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Turbulent Flow Over a Very Rough Surface

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SUMMARY A knowledge of the nature of turbulent flow over very rough surfaces is important for an understanding of the environment of crops, forests, and cities. For this reason, a wind-tunnel investigation was carried out on the variations in mean velocity and Reynolds shear stress above a rough surface having a fair degree of randomness in the shapes, sizes, and positions of its elements.

There was a layer close to the surface with considerable variations in both mean velocity and shear stress, and it was found that the horizontal scale over which the mean velocity varied was much larger than the average distance between roughness elements. Above this layer, whose depth was of the order of the roughness element spacing, shear stress was constant with height, and the velocity profile had a logarithmic form. The usefulness of both mean profile and eddy correlation methods for estimating fluxes above very rough terrain is discussed in the light of these findings.

1 INTRODUCTION

The difficulties associated with the application of conventional flux-gradient relations to the flow above very rough surfaces, such as crops, forests, and urban areas, have received increasing attention in recent years [e.g., Thom et al. (1975)]. The theoretical derivation of the form of the mean velocity profile above a rough surface has been discussed by Tennekes and Lumley (1972, pp. 146-7), who showed that the classic logarithmic law is valid only for $z/k \gg 1$, where z is height above the ground, and k a characteristic height of the roughness. It follows that, immediately above very rough surfaces such as forests and towns, when $z/k = O(1)$, there is no reason to expect the log-law to hold. However, it is not known how large z/k has to be.

Because of the influence of individual roughness elements, there is, close to a rough surface, a region in which the mean velocity varies horizontally. The decrease in shear stress as the surface is approached, reported in the laboratory experiments of Chanda (1958), Makita (1968), and Antonia and Luxton (1971) is, perhaps, associated with this region. Its depth is unknown over most surfaces.

To improve understanding of the flow above very rough surfaces, a wind-tunnel investigation of the flow over a surface whose elements had a fair degree of randomness in their sizes, shapes, and positions was carried out. This study is part of a wider wind-tunnel programme designed to model transfer processes in the lower atmosphere. The extent to which the wind-tunnel flow simulated atmospheric flow over rough terrain is discussed.

2 EXPERIMENTAL ARRANGEMENT

2.1 Wind-Tunnel Set Up

Experiments were performed in an open-return, blower wind-tunnel with working section 1.83 m wide, 0.61 m high, and 11 m long. More details on this tunnel are in Mulhearn et al. (1976). To generate a deep turbulent flow, a 49 mm high fence was placed at the start of the working-section. (Its separation bubble was 19 fence heights long.) The fence was followed by 1.22 m of smooth surface and 4.88 m of the very rough random surface, which was formed by coarse gravel glued to 0.61 m x 1.83 m sheets of particle board.

The gravel pieces were arranged, as nearly as possible, at random. To do this without having large scale variations in the number of roughness elements/unit area a fixed weight of 1.59 kg of gravel was glued, at random, to each 0.61 m x 0.61m square of the surface. The stones were, however, arranged so as to avoid any obvious large spaces and so that very few were touching. There were, on average, 1017 stones/m^2. The stones had a bulk density of 2660 kg m^{-3}, and if the shape of each stone is approximated by a sphere, it can be shown that an average diameter is 14.5 mm. The rough surface is shown in Figure 1.

Figure 1 The drag plate in the rough surface

A rough surface can be characterised by the autocorrelation of surface height. The height variation along two parallel straight lines 1.2 m long and 80 mm apart was determined. One of these traverses is illustrated in Figure 2, where r is the distance from an arbitrary origin, and h is the maximum stone height along the straight line. A stone width along this line is represented by the width of the corresponding "square-wave" pulse. Approximate autocorrelations R(Δr) of surface height were formed from these trains of pulses, and are presented in Figure 3. Beyond separations, Δr, greater than 100 mm the autocorrelation shape was not reproducible, due to limited sample length. The average spacing between stones along the two traverses was 47 mm. It can be seen that the correlation is low for distances greater than this, but that there is evidence of periodicity in the spatial distribution of stones. The power spectrum of surface height was also obtained and its only feature was a large, broad peak at a wave number of 19 m^{-1}, which is close to 21 m^{-1} the average number of stones per metre along the two traverses.

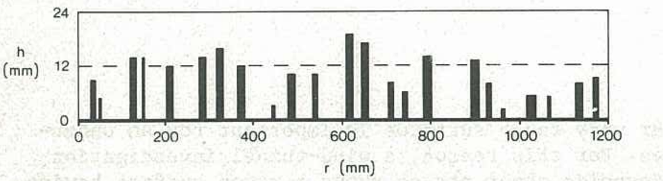

Figure 2 Height variation of rough surface along a 1200 mm straight line. Dashed line is level of zero plane displacement, from log-law.

