1969

Agricultural Meteorology – Elsevier Publishing Company, Amsterdam – Printed in The Netherlands

TURBULENCE AND WIND SPEED CHARACTERISTICS WITHIN A MODEL CANOPY FLOW FIELD

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(Received June 4, 1969)

SUMMARY

A model study of canopy flow over tall roughness elements was carried out in a wind tunnel using roughness consisting of pegs 9 cm high and 0.48 cm in diameter, arranged in four geometrical patterns. The mean and fluctuating velocities were measured within and above the roughness elements. Empirical expressions derived from field measurements for mean velocity profiles and fluctuating velocity were used to examine the data obtained in this model study. The logarithmic profile was adapted to analyze the data of mean velocity above the canopy. In this analysis, the friction velocity and the roughness parameter were calculated from the mean velocity profiles and related to the density of roughness elements to show the effects of roughness density on the flow field. Although the coefficient of anisotropy above the canopy in this model study is larger than in the field, the model study produced a turbulent flow field similar to field conditions.

INTRODUCTION

A canopy flow field, which is a wind field as affected by a crop or a forest, changes its characteristics with variations in the shape, stiffness, and geometric arrangement of the vegetative element. That is, variations of mean velocity and turbulence occur depending upon the characteristics of the roughness element.

The flow field in the case of flexible roughness — wheat, rice — is quite different from that of stiff roughness — trees, corn — (POPPENDIEK, 1949; UCHIJIMA and WRIGHT, 1963). Numerous experiments have been made in variations of roughness characteristics, for example, by changing height, diameter, or stiffness or by changing the free stream velocity (IIZUKA, 1952; PLATE and QURAISHI, 1965). Many theoretical and experimental expressions have been proposed for these individual experiments (TAN and LING, 1960; CIONCO, 1963; CIONCO et al., 1963; UCHIJIMA and WRIGHT, 1963).

Since the canopy flow field shows different aspects depending upon roughness characteristics, most of the equations proposed for a specific configuration cannot be successfully applied to a different configuration. Progress in the tall roughness problem has been curtailed because most of the data available that describes the phenomena has been obtained in field experiments. Field experiments are inherently difficult and costly due to the vagrancies of the atmosphere.

In this study, a wind tunnel was used to eliminate this difficulty because the necessary flow conditions could be maintained as long as desired. The structure of a prototype canopy flow field is so complex that only a limited number of parameters may be selected to vary in a model flow field. Even if a surface has only a single type of roughness element, the flow depends not only upon the form and height of the elements, but also upon the density, i.e., the number of elements per unit surface area. Furthermore, the manner in which the roughness elements are distributed on the surface also influence the flow.

A study of the flow in and above various types of model canopies was initiated in the Colorado State University Fluid Dynamics and Diffusion Laboratory (PLATE and QURAISHI, 1965; YANO, 1966; MERONEY and CERMAK, 1967; MERONEY, 1968). The primary purposes of this study are: (*1*) to characterize the affect of a given roughness configuration on the mean velocity and turbulence intensity profiles; and (*2*) to determine if a simple model would produce the same character exhibited by empirical formulas developed for field data.

REVIEW OF LITERATURE

Many experiments to study flow characteristics over a variety of large size roughness elements have been completed. Early work in this area is summarized by GEIGER (1950). Further studies may be classified according to the character of the roughness elements. Measurements have been made over wheat, rice, corn, sugar beets, and tea plants and over various forests (GEIGER, 1950; TAN and LING 1960; TANI, 1963; UCHIJIMA and WRIGHT, 1964; SAITO, 1964; ALLEN, 1968).

Among the various types of large size roughness elements, rice and wheat plants are similar in their response to the wind. These roughness elements are characterized by a waving phenomena and a self sealing, which depends upon the wind speed. The waving phenomena causes the eddy structure to be different from that generated by stiff roughness. Self sealing causes a change in the roughness parameter in the estimation of mean velocity profiles.

The flow field above and within rice plants has been investigated by the staff of the National Institute of Agricultural Sciences (Japan) (INOUE et al., 1955; INOUE, 1963a, b; TANI, 1963) in order to study the exchange processes of its growth. The flow field over a wheat crop has been examined by PENMAN and LONG (1960). In their measurements, wind profiles are observed to have a completely different shape in calm weather than in windy weather. To study the vertical transport processes in the lowest portion of the earth's atmosphere, TAN and LING (1960) proposed that separate studies be made of the quasi-steady and transient states in the micrometeorological boundary layer.

