MODELING OF VELOCITY DISTRIBUTIONS INSIDE AND ABOVE TALL CROPS

E. J. Plate

Colorado State University, Fort Collins

and A. A. Quraishi

East Pakistan University of Engineering and Technology
Dacca, East Pakistan

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E. J. PLATE

Colorado State University, Fort Collins

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East Pakistan University of Engineering and Technology, Dacca, East Pakistan

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E. J. PLATE
Colorado State University, Fort Collins
AND A. A. QURAISHI
East Pakistan University of Engineering and Technology, Dacca, East Pakistan
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ABSTRACT

Velocity distributions inside and above a model crop were investigated. The model crop consisted of flexible plastic strips fastened to the floor of a low speed wind tunnel. The experimental results indicated that at some distance x_o downstream from the edge of the roughness cover the velocity profiles were similar inside and also above the cover. The length x_o is discussed.

The experimental results for the velocity distribution inside the plant cover were compared with field data obtained from different sources. A presentation of the velocity profiles inside the canopy in nondimensional form collapsed all field and laboratory data for a given crop type on one curve. The laboratory flow above the crop cover was analyzed using a power law form and using the logarithmic velocity distribution law. On the basis of the experimental results it is recommended that a two-tower arrangement of wind velocity measuring devices be used both for the evaluation of the surface shear stress and for checking the establishment of similarity profiles in the field.

1. Introduction

Evaporation and other exchange processes near vegetation are determined to an important extent by wind distributions in and above plant covers. With the growing interest in transfer processes in crops, it becomes desirable to predict wind profiles. Such predictions must be based on experimental results.

Only a limited number of field observations is available. Some measurements of wind profiles in and above crops were reported by Paeschke (1937), and Geiger (1957) gave some data on wind velocities in tree stands. More recently, Tan and Ling (in Lemon, 1963) presented wind profiles in and over wheat and corn. Stoller and Lemon (in Lemon, 1963) also measured some wind profiles over and in corn crops. These and a few other, less complete sets of data are essentially all the results available at present, and there exists a definite need for more elaborate and extensive measurements for different types of crops. Since field measurements are not easy to obtain because of the cost involved in setting up a perfect measuring station, a program of modeling the flow in and above plant covers has been initiated in our laboratory. First results of this program were presented by Quraishi (1963). It is the purpose of this paper to discuss some problems which become apparent when modeling of a vegetative plant cover is attempted. Also, empirical distribution laws for the wind in and above a plant cover are given.

[1] Presented at the Sixth National Conference on Agricultural Meteorology, 8 October 1964, Lincoln, Nebr.

2. The modeling of a crop cover

The wind tunnel is a research tool which has proved its usefulness for aerodynamic research on countless occasions. In meteorology, however, the wind tunnel is seldom used because of the difficulties in modeling Coriolis effects and temperature stratifications. If turbulent shear flows near the earth's surface are considered, then the Coriolis effect is not important, and under some circumstances the stratification of the air flow is of no consequence, so that one would expect the wind tunnel to find its place as a useful "analog computer" for micrometeorological studies. But a serious obstacle to the widespread application of the wind tunnel for micrometeorological research is the difficulty of defining scaling parameters for the atmospheric boundary layer.

As is well known, boundary layers in the wind tunnel are modeled by using the boundary layer thickness, δ, as the length scale, and the velocity u_a in the wind tunnel outside of the boundary layer as the reference velocity. Unfortunately, these two parameters do not have a well defined counterpart in the atmosphere. However, another set of parameters used in aerodynamics can be used to describe wind profiles in the atmospheric boundary layer. These parameters are the shear velocity u_* and the roughness height z_o. The shear velocity u_* is obtained from the wall shear stress τ_o through the relation $u_*=(\tau_o/\rho)^{\frac{1}{2}}$, where ρ is the density of the air. In the field, the parameters u_* and z_o are determined from a measured velocity profile by assuming the profile to be described by the logarithmic law of

Prandtl:

$$\frac{u}{u_*}=\frac{1}{k}\ln\frac{y}{z_o}, \tag{1}$$

where k is the "universal constant" of Karman, which is generally assumed to be about 0.4. From Eq. (1), z_o and u_* can be determined if the wind velocities u at two different elevations y are known. Values of z_o obtained in this manner have been tabulated by Geiger (1957) and Deacon (1953) for different types of crops.

Eq. (1) is based on results obtained for the flow along a flat plate in the wind tunnel. Clearly, for the case of a flat plate with zero pressure gradient, velocity profiles are scaled by Eq. (1) if z_o is used to scale the length, and if u_* is used to scale the velocity.