There is evidently some weak periodicity in the positions of stones. The effect of the rough surface on the air flow may be even less periodic than these results suggest. Because velocity increase rapidly with height, tall stones will exert a disproportionately larger effect than short ones. The variation of surface height above 12 mm (the approximate level found for the zero-plane displacement, from an assumed log-law) can be seen for one traverse in Figure 2. In the other traverse only one stone was taller than 12 mm. No particular physical significance need be attached to the level of zero-plane displacement, but the large variability in the positions of tall stones suggests that surface drag may be distributed in a very random fashion.

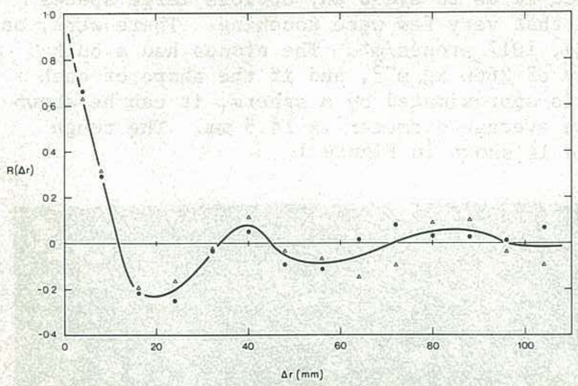

Figure 3 Autocorrelations of surface roughness: ●, traverse 1; △, traverse 2.

The roof of the wind-tunnel was adjusted to obtain zero pressure-gradient. The pressure was constant within ± ½% of the dynamic pressure, measured at 0.25 m height, for streamwise distances greater than 2.65 m from the start of the working section. Because the flow accelerated over the fence at the start of the working section, there was an adverse pressure gradient for distances less than 2.65 m.

The combined effects of the fence at the start of the working section, and the very rough surface, were to produce a turbulent shear flow which by the end of the gravel surface almost filled the whole tunnel. There were, however, still some patches of irrotational fluid which had not been entrained into the turbulent region.

It is unlikely that the results reported here were influenced by turbulence from the 49 mm fence at the start of the working-section, because the measurements were performed 110 to 120 fence heights downstream of the fence and the surface was extremely rough.

2.2 INSTRUMENTATION

Mean velocities were measured with a boundary-layer pitot tube of stainless-steel tubing. It had a flattened mouth with an internal height of 0.8 mm. Turbulence quantities were measured with an X-configuration hot-wire anemometer probe (Disa type 55 P63) connected to two channels of Thermo-Systems Inc. Model 1050 hot-wire anemometry. The anemometers were connected to an Electronic Associates Inc. TR-20 Analogue Computer, where the signals were scaled to vary from -5 volts, at zero wind speed, to +4.3 volts at maximum wind speed. The signals were then fed to a Digital Electronics Corporation PDP11/40 Computer to be digitised and stored on magnetic tape for later processing. Linearisation was performed by the digital computer.

The X-configuration hot-wire probes and the data analysis system were checked by moving a probe around a known path, in a uniform air flow, at a number of rotation rates. The Reynold's shear-stress, which should have been sensed by the probe, was readily calculated, and agreed, within a few percent, with that produced by the measurement system.

The drag on a section of the rough floor was measured directly with a drag-plate, built on the same principle as that described by Lynch and Bradley (1974).

3 RESULTS

Throughout this paper X is measured downstream of the last roughness sheet, so that negative X values signify distance upstream of this position. z is height above the base-board to which the stones are glued.

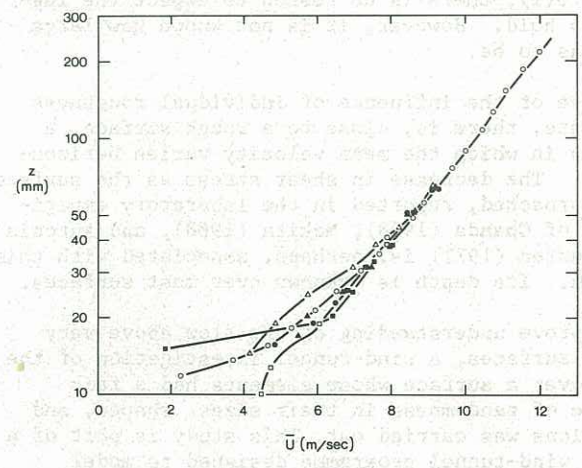

Figure 4 Mean velocity profiles at various streamwise locations:

□, X = -190 mm; ■, X = -392 mm; ○, X = -497 mm; ●, X = -595 mm; △, X = -913 mm; ▲, X = -1142 mm.