Roughness like corn and trees is less flexible than rice and wheat, therefore, stiff roughness results in a different behaviour of the wind. UCHIJIMA and WRIGHT (1964) measured mean velocity and turbulent velocity in and above a corn crop. The generalized wind profile in the corn crop is approximated by an empirical equation in which the wind velocity at the top is used as the reference wind velocity. In a similar manner, the turbulent velocity profile is empirically approximated by using velocity at the plant height as the reference. Mean horizontal wind speed profiles within and above a plantation of Japanese larch were obtained by ALLEN (1968). He pointed out that a log-profile analysis of above-vegetation wind speeds yields a wide range of values for the roughness length parameter, Z_o, and the zero-plane displacement, d. His turbulence measurements show deeper penetration of large eddies during high winds. The tree spacing is shown to be the important factor for the estimate of the variation in wind speed from power spectra.

Relatively few model studies have been carried out concerning the flow over tall roughness elements in a shear layer. A study of the flow over flexible roughness was made in the wind tunnel by PLATE and QURAISHI (1965). This model study showed agreement of the laboratory data with the field data using wheat and corn.

To determine the necessary width of a normal windbreak, a wind tunnel experiment was performed by IIZUKA (1952). In his experiments, model trees were 15 cm in height and had crowns of iron net. The results of this experiment were also found to be similar with those of field experiments. In the study of turbulent diffusion over a rough surface, YANO (1966) developed the concept of momentum defect superposition in the wakes of an array of roughness elements. Similarity of flow patterns over barriers in the wind tunnel are discussed in detail in the report by WOODRUFF and ZINGG (1952). It is pointed out that the problem of similarity becomes complicated if the body is placed in an already existing turbulent boundary layer, but at sufficiently high Reynolds numbers, the drag coefficient is independent of Reynolds number.

The characteristic parameters of wind flow in an idealized vegetative canopy were examined by CIONCO et al. (1963). The velocity profile above the canopy resulting from their idealized canopy is similar to a logarithmic wind profile with zero-plane displacement. The canopy is characterized by exponential mean velocity distribution beneath the canopy top and a constant turbulence intensity.

Mean velocity profile

For the case where the size of the roughness elements is such that the Reynolds number is large, the structure of the flow field becomes very complex. A number of parameters should then be considered to describe the flow field.

For instance, the roughness height, the number of roughness elements per unit area, and the manner in which the roughness elements are distributed on the surface will all affect the flow field. In order to develop simple mathematical models for the canopy velocity profiles, the flow field is usually divided into two regions. One of the regions is the flow field above the roughness, the other is the flow inside the roughness elements.

Correlation of wind profile data taken over a wide variety of terrain roughness has confirmed that the velocity profile measured from the ground at positions located above several roughness heights may be satisfactorily described by a displaced "logarithmic" profile law (Sutton, Lumley, etc.). This relation generally takes the form:

$$\frac{U}{U_*} = \frac{1}{k} \ln \frac{Z - d}{Z_0} (Z > h) \tag{1}$$

where U = wind velocity; Z = height above ground; h = height of roughness element; $U_* = \sqrt{\tau_o/\rho}$ friction velocity; (τ = shear stress; ρ = mass density); d = zero-plane displacement; Z_o = roughness length. k = von Karman's constant.

SAITO (1964) examined several normalized wind profiles measured within a corn field by STOLLER and LEMON (1963) and concluded that the gradient of wind velocity within the canopy is proportional to the local wind velocity, so that:

$$\frac{dU}{dZ} = P(Z) \cdot U \tag{2}$$

where $P(Z)$ is a proportionality factor dependent upon height only. Integration of eq. 2 across the roughness height with the boundary condition $U = U_h$ at $Z = h$ produces:

$$U = U_h \, e^{-\int_z^h P dZ} \tag{3}$$

Saito also suggested that eq. 3 is valid for wheat field data; however, P for flow over a surface covered by wheat is a function of, not only Z, but also U due to the self sealing effect of flexing stalks at higher velocities.

An exponential wind profile within the wheat field has also been obtained empirically by INOUE (1963a), that is:

$$U = U_h \, e^{-\alpha(h-Z)} \tag{4}$$

where α = constant. He indicated, however, that the condition, α = constant, throughout the height of the roughness element generally is not well satisfied. The roughness in the experiments discussed herein consists of pegs whose height, h, and diameter, ϕ, are 9 cm and 0.48 cm, respectively. Therefore, the behavior of flow within these roughness elements might be similar to the behavior of flow in a corn field rather than in a wheat field.