The value of z_o is well defined in the wind tunnel through the use of the equivalent sand roughness (Schlichting, 1960, p. 527). Therefore, a given z_o of the natural conditions can be scaled down to an equivalent sand roughness in the wind tunnel. Difficulties will, however, arise if a sand roughness is not suitable to represent the boundary of the atmospheric situation, but in general it will be a simple matter of arranging, by trial and error, model roughness elements to define a usable surface.

It is not difficult to obtain a suitable shear velocity u_*. Since the shear velocity can be written:

$$u_*=u_a(\tfrac{1}{2}c_f)^{\frac{1}{2}}$$

where c_f is the local friction coefficient, it becomes possible to establish a desired u_* by either varying the mean velocity u_a or the friction coefficient c_f. For a given mean velocity u_a, the friction coefficient depends only on the distance from the wind tunnel entrance, or on the boundary layer thickness, δ, and on the viscosity ν of the air. Changes of c_f with δ and with ν are small, however, and the most effective modeling is obtained by adjusting the mean velocity, provided that c_f for the model and for the natural situation are about of the same magnitude. Only in rare cases will it be necessary to improve the relationship by artificially thickening of the boundary layer.

Both u_* and z_o are parameters depending on local conditions. If they change rapidly along the boundary, then the local velocity profile cannot be expected to scale according to Eq. (1) even if the parameters u_* and z_o are known. The velocity distribution will reflect an average effect of local values of u_* and z_o over some area upwind of the point considered, which will increase for velocities at increasing distances above the ground. A similarity law in the form of Eq. (1) can thus be expected to hold only where local boundary conditions are relatively uniform over the region considered. This condition is rarely ever satisfied in micrometeorological situations. The closest approximation is probably found in and above man planted crops, where the uniformity of plant density and plant growth rate assures a reasonably uniform surface configuration. One has therefore reason to expect that of all micrometeorological situations the wind velocity distribution above and in crops can most easily be modeled in the wind tunnel.

For large crops, a description of the velocity distribution by (1) is not satisfactory because no meaningful logarithmic curve can be found which describes the profile inside and outside the plant cover. An attempt to fit the logarithmic law only to the flow above the crop has led to the translation of the vertical coordinate by an amount "d", the zero plane displacement. The velocity distribution law becomes:

$$\frac{u}{u_*}=\frac{1}{k}\ln\frac{y-d}{z_o}. \tag{2}$$

In this form, the logarithmic law has been used by meteorologists since Rossby and Montgomery (1935). The zero plane displacement d is the third parameter which has to be determined experimentally, and which has to be scaled if the distribution of wind above large crops is to be modeled. One may interpret the use of (2) as an attempt at separating the flow field into two horizontal layers. The velocity distribution law in the upper layer, at some distance above $y=d$, is given by the logarithmic law (2). For tall crops, the lower layer $y<d$ is confined largely to the flow inside the crop cover, and thus an attempt to derive the velocity distribution law amounts to an attempt at describing or calculating the velocity distribution inside the crop. The velocity distribution inside the plant cover is not defined through a logarithmic law. The numerous obstructions formed by the crop elements cause a highly turbulent three-dimensional flow pattern which cannot easily be expressed analytically.

Tan and Ling (in Lemon, 1963) were apparently the first to try to obtain an analytical formula for the velocity distribution inside the plant cover. Other attempts have been made by Cionco *et al.* (1963), but the proposed methods are unsatisfactory because they do not take into account the definitely three-dimensional nature of the flow field. Even though a mathematical model does not seem feasible, it can nevertheless be investigated whether or not an empirical similarity law, with well defined similarity parameters, can be found that describes the mean velocity distribution inside the crop.

The introduction of a two-layer flow changes the boundary conditions for the outer flow. Prandtl's original derivation of the logarithmic law contained the assumption that the horizontal shear inside the boundary layer is constant and equal to the wall shear. This assumption has been retained in most of the more recent derivations of the logarithmic law (e.g., Townsend, 1956), and its validity for the case of the boundary layer along a smooth flat plate is well documented. But the existence of a constant stress region above a crop

