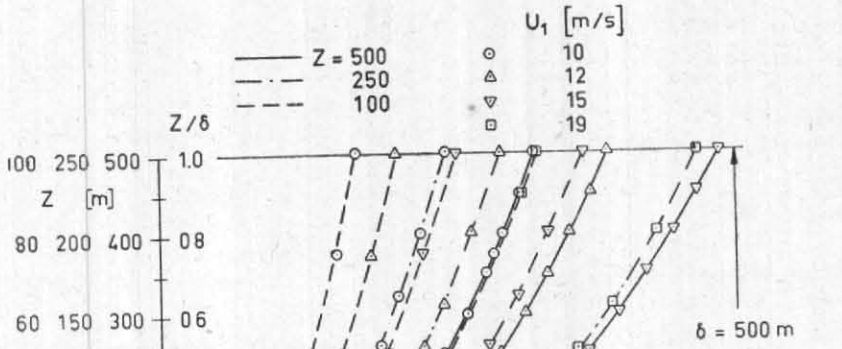

Fig. 3. Various layers of the atmosphere for varying reference flow velocities at $Z_1 = 10$ m, for the same power law index ($n = 2\cdot5$)

almost concides with the mean velocity profile for the 100m thick atmospheric layer with a reference flow velocity of 19 m/s at the same reference height of 10 m. Similarly by choosing a proper combination of the atmospheric boundary layer thickness and the reference flow velocity one can show any two arbitrary mean velocity profiles of different boundary layer thickness to be identical.

Thus, a given power law curve may correspond to the various layers of the atmosphere for varying reference flow velocity U_1 at a given reference height Z_1. In fact, the effect of increasing the reference velocity U_1 at a given reference height Z_1 is the same as that of reducing the height of the boundary layer to which a given velocity profile curve may correspond, for the same boundary layer thickness and the power law exponent.

Since one does not need to specify the reference flow velocity U_1 (Reynolds number similarity is automatically satisfied for bluff bodies and rough surfaces) one may assume as high a U_1 in nature as necessary, within reason, and correspondingly one may take the simulated mean velocity profile curve to correspond to the lowest fraction of the atmospheric boundary layer desired. Thus one may choose the highest model size (since the model scale is generally assumed to be given by the ratio of the wind tunnel boundary layer height to the corresponding full scale boundary layer height simulated in the wind tunnel) as dictated by the wind tunnel height and the wind tunnel blockage.

2.2. *Longitudinal turbulence intensity*

Fig. 4 shows the distribution of the longitudinal turbulence intensity (defined as the ratio of the rms value of the fluctuating velocity to mean flow velocity at the top edge of the boundary layer) in the vertical direction from full scale measurements for three different sites. For Brookhaven, the turbulence intensity increases with height, but scatter in the data is too large to suggest any thing definite. For Sale, the turbulence intensity is almost constant with height, at least in the lower part of the boundary layer, but the data are too scanty to conclude anything with certainty. For Rugby, the turbulence profile shows a maximum in the very lower layers of the atmosphere, then shows a definite decreasing trend and in the middle layers of the atmosphere is almost constant. Shitoni and Arai (1967) noted that u'/U varied from 0.03 to 0.25, at the same location, depending upon strength and direction of the wind.

Notwithstanding the contradictory trends in the various turbulence profiles from different terrains, it is generally agreed [based partially on the above data; for a summary of the data on turbulence characteristics of the atmosphere (*see* Shárán 1976 b)] that the turbulence intensity over suburban terrain is in the range of 10 per cent and over urban terrain, it is higher, perhaps upto 15 to 20 per cent; over rural terrain it is even less than 10 per cent. However, the turbulence level may show some variation from the above depending upon any changes in surface roughness of local nature, direction and/or strength of the wind etc.