In Figure 4, mean velocity ($\bar{U}$) profiles obtained at various streamwise locations over the rough surface are presented . (The profiles are really of $\sqrt{P}$ where P = total pressure measured by a pitot tube less the static pressure well above the roughness. Very close to the surface, static pressure and flow direction will vary spatially and then $\bar{U}$ and $\sqrt{P}$ are only approximately equal.) The spatial variability of the mean flow below a height of 50 mm is quite evident. Between 50 mm and 250 mm, mean velocity was independent of streamwise location, within experimental accuracy. The large length scale of spatial variations in the mean flow is shown by Figure 5, in which P is plotted against X for three different heights.

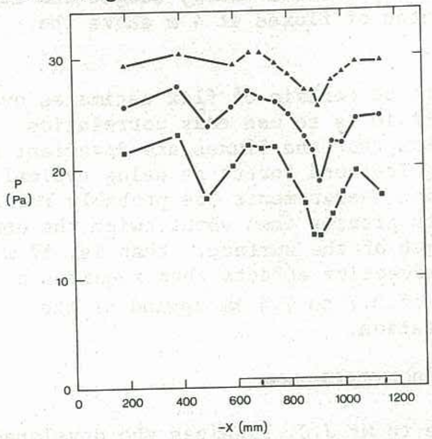

Figure 5 Longitudinal variations in mean dynamic pressure: ■, z = 20 mm; ●, z = 25 mm; ▲, z = 30 mm. Open box on X-axis indicates location of circular drag plate and stippled region indicates location of circular drag plate.

Reynolds shear-stress ($-\overline{uw}$) profiles at a number of streamwise locations are presented in Figure 6. Spatial variation is quite evident below 100 mm, while above this level shear-stress is reasonably constant with height up to approximately 200 mm. In interpreting X-configuration hot-wire probe results close to the rough surface, it should be pointed out that mean velocity measurements with this instrument did not agree with pitot tube results below 40 mm. This is probably due to the three-dimensional nature of the flow in this region.

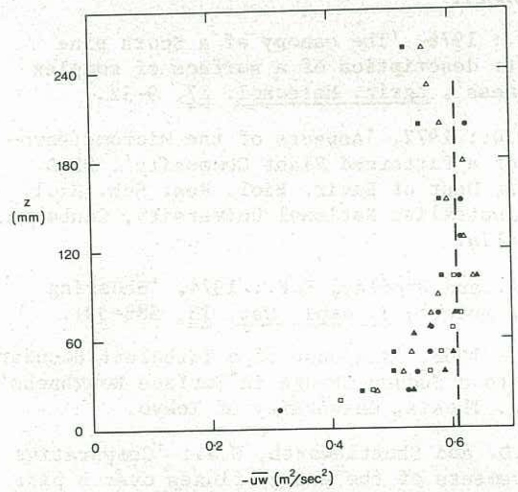

Figure 6 Reynolds shear stress profiles at various streamwise locations:
△, X = -157 mm; ■, X = -197 mm; ▲, X = -310 mm; □, X = -503 mm; ●, X = - 579 mm. The dashed line is at $-uw$ = 0.61 m^2/sec, the value taken as the average.

A square 0.61 m x 0.61 m section was cut from the second last sheet of the rough surface and mounted on the drag-balance. Later, from the centre of this same section, a 0.46 diameter circular section was cut and also mounted on the drag-balance. This can be seen in Figure 1. The centre of both sections was at X = -0.92 m. Both gave a drag/unit area of 1.16 Nm^{-2}. Edge effects were checked by shielding the gap between the drag-plate surface and the surrounding area with paper strip: no change in reading was found. Rotating the circular drag-plate through 180° also caused no appreciable change.

The measured Reynolds shear-stress above 100 mm was constant at 0.61 m^2sec^{-2}, implying a drag/unit area of 0.69 Nm^{-2}, which is approximately 60% of that measured directly by the drag plate. The difference between the hot wire results well above the surface, where 100 mm $\leq z \leq$ 200 mm, and the drag plate results is explained by the spatial scale and magnitude of the mean flow variations illustrated in Figure 5. The position of the drag plates is indicated on this figure.

These results show that close to the very rough surface there is considerable variation in surface shear and mean velocity, and that the horizontal scale of these variations is large. At a higher level, however, above 100 mm, a region of constant shear-stress exists. Using the measured Reynolds shear-stress of 0.61 m^2sec^{-2} the mean velocity data for z > 50 mm can be plotted on log-linear paper to obtain the parameters z_o and d in the equation

$$U = \frac{u_*}{k} \ln \frac{z-d}{z_o}$$

where u_* is the friction velocity ($\sqrt{0.61}$ m sec^{-1}) and k (= 0.41) is von Karman's constant. A good straight line with the correct slope is obtained for d = 12 mm, giving z_o = 0.38 mm (Figure 7). However, d may be varied ± 10% and the data still follow a line of the correct slope.