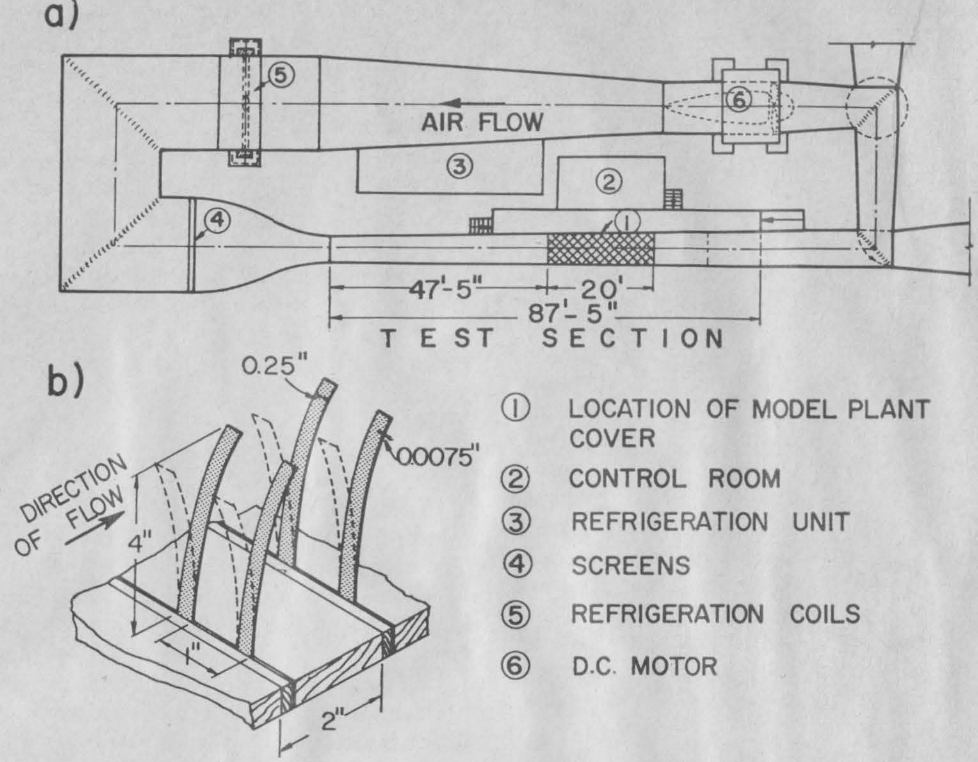

FIG. 1. Wind tunnel+roughness element strips: a) The wind tunnel; b) Typical flexible roughness elements.

cannot be taken for granted, and it is therefore worthwhile to check whether the logarithmic velocity distribution is found valid above a roughness height that is a substantial fraction of the boundary layer thickness.

The considerations on the modeling of an atmospheric boundary layer have led to an experimental program whose objectives were as follows. First, similarity laws for the flow inside and above a model crop were to be determined, and the region of applicability of the similarity laws. Second, the similarity parameters u_*, z_o and d were to be determined, with the purpose of finding similarities with field data. Finally, the results are compared with field data.

3. Experimental equipment and procedures

The experimental data were obtained in a low-speed wind tunnel with a 6 ft square and 80 ft long test section. No attempt was made to model other than wind conditions. The roughness elements consisted of strips of flexible plastic 0.25 in. wide, 0.0075 in. thick and 4 in. high fastened to wooden strips. The roughness elements were arranged to face the direction of the wind with their broad side, with a spacing in the direction normal to the flow of one element per linear inch, and a spacing in the direction of flow of one row every 2 in. The set-up is shown in Fig. 1.

A constant-temperature hot-wire anemometer was used to measure the velocity. The sensing element of the hot-wire anemometer used was platinum wire of 0.001 in. diameter and about 0.4 in. long. The ambient-velocity was adjusted by using either a micromanometer (Flow Corporation Model MM-2) or an electronic pressure meter (Transonics Model A, Type 120) and a pitot tube.

4. Experimental results

Velocity profiles were taken over the roughness elements for two different velocities outside the boundary layer of 20 and 40 ft sec^{-1}, at various stations downstream from the leading edge of the roughness cover. Stations are denoted by their distance from the leading edge in feet.

a. Flow inside the model plant cover. Under the influence of the wind, the flexible plant models deflect, with the front (i.e., the upstream end) of the cover suffering the largest deflections. An approximately constant deflection height is reached at both velocities at distances of about 10 ft from the upstream edge of the plant cover. The deflected height has been taken as the reference height h for the calculation of the profile inside the plant cover. The deflected height was 3.9 inches for the velocity of 20 fps and 3.3 inches for the velocity of 40 fps.

For the flow inside the plant cover, the non-dimensional profiles were computed by dividing the distance from the floor by the deflected model plant height h and the velocities by the velocity u_h. With these reference parameters the profiles become similar in the model cover for both velocities at stations farther than 6 ft from the leading edge of the roughness as is shown in Fig. 2.