Turbulence intensity

Several scientists have attempted to correlate the turbulent intensity (ratio of local velocity fluctuation to local average velocity $\sqrt{\bar{u}^2/U}$) at various canopy heights with the mean velocity history because the structure of turbulence depends on the flow's upstream history. A general expression of this sort is difficult to determine from the limited data available from field measurements; however, INOUE (1952) proposed the following expression for the vertical variation of intensity above a rough surface:

$$\sqrt{\bar{u}^2}/U \propto Z^{-1/3} (\log Z/Z_0)^{-2/3} \tag{5}$$

If one replaces the log term by a Taylor series expansion and retains as an approximation only the first term, eq. 5 becomes:

$$\sqrt{\bar{u}^2}/U \propto Z^{-1/2}$$

or for tall roughness:

$$\sqrt{\bar{u}^2}/U \propto (Z - d)^{-1/2} \tag{6}$$

This relationship has been compared with the data taken in the wind tunnel.

For the local velocity fluctuation within crops, the following expression was determined empirically by INOUE (1963a):

$$\sqrt{\overline{u}^2}/U_h \propto e^{-\beta(1-Z/h)} \tag{7}$$

where β is a constant. The above expression is based on experimental data which indicated that the turbulence intensity within a canopy is almost independent of height. UCHIJIMA and WRIGHT (1963), however, claim that the intensity of turbulence within crop canopies is not constant but decreases gradually downward from the top of the crop height.

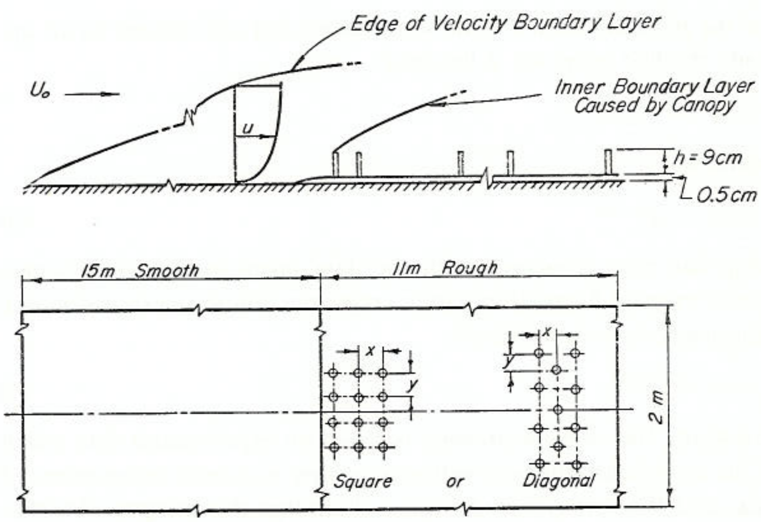
EXPERIMENTAL APPARATUS AND PROCEDURE

The wind tunnel recently has proven its worth in atmospheric science after completion of an extensive sequence of programs to study modeling feasibility for micrometeorological research. For those situations where Coriolis effects are secondary, it is possible to duplicate many important features of the atmosphere. Suggestions concerning the modeling criteria for vegetative canopies have been made by PLATE and QURAISHI (1965).

All measurements were completed in the Army and Meteorological Wind Tunnel in the Fluid Dynamics and Diffusion Laboratory at Colorado State University (PLATE and CERMAK, 1963). The wind tunnel is a recirculating type and has a 27 m long test section with a normal cross section of 1.8 × 1.8 m. The ambient turbulence level is less than 0.1 %. The wind tunnel ceiling may be adjusted to obtain a zero longitudinal pressure gradient.

An artificial roughness, consisting of pegs, that covered an 11 m length of the test section floor beginning 15 m from the upstream end was placed in the tunnel. An additional turbulence stimulator, made from thin flexible strips of plastic 6.3 cm high, was installed on the first 3 m of the wind tunnel floor to make the turbulent boundary layer thicker over the model crop.

The roughness utilized in this study was the result of arrays of pegs (1.27 × 1.27 cm diagonally, 2.54 × 2.54 cm square, 2.54 × 2.54 cm diagonally and 5.08 × 5.08 cm square), the individual height and diameter being 9 cm and 0.48 cm, respectively. The arrangement of pegs is illustrated in Fig.1.



PEG ARRAYS STUDIED

x (cm)	y (cm)	ARRAY
1.27	1.27	DIAG.
2.54	2.54	SQ.
2.54	2.54	DIAG.
5.08	5.08	SQ.

Fig.1. Arrangement of pegs.

The mean velocity profiles were measured by using both a pitot static tube in the outer layer and a hot-wire anemometer within the canopy. Such an arrangement was required because the turbulence level in and immediately above the canopy is very high, a large error in the local velocity head may be introduced in the measurement of mean velocity by the pitot-static probe, however, the mean output of a hot-wire anemometer was not expected to be as sensitive to large velocity excursions.