It is generally believed, based on scant and scattered results, that the turbulence intensity does not show any significant variation with height in the lower layers, except very close to the ground where turbulence is primarily controlled by the local nature of the terrain. Further, any changes in a short stretch of surface roughness primarily influence only the lower layers of the boundary layer; this is confirmed by our measurements on the effects of changes in the nature and distribution of surface roughness on flow development downstream, to be reported later. This suggests that even though the turbulence intensity over an urban terrain is reported to be higher than over suburban terrain or rural terrain in the lower layers of the atmoshere (where most of the measurements have been carried out), the turbulence level may not differ very much over different kinds of terrains in the upper and perhaps the middle layers of the atmosphere.

The ambiguity reflected in the above discussion of the turbulence intensity distribution is mainly because of lack of data on the turbulence intensity variation in the atmosphere. However, it may safely be said that in the lower part of the natural boundary layer, the longitudinal turbulence intensity varies between 10 to 20 per cent depending upon the type of terrain and is almost constant with perhaps a slightly decreasing trend with height. The turbulence intensity decreases further perhaps significantly, with height in the middle and upper layers of the atmosphere. At very high altitudes one encounters what is commonly termed as "Clear Air Turbulence".

For the purpose of simulating the varying fraction of the lower part of the natural boundary layer, it may be said that, the larger the extent of the constant turbulence intensity region in the simulated wind tunnel boundary layer, the lower the fraction of the atmospheric boundary layer, the simulated boundary layer may correspond to. Further, as long as the turbulence intensity does not show a very significant decrease in the upper part of the simulated boundary layer, the entire simulated turbulent boundary layer, and not only the region of the constant turbulence intensity, may correspond to the varying fraction of the lower part of the natural boundary layer. However, the turbulence intensity characteristics may restrict the limit of the lowest fraction of the atmospheric boundary layer, an artificially thickened turbulent boundary layer may correspond to; the velocity profile does not impose any such restrictions.

2.3 *Power spectral density*

A number of analytical expressions have been suggested to represent the longitudinal power spectrum, of which the von Karman model provides the best fit to the data from the various sites and varying stability, if a suitable scale value is used in the model (Gunter *et al.* 1969, Templin 1969). Besides, the spectral model proposed independently by Harris (1970), based on data collected by Davenport (1961) from various sources, is identical with the von Karman model. This lends further weight to the credibility of the von Karman spectrum model, and therefore, the von Karman spectral model is used to represent the atmospheric turbulence power spectrum which is given by $\frac{\phi_{xx}{}^{(n)}}{u'^2} = \frac{4L/U}{[1+70.78(nL/U)^2]^{5/6}}$

The model (Fig. 5), based on the assumption of isotropy, does not show any explicit dependence on height, except if one assumes that the scale

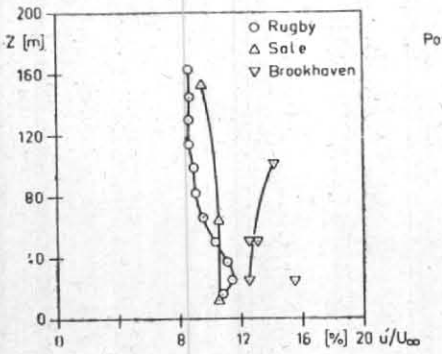

Fig. 4. Available data on the variation of longitudinal turbulence intensity in the vertical direction. Rughby results from Harris (1970); Sale and Brookhaven results from Davenport and Isyumov (1967).

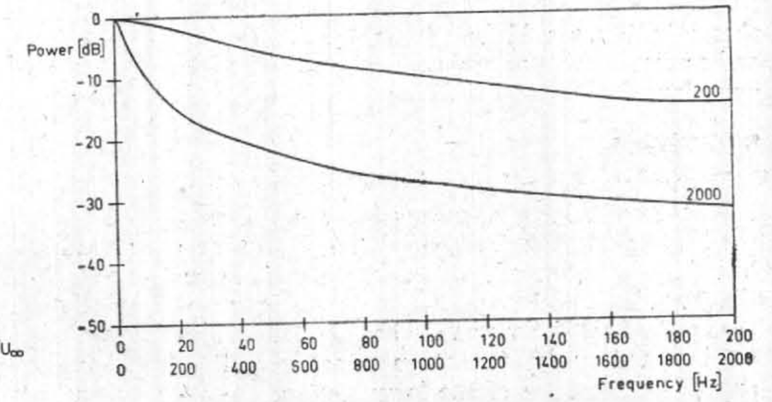

Fig. 5. Graphical representation of the von Karman model for longitudinal power spectrum

length appearing in the von Karman model, varies with height; in building arodynamics investigations one generally assumes a constant value for this scale length. Further, it is generally believed that the longitudinal power spectrum is invariant with height (Shárán 1976 b).