The data points show considerable scatter, but the deviations of the profiles from the average profile are not systematic with velocities and distances from the leading edge, and can at least partly be attributed to slightly different positions of the velocity probe in the canopy. There is no question that there exists considerable three-dimensionality in the flow, even though no measurements of horizontal profiles between roughness strips were made. An indication of the three-dimensional nature of the flow can be obtained from Fig. 3, which shows some horizontal profiles taken inside a model roughness cover, consisting of wooden dowels, 2 in. high and $\frac{3}{16}$ in. in diameter, arranged in a pattern of squares, 1 in. on a side, with a dowel on each corner. Notice that the vertical profiles change substantially with horizontal distance from the center line. Thus, a profile inside the cover of roughnesses is a valid representation of the flow only if the three-dimensional pattern of flow is known, and this depends on the spacing and the arrangement of the individual roughness elements.

There is some question whether other roughness elements would also give similarity profiles whose shapes are independent of the mean external velocity. The sharp edges of the plastic strips used in this study will result in a drag coefficient for each element which is approximately independent of the velocity. Also, it is not established that there exists a turbulence pattern

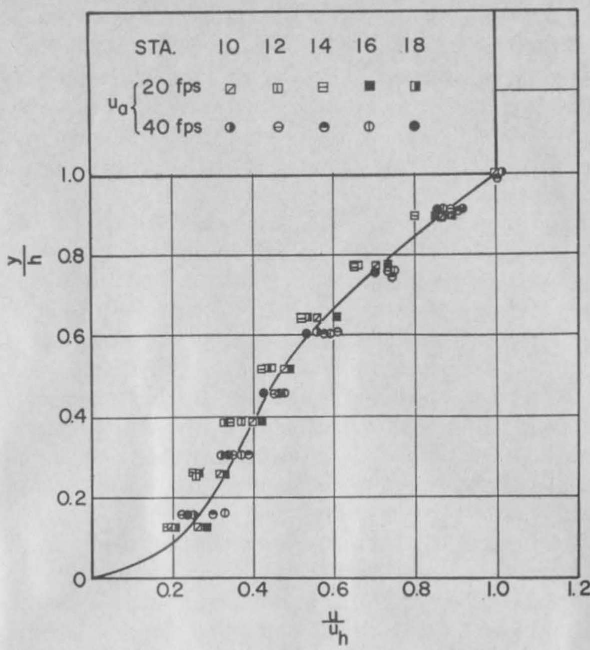

FIG. 2. Canopy velocity profiles of experiments.

which is uniquely determined by the mean velocity profile in the center of the row. Experimental evidence is not available at present to investigate this point. Until such results become available, we propose to model a plant cover by arranging roughness elements—cylinders, strips of material and the like—in such a way that the dimensionless velocity profile inside the roughness cover in the center between rows coincides with the nondimensional profile of the crop to be modeled.

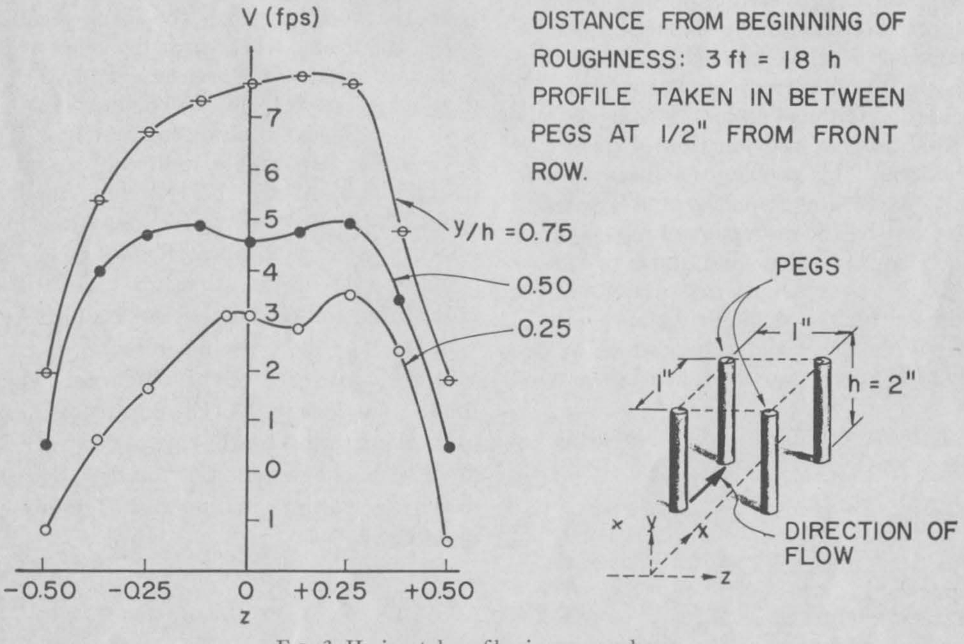

FIG. 3. Horizontal profiles in peg roughness.