A constant-temperature anemometer circuit designed at Colorado State University for low noise level was used in conjunction with a tungsten wire 0.005 mm in diameter and approximately 2.5 mm in length, soldered on a Disa hot-wire probe. The longitudinal and vertical fluctuating velocity components (u' and w') were measured by single and cross wire probes, respectively.

RESULTS

All measurements were taken at a free stream velocity of 12 m/sec. The ceiling of the test section was adjusted for zero pressure gradient and the upstream velocity profile was measured and found to be logarithmic. The temperature condition was constant, hence, neutral stability existed.

Discussion of the experimental results follows in the next two sections with respect to mean velocity profiles and turbulence intensity.

Mean velocity profiles

The vertical distribution of the mean velocity profiles may be divided into two sections because within and above the canopy, they are quite different.

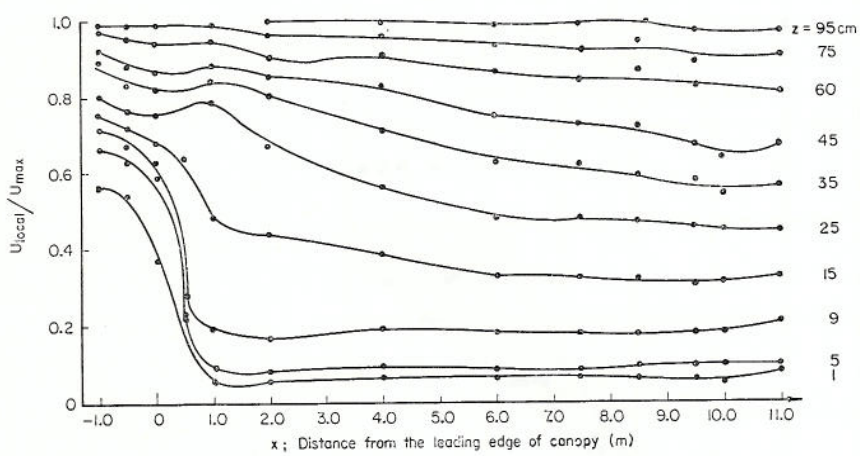


Fig.2. Non-dimensional isoheight of the flow along the canopy.

Fig.2 displays non-dimensional isoheights of the flow above and within the canopy for the 2.54 × 2.54 cm square array. Fig.2 suggests that the flow above the canopy is also divided into longitudinal regions, an initial region (~ 4 m), and a quasi-established region. In the initial region, large changes in the mean velocity occur. In the quasi-established region, the velocity is characterized by smaller, yet finite changes.

Through comparison of length of the initial region in four different densities of roughness, it was observed that the retardation of flow is closely related to the density. Obviously for the more dense roughness, the retardation of flow becomes larger. It is also revealed that the area between $x/h = 85$ and 110 can be regarded as the region that characterizes an equilibrium flow field and might be a model of an actual fully developed canopy flow. The abrupt inception of the forward edge of the canopy to the wall shear flow results in a lifting of the bulk of the flow. The air actually appears to exhale upward from the canopy in the first part of the region. Between $x/h \simeq 20$ and 35, the flow immediately above the roughness elements seems to repenetrate the roughness. Finally, as the canopy terminates, the flow field accelerates near the ground during the last few meters.

The mean velocity taken in the wind tunnel is compared with field data taken by TOURIN and SHEN (1966) in Fig.3 for a deciduous forest. The roughness, consisting of pegs, is expected to simulate the leafless deciduous forest in winter. As shown in Fig.3, the wind tunnel data of the velocity profile, especially the data for the cases of 1.27 × 1.27 cm diagonally and 2.54 × 2.54 cm square, fit the field data