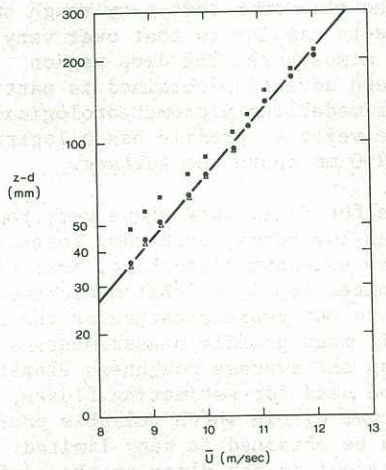

Figure 7 Mean velocity profile on log-linear plot: ■, d = 0; ●, d = 12 mm; △, d = 13 mm.

4 COMPARISON WITH FIELD AND OTHER LABORATORY DATA

In these experiments measurable spatial variations in mean velocity persisted to approximately 50 mm above the surface. This is nearly the same as the average spacing between stones, or 3.5 stone heights. O'Loughlin (1965) measured variations of order 10% of the mean, up to seven roughness element heights, or one average element spacing, above a floor roughened by cubes in a laboratory air conduit (his Figure 23). Graetz (1972) measured spatial variations in mean velocity up to 2.5 m above ground in a vineyard with vines approximately 1.3 m high arranged in long straight rows 5.4 m apart. The height to which spatial variations in mean velocity were observed in the present investigation was thus of the order of the average spacing between roughness elements, and this agrees reasonably well with results of other investigations.

In this study, measurable variations in Reynolds shear stress were observed, up to a height of order twice the spacing between roughness elements. Similarly, Chanda (1958) measured Reynolds shear stress values in a laboratory boundary layer above a surface roughened by regularly positioned stones, which were lower than the calculated equilibrium profile up to a height above the surface of the same order as twice the average stone spacing. Chanda's shear stress profiles were very similar to those of Antonia and Luxton (1971) in a boundary layer over a surface of two-dimensional bars. Both peaked at a height which was of the same order as the roughness element spacing.

5 DICSUSSION AND CONCLUSIONS

It has been found that close to a very rough surface there is a region within which there are considerable spatial variations in mean velocity and shear stress, and that these variations have a surprisingly large horizontal length scale. The depth of this region for appreciable mean velocity variations is of the same order as the spacing between roughness elements, while measurable variations in shear stress occur over approximately twice this depth. At higher levels, shear stress is constant with height.

Less spatial variability was found in other turbulent quantities, and the vertical variations in $\overline{u^2}$ and $\overline{w^2}$ not presented here agreed with atmospheric data from some other sources.

Comparison with the limited available field data suggests that the flow over this very rough surface is in many respects similar to that over very rough surfaces in the atmosphere. The deep region (200 mm) with zero advection obtained is particularly useful for modelling micrometeorological problems and the velocity profile has a logarithmic form up to 250 mm above the surface.

The implications for field work above very rough surfaces, such as low scrub, orchards, forests, and city suburbs, are somewhat disturbing. Most field sites have a limited fetch, so that measurements taken too high are not representative of the underlying surface. If mean profile measurements at heights less than the average roughness element spacing cannot be used for estimating fluxes, then the height interval within which reliable profile measurements can be obtained is very limited. Because this interval is not close to the surface it will also be a region of weak gradients, so that fluxes estimated from the profiles will be very unreliable. With profile methods there is the additional complication of estimating the zero-plane displacement which leads to further uncertainties. Eddy correlation measurements appear to have more chance of success, provided one can be sure that the measuring point is above the region in which fluxes vary horizontally because of surface geometry.

A great deal of micrometeorological work has been carried out from a tower in Thetford Forest, England (e.g. Thom et al., 1975). Ford (1976) obtained autocorrelations and power spectra for the geometry of the forest canopy in the region of the instrumented tower. He found strong periodicity in the autocorrelation with a wave-length of 18.6 m. The tower rises about 15 m above the top of the forest but many of the flux measurements have been carried out only 4 m above tree-top level. In the light of the wind-tunnel findings there is a strong suspicion that none of the data have been obtained at a great enough height. This may explain the differences between profile and eddy correlation measurements of heat flux reported by McNeil and Shuttleworth (1975) and the discrepancy found by Thom et al. (1975) between energy budget and aerodynamic estimates of fluxes at 4 m above the forest.

The only way to be certain of flux estimates over very rough terrain is to use eddy correlation methods and show that the fluxes are invariant with height. Taking Thetford Forest as being typical, eddy correlation measurements are probably reliable only at heights greater than about twice the dominant wave-length of the surface: that is, 37 m. Avoidance of advective effects then requires a uniform fetch of 3.7 to 7.4 km upwind of the measurement station.

6 ACKNOWLEDGEMENTS

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