b. The transition distance between beginning of roughness cover and established similarity profiles. In the first 6 ft of the model roughness the profiles inside and outside the plant cover are still in the transition stage. They adjust from the conditions upstream from the roughness to those above the roughness. In this distance of adjustment x_o, the velocity profiles cannot be expressed by a function of u_* and z_o only. Both u_* and z_o are parameters which depend, by definition, on the condition of the ground surface at that location where the profile was taken. However, the velocity profile is not dependent on the configuration of the surface at a point, but it reflects the effects of all different surface configurations upwind of the section at which the profile is taken. Thus, the local value of z_o and u_* can be reflected in the whole of the velocity profile only if the surface configuration is the same over the distance x_o upwind from the test point.

If a natural wind profile over a uniform roughness is to be modeled, one must therefore not only be able to define u_* and a value of z_o or any other suitable length, but also one must know the downwind distance beyond which the profiles are described by z_o and u_* as given by the local conditions. If profiles are taken in a boundary layer where the roughness of the ground changes rapidly with distance, then an interpretation of the velocity profiles in terms of a single roughness element is inadequate, and the calculation of a single roughness length z_o in terms of the configuration of the local surface is quite difficult and has apparently not yet been attempted.

If profiles are taken in a boundary layer where the roughness is uniform except for one step change in roughness, then approximate solutions for wind profiles above the crop can be found by assuming an inner boundary layer to develop over the downwind roughness, with the outer flow essentially unaffected and reflecting the conditions over the upwind roughness. The calculations of wind profiles from this assumption are not straightforward, additional assumptions have to be made on the conditions at the junction of inner and outer boundary layer. This problem has been investigated by Elliott (1958) and Panofsky and Townsend (1964). Here, we restrict the discussion of modeling the atmospheric boundary layer in a wind tunnel to a study of the profiles in and over a uniformly rough surface extending downwind further than the distance x_o.

Table 1 indicates some of the values which x_o can assume. The table is based on data taken in the wind tunnel, with roughness elements which extend over the full width of the wind tunnel. The data indicate that the distance x_o is related to the area of obstruction which the cover front offers to the flow, with the solid fence requiring the largest recovery distance x_o and the peg roughness which has the least distorted velocity profile (as indicated in Fig. 7) having the smallest x_o.

TABLE 1. Values of x_o for various roughness elements.

Configuration	Velocity range	x_o
Peg roughness (Fig. 1)	20–40 fps	15 h
Strip roughness (Fig. 2)	20–40 fps	30 h
Solid single fence on smooth plate	10–60 fps	~100 h

c. Wind distributions above the model roughness. For the velocity distribution above the model plant cover the validity of Eq. (2) was investigated. Since the velocity distribution law for $y<d$ is given by the non-dimensional plot of Fig. 2, the outer layer starts at $y=h$. The zero plane displacement d must therefore be of the order h, and it was found that good approximations were obtained by assuming $d=h$. This result shows the convenience gained by separating the flow into two layers.

The similarity parameters for the outer layer and for the inner layer must be identical if a smooth junction of the two profiles is to be postulated under all conditions. However, the velocity distribution for the outer flow cannot be described by a law which is valid from $y=h$ to $y=\delta$, as will be shown; and a region exists in which a smooth transition takes place between the inner and the outer profile. For this transition region, no equation can be given.

With $d=h$ it can be expected that the velocity distribution in the flow above the plant cover can be represented either by Eq. (2) or by a power law relationship of the form

$$\frac{u}{u_a}=\left(\frac{y-h}{\delta-h}\right)^{1/n}. \tag{3}$$

The power law relationship (3) was checked first. The boundary layer thickness δ was defined as that distance from the floor at which the local velocity reaches a value of $0.995u_a$, where u_a is the velocity outside of the boundary layer. As is seen in Fig. 4, the experimental data for $y-h>0.15\ (\delta-h)$ could well be fitted by (3) with an exponent n of approximately 3. The exponent $n=3$ agrees remarkably well with exponents in power laws found by Moore (1951) and by Bhaduri (1963) for roughness elements consisting of solid strips of material fastened to the wind tunnel floor at equal intervals.