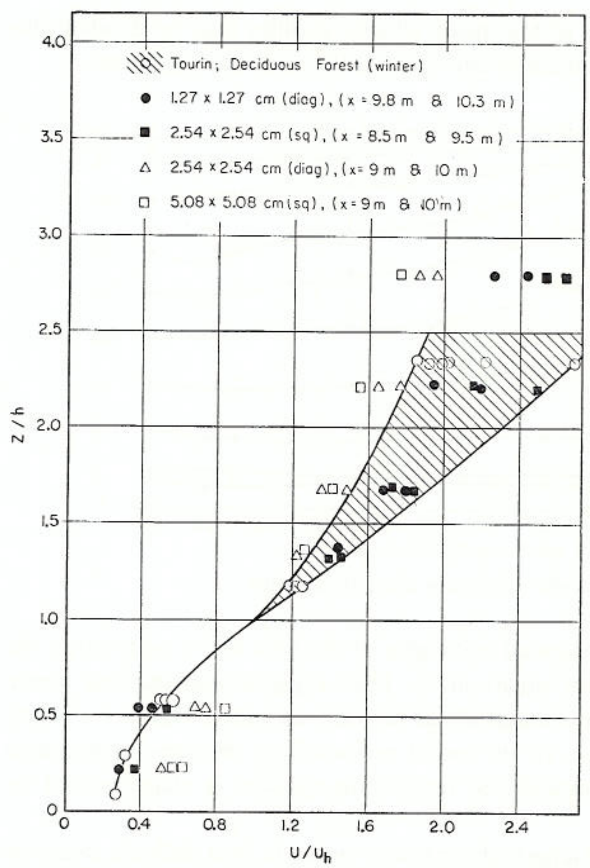


Fig.3. Comparison of the wind tunnel data of velocity profiles with field data.

well. Since the flow above the forest is very similar in summer and winter, the data for the cases of 1.27 × 1.27 cm diagonally and 2.54 × 2.54 cm square also fit the field data taken by Tourin and Shen in summer above the canopy.

Mean velocity profiles above canopy

In eq. 1, which is the expected expression of the velocity profile in the established region, three parameters, U_* (friction velocity), d (zero-plane displacement), and Z_0 (roughness length), are unknowns. They may be determined from the measured wind profile if three values of the velocity are known at three different heights. A least-square method has been described by ROBINSON (1963) by which the three parameters of the wind profile in the adiabatic surface layer of the atmosphere can be determined with the aid of the electronic digital computer. This program (a version of which is known as the "Three Bears" program) unfortunately assumes that U_*, d, and Z_0 are independent causing some investigators to obtain the physically suspect result that d is negative (KUNG, 1961). Therefore, in our computation, d is assumed to equal the height of the roughness elements (h = 9 cm) since d is difficult to evaluate from the measured velocity profiles. This approximation for flow over a canopy of flexible plastic strips has been applied successfully by PLATE and QURAISHI (1965). Hence, U_* and Z_0 are given by:

$$U_* = \frac{k(U_1 - U_2)}{\ln\left(\dfrac{Z_1 - h}{Z_2 - h}\right)}$$

and:

$$Z_0 = \frac{Z_1 - h}{\rho^{kU_1/U_*}}$$

where U_1 and U_2 correspond to the wind speed at heights Z_1 and Z_2, respectively. Some value of the friction velocity, U_*, and the roughness length, Z_0, in the quasi-established region are presented in Fig.4 and Fig.5 with respect to the density of roughness. Note that other density parameters are possible such as frontal area of pegs to total frontal area forest; however, no best density function is obvious as has been evident by the indecision within the forestry science area itself.

The values of the friction velocity, U_*, in the region of $x/h = 85 \sim 110$, were recalculated by adopting the average values of Z_0 in this region for each case of four different densities of roughness. Fig.6 shows the logarithmic velocity distribution calculated with the values of $k = 0.4$, $d = h = 9$ cm, the average value of Z_0, and the corrected (or recalculated) value of U_* in the case of 1.27 × 1.27 cm diagonally. The mean velocity profiles for the four cases of roughness density are approximated by the logarithmic profile, except near the top. In fact, the mean

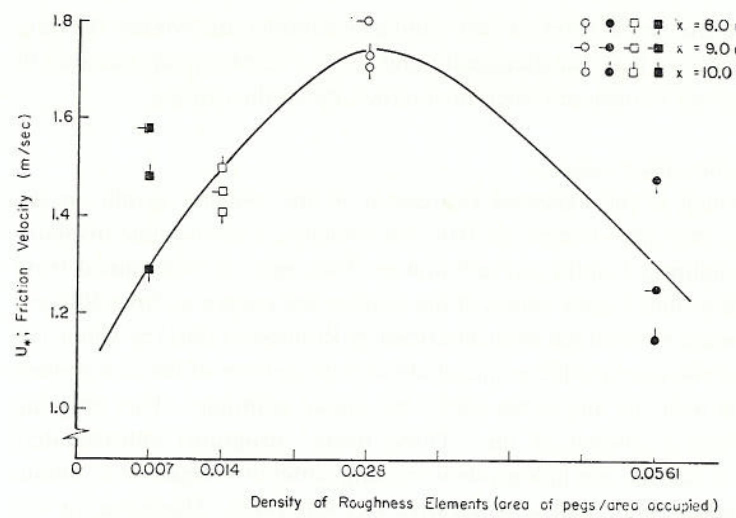


Fig.4. Friction velocity U_* vs. density of roughness element.