It should be noted that all the proposed model spectra are valid in the inertial subrange and do not take into account the viscous subrange. It is not a serious restriction since the viscous subrange is usually beyond the frequency range that affects the motions of aircrafts, buildings and other structures. Templin (1969) has suggested that as long as the inertial frequency subrange extends to between 1 to 2 orders of magnitude along the frequency scale from the spectral peak, the spectral range of the simulated boundary layer, of thickness 0.30 m or more, should be adequate for most building aerodynamics and other engineering investigations.

Thus, as long as the power spectra in the simulated boundary layer do not show any significant change with height and show good agreement with the von Karman model spectrum in the above mentioned frequency range, the simulated boundary layer may be taken to correspond to the lowest fraction of the atmospheric boundary layer desired.

3. Wind Tunnel Investigations.

The experimental investigation was divided into two parts. In part one, the flow characteristics of the various simulating elements such as plane, castellated and perforated barriers, turbulence, generators, surface roughnesses etc were studied, first in isolation and then in various combinations. Subsequently, similarities in the so generated turbulent boundary layers and the lower portion of the atmospheric boundary layer were studied in detail. Further tests were carried out to enable one to exercise greater control on the flow features of the artificially thickened turbulent boundary layers, by varying, for example, either the barrier height or porosity or the stretch length of the surface roughness in the downstream direction. Following this a synthesis of the simulation work was carried out and it is hoped that the results of this part of the investigation will be published later.

In part two, characteristics of flow around five different building models immersed in the above generated turbulent boundary layers were studied from the point of view of investigating the important characteristics of the atmospheric boundary layer to be simulated in the wind tunnel for building aerodynamics investigations. Tests were also conducted to determine the minimum height of the lower part of the natural boundary layer to be simulated in the wind tunnel (Shárán 1973, 1975, 1976 a). It was tentatively concluded that the atmospheric boundary layer height of at least two to three times the structure height should be simulated in the wind tunnel. It is essential to produce the correct atmospheric turbulence characteristics in the simulated turbulent boundary layer. However, the exact shape of the velocity profile is not of major importance and any inconsistencies in the shear profile of the simulated boundary layer and the atmospheric boundary layer should not affect the flow around the structure significantly. Further, proper simulation of the turbulence characteristics would inherently imply reasonable simulation of the shear profile because of the close relationship between shear and turbulence. This corroborates the earlier conclusion that proper simulation of the turbulence characteristics should be of primary importance and correct simulation of shear profile of secondary importance.

4. Conclusions

From the mean velocity profile point of view, the entire simulated boundary layer may correspond to the lowest fraction of the atmospheric boundary layer desired, within reason. However, the turbulence intensity characteristics may impose certain restrictions on the height of the simulated boundary layer that may correspond to any desired fraction of the lower part of the atmospheric boundary layer. The power spectra in the simulated boundary layer should show good agreement with the von Karman model spectrum and should not show any significant variation in the vertical direction. Further, adequate inertial frequency range should be generated in the simulated turbulent boundary layer. It is imperative to simulate the correct turbulence characteristics and shear profile is only of secondary importance. It is believed that this provides a theoretical basis and a fundamental framework for simulating the varying fraction of the lower part of the atmospheric boundary layer.

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LIST OF SYMBOLS

L	length scale
n	frequency in Hz; inverse power law index
u'	rms value of the fluctuating velocity in the longitudinal direction
U	local flow velocity
U_1	reference flow velocity
U_∞	flow velocity at edge of the boundary layer
Z	height in the vertical direction
Z_1	reference height
α	power law exponent
(δ)	boundary layer thickness
$\phi_{xx}(n)$	longitudinal power spectral density