The power law relationship (3), satisfactory as it may appear for wind tunnel use, is of little value to field workers. The more useful presentation by Eq. (2) requires a knowledge of the roughness height z_o and of the friction velocity u_*. The parameter u_* can be found in the wind tunnel for the case of flow with zero pressure gradient in the direction of the flow, by applying Karman's momentum equation to the flow above and in the plant cover:

$$u_*=u_a\sqrt{\frac{d\theta}{dx}}, \tag{4}$$

where the momentum thickness

$$\theta=\int_0^\delta \frac{u}{u_a}\left(1-\frac{u}{u_a}\right)dy \qquad (5)$$

is calculated over the whole profile; that is, from the bottom of the roughness to the edge of the boundary layer. The momentum thickness in this form incorporates the effect of the flow inside the plant cover and also the effect of the momentum change in the outer flow, and the inclusion of the inner flow might be questioned. This question is pertinent because the shear stress calculated by (4) is that at the floor, while the shear τ_h at the plant height h appears to be the logical choice for scaling the velocity profile of the flow above the plant cover. Fortunately, the shear stress at $y=h$ is approximately equal to the shear stress on the ground. For if Eq. (5) is written in the following form

$$\theta=\int_0^h \frac{u}{u_a}\left(1-\frac{u}{u_a}\right)dy+\int_h^\delta \frac{u}{u_a}\left(1-\frac{u}{u_a}\right)dy \qquad (6)$$

then the contribution of the first integral to the shear velocity u_* can be written

$$\tau_o-\tau_h=u_a\frac{d}{dx}\int_0^h \frac{u}{u_a}\left(1-\frac{u}{u_a}\right)dy$$
$$=u_a\frac{d(u_h/u_a)}{dx}\cdot\int_0^h\left(\frac{2u}{u_h}-\frac{2u^2}{u_h u_a}+\frac{uu_h}{u_a^2}\right)dy. \qquad (7)$$

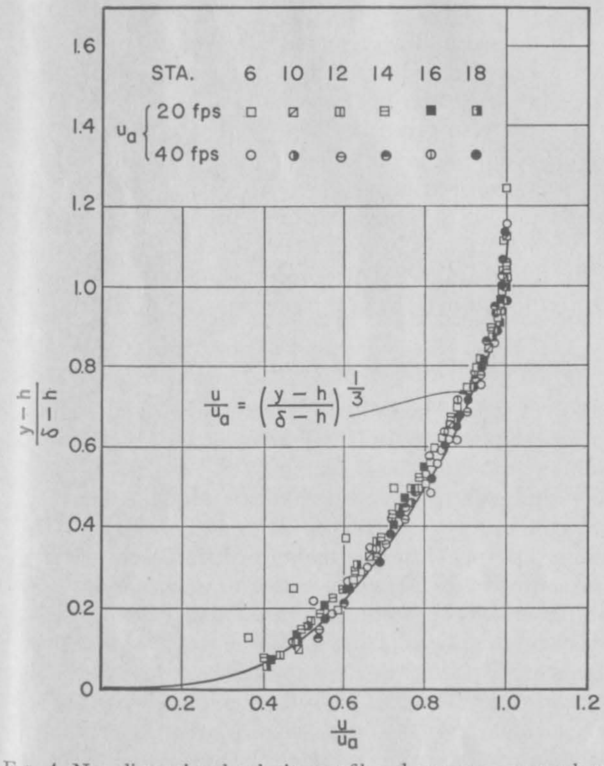

FIG. 4. Non-dimensional velocity profiles above crop: power law.

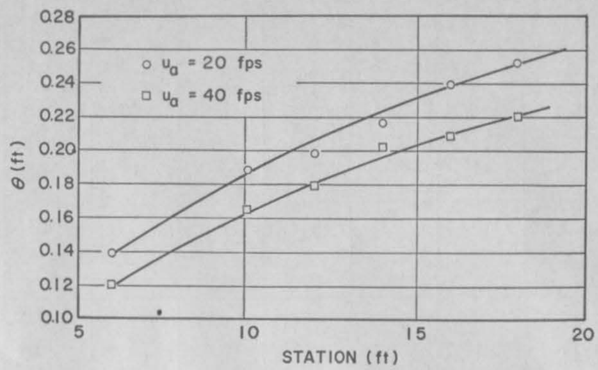

FIG. 5. Momentum thickness as function of distance.

Experimental data show that within the accuracy of measurement u_h/u_a=constant=0.4. Thus, the right side of (7) becomes zero, and therefore $\tau_o=\tau_h$. Therefore, neither h nor u_h needs to be known if it is required to calculate the shear stress from the boundary layer's momentum thickness.