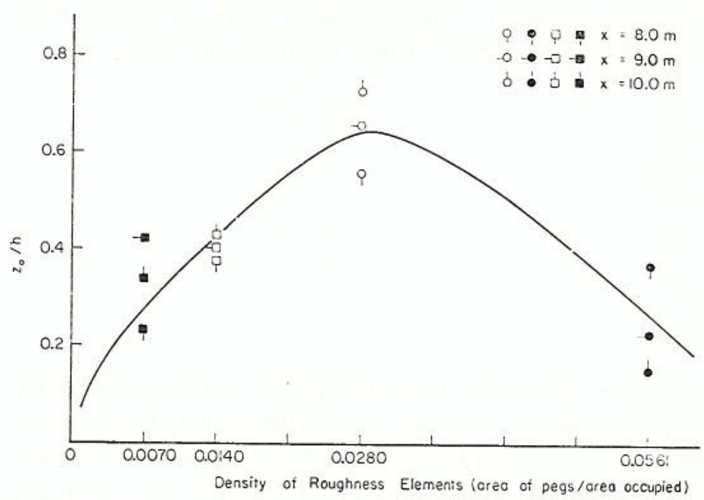


Fig.5. Roughness length Z_0 vs. density of roughness element.

velocity profiles measured in the field are also approximated by the logarithmic form, but cannot be defined well in that form. YANO (1966) pointed out that when the logarithmic or power law is applied to the velocity profile in the turbulent shear flow zone and the theory satisfies the experimental data, then it is necessary to specify zone limits; however, the upper limit of the canopy top transition zone is not clear. If the upper limit of the transition zone is defined as the height where the velocity profiles deviate from the logarithmic profile, then the transition zone for the 9 cm high pegs to 2.5 $\sim$ 3.0 h is limited.

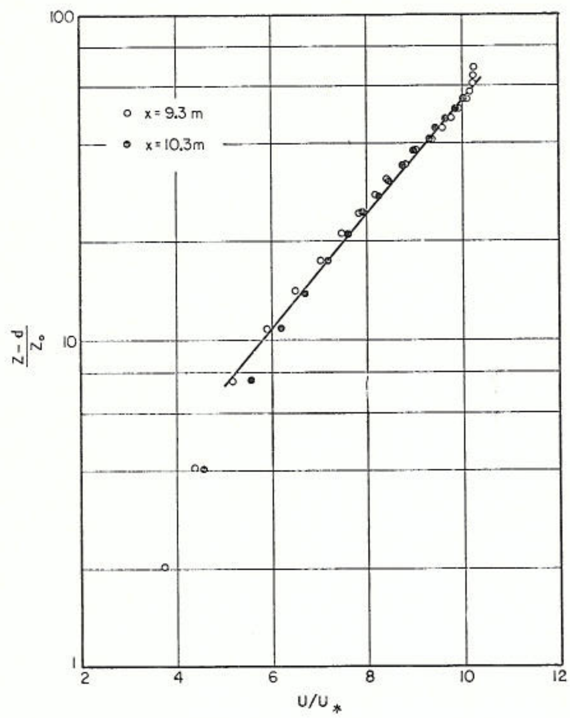


Fig.6. Mean velocity profile above canopy (1.27 × 1.27 cm diagonally).

In the case of roughness elements spaced 2.54 × 2.54 cm diagonally, the friction velocity, U_*, is also estimated from the measurements of the drag force by means of a shear plate. In the initial region, when the difference between the values of the friction velocity, U_*, estimated from the velocity profiles and from the drag measurements is large, the velocity is in the state of transition. In the quasi-established region, this difference between the friction velocities calculated from velocity profiles and the drag force is, at most, 32% of the values obtained from the drag balance.

Mean velocity profiles within canopy

Experimental wind profiles within the canopy are expressed empirically for field data by eq. 4. The logarithmic values of U/U_h are plotted against $(h-Z)$ as shown in Fig.7. It is concluded that the above relationship describes the variation of the data obtained in the wind tunnel as well as the data obtained in the field. This relationship fits quite well for the cases of 5.08 × 5.08 cm (square) and 2.54 × 2.54 cm (diagonally), although the value of α is not constant along the canopy. For the case of 1.27 × 1.27 cm (diagonally), the roughness is so dense that the flow near the ground surface is almost zero. Therefore, it cannot be confirmed as to whether the exponential velocity profile actually exists in very