For the experimental data, u_* has been calculated from smooth curves through the momentum thickness as function of distance x which are shown in Fig. 5. The values of u_* found in this manner are tabulated in Table 2, designated as u_{*1}. Also tabulated are the corresponding friction coefficients c_{f1}, indicating a very large value c_f compared with smooth flat plate data.

A second, less valid method for determining the friction velocity u_* is obtained by assuming that the velocity in the flow above the plant cover obeys, at some reasonable distance above the cover, a logarithmic velocity distribution law of the form commonly found for rough boundaries:

$$\frac{u}{u_*}=5.65\log\frac{y-d}{z_o}. \qquad (8)$$

If three values of the velocity distribution are known, then the three parameters u_*, d, and z_o can be found from a system of three equations with three unknowns. This is the technique commonly used for field data. For the laboratory data, a technique was employed for which u_{*1} was given by Eq. (4) and $d=h$. Then z_o was

TABLE 2. Values of u_* calculated for the experimental data.

Sta.	u_a (fps)	u_{*1} (fps)	c_{f1}	c_{f2}	u_{*2} (fps)	θ (ft)
10	20.2	2.94	0.042	0.039	2.84	0.189
12	20.4	2.81	0.038	0.041	2.76	0.197
14	20.3	2.58	0.032	0.033	2.62	0.216
16	20.1	2.46	0.030	0.031	2.52	0.239
18	20.5	2.42	0.028	0.029	2.48	0.252
10	40.0	5.68	0.040	0.037	5.45	0.165
12	40.0	5.20	0.034	0.036	5.35	0.179
14	40.0	4.88	0.030	0.032	5.08	0.202
16	40.4	4.76	0.028	0.030	4.95	0.208
18	40.0	4.56	0.026	0.028	4.78	0.220

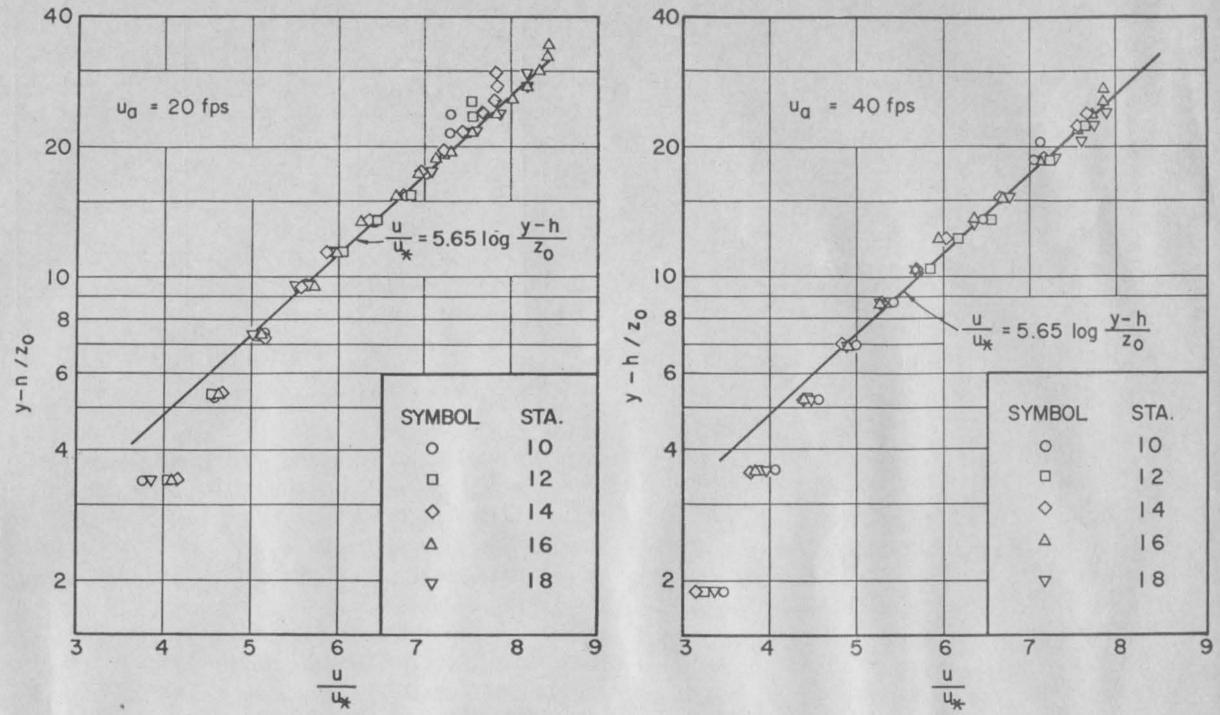

FIG. 6. Non-dimensional velocity profiles above crop: logarithmic law.

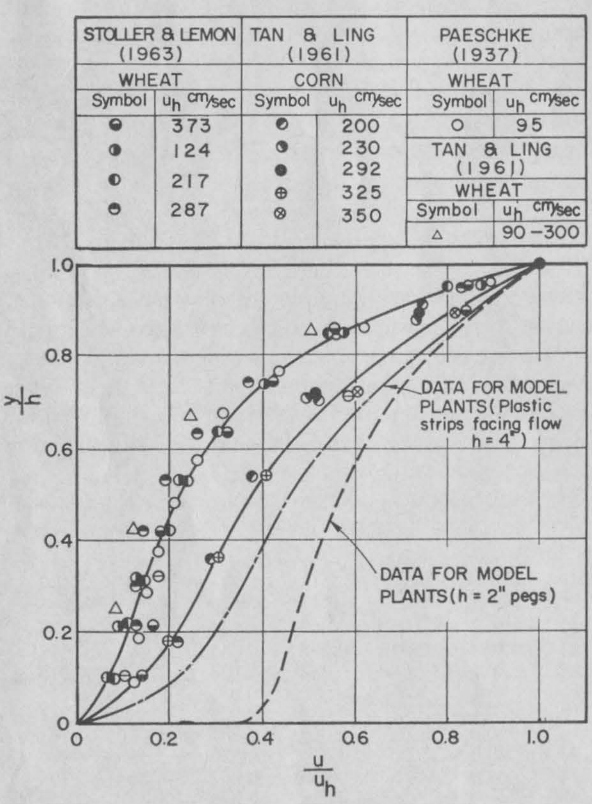

FIG. 7. Field data in canopy.

calculated for each profile from Eq. (8). The result of this calculation indicated that, with some scatter of the data, z_o is constant and equal to 0.15 h. This value of z_o was then used and a corrected value of u_* was found from a curve fitted through a logarithmic plot of u versus $(y-h)/0.15h$. The corrected values of u_* denoted by u_{*2}, are also given in Table 2. The agreement beween u_{*1} and u_{*2} is quite good. For the final check, a plot was prepared of u/u_{*1} versus $(y-h)/0.15h$ which is shown in Fig. 6. The logarithmic velocity distribution (2), with Karman's k equal to 0.4, $h=d$, $z_o=0.15h$, and u_* given by (4) is a good representation of the velocity distribution above the plant cover in the wind tunnel.

5. Comparison with field results

In comparing the laboratory data with field results, agreement between similarity laws, as well as between scaling parameters, has been checked. Also, an attempt has been made to give some indication of the length x_o that can be expected in the field. Finally, some suggestions are made on the taking of future field data.

a. The velocity distribution inside the canopy. The non-dimensional presentation of the flow within a plant cover obtained by plotting u/u_h versus y/h used for the laboratory data can also be applied to field data. This was shown by Tan and Ling (in Lemon, 1963). Therefore, all available field data were plotted in this form with the results given in Fig. 7. The remarkable result is obtained that all profiles for wheat fall on essentially the same curve regardless of the origin of the data, and so do the results for corn. The conclusion can be drawn that the flow inside a plant cover can be described by a representative profile which depends only on the type of crop. The scarcity of data does not permit us to infer any systematic variation of the profiles for a given crop with wind velocity or with different stages of maturity. Tan and Ling (in Lemon, 1963) detected a small change in the profile shape with wind velocity; however, this is not evident in the data of Fig. 7.

The field velocity distributions were obtained by measuring the velocities in the vertical plane at the center between rows of crops. The equality of the similarity profiles for all wheat or corn data might perhaps be attributed in part to the fact that the spacings of the rows do not vary significantly, but are determined by the machine which seeds or plants the crops.

A description, or analytical representation of the flow velocity distribution inside the canopy in terms of a shape factor as given for example by Tan and Ling (in Lemon, 1963) does not, in the light of these results, seem to be serving a useful purpose, unless there exists a unique turbulence field for each shape factor, but not for the wheat profile, or the corn profile. Until the advantages of analytical descriptions which give unique relations between turbulence and mean velocity distributions are demonstrated, it is recommended that a velocity profile be specified in terms of the crop which produces it. Experiments need to be performed in the wind tunnel which show that there exists, or there does not exist, a correspondence between the mean velocity distributions and the turbulence field for different types of model crops, arranged at different spacings and directions.

b. The transition distance x_