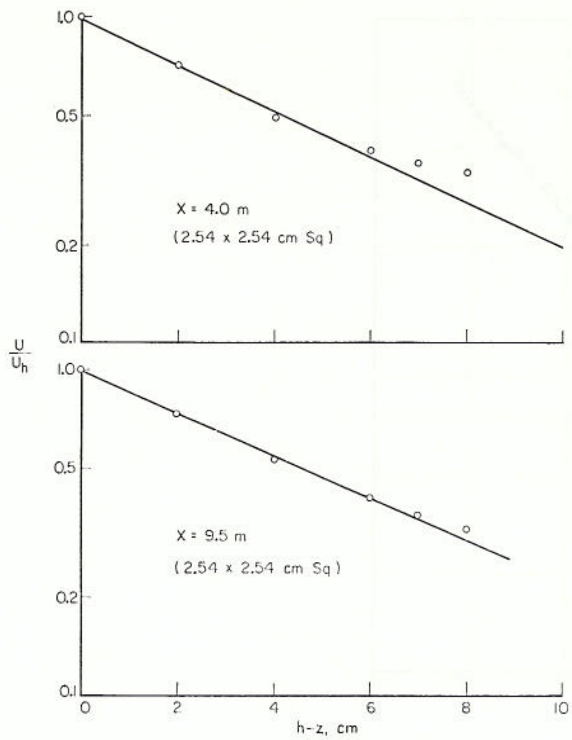


Fig.7. Velocity profiles within canopy $x = 4.0$ m and 9.5 m (2.54 $\times$ 2.54 cm square).

dense roughness. As pointed out above, the value of α is not constant along the canopy. It has been verified that the velocity at an arbitrary height within a canopy is readily estimated if the velocities at the top of the roughness element and at any other height are measured.

Turbulence intensity

Turbulence is observed to reach an equilibrium state beyond $x/h \simeq 89$ in the model peg canopy experiment. As stated in the preceding section, the turbulence intensity profiles are proposed to be functionally:

$$\log (u'/U) \propto -\tfrac{1}{2}\log (Z - h)$$

where $u' = \sqrt{\bar{u}^2}$.

According to the above relation, the ratio of log (u'/U) to log $(Z-h)$ must be equal to $-\frac{1}{2}$. As seen in Fig.8, however, a "kink" exists at $Z - h \simeq 20$ cm $(Z/h \simeq 3.3)$. The ratios log (u'/U)/log $(Z-h)$ for $(Z-h)$ larger than 20 cm lie between -0.48 and -0.70, while the ratios below the "kinks" are far from $-\frac{1}{2}$. Apparently, in the lower region, a three-dimensional wake caused by the top of the roughness elements interacts with the upper shear layer. To describe the turbulence intensity profiles immediately above the roughness, the interaction of the three-dimensional wake should be considered in more detail.

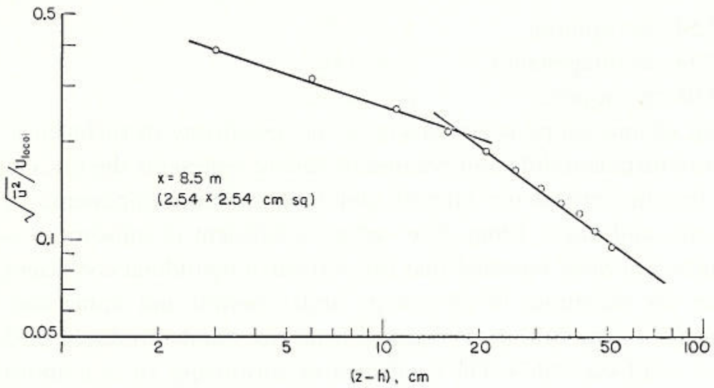


Fig.8. Turbulence intensity profile above canopy.

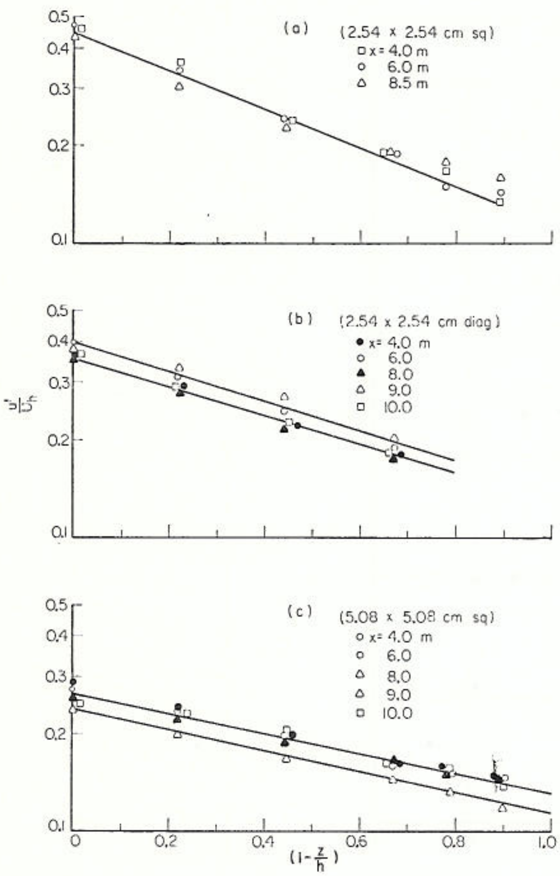


Fig.9. Fluctuating velocity within canopy.

Fig.9 shows the fluctuating velocity profiles within model crops plotted according to eq.7. A constant β for each case is estimated from the slope of those profiles as follows:

for 2.54 × 2,54 cm (square), $\beta = 1.38.$
for 2.54 × 2.54 cm (diagonally) $\beta = 1.02.$
for 5.08 × 5.08 cm (square) $\beta = 0.72.$

The coefficient of anisotropy is a measure of the anisotropy of turbulence. It is very important in turbulent diffusion because its square represents the ratio of total eddy energy for the vertical (or lateral) and longitudinal components of wind velocity (TOURIN and SHEN, 1966). The vertical coefficient of anisotropy is given by w'/u'. Tourin and Shen reported that the vertical–longitudinal coefficient of anisotropy above the deciduous forest canopy under neutral and stable conditions has a value of 0.4. The field data obtained from rice plants produced 0.33 as this coefficient, w'/u' (TANI, 1963). The coefficient of anisotropy, (w'/u'), above the canopy for the measurements in this study falls between 0.5 and 0.7. Within

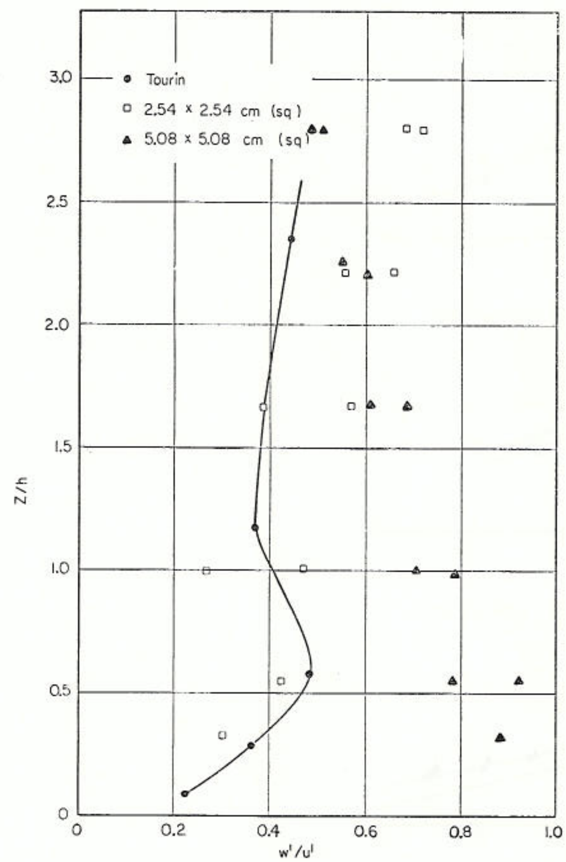


Fig.10. Distribution of the coefficient of anisotropy.

the canopy, high-intensity turbulence exists so that the measurements of u' and w' are not sufficiently accurate to give a quantitative picture. In Fig.10, the wind tunnel data are compared with field data taken by TOURIN and SHEN (1966).

CONCLUSIONS

(*1*) The mean velocity profiles above the canopy are roughly approximated by the logarithmic profile except for the region below a height of $2.5 \sim 3.0\ h$ from the floor.

(*2*) The exponential velocity profile holds well for the mean velocity within the canopy for data obtained both in the wind tunnel and in the field.

(*3*) The turbulence intensity profiles above the canopy can be divided into two parts. One is the region above $Z/h = 3.3$ and the other is the region below $Z/h = 3.3$. In both, the turbulence intensity profiles can be approximated by:

$$\log (u'/U) \propto - \alpha \log (Z - h),$$

but the values of α in two regions are quite different. To represent the turbulence intensity profiles below $Z/h = 3.3$, the three-dimensional wake effects of the canopy top should be considered.

(*4*) The turbulence velocity within the canopy can be represented in the exponential form (eq. 7) and is related to the mean velocity at the top of roughness.

(*5*) The coefficient of anisotropy above the model canopy is somewhat larger than that measured in the field, indicating accelerated redistribution of turbulent energy.

ACKNOWLEDGEMENT

The authors gratefully acknowledge support for this work under DOD Grant DA-AMC-28-043-65-G20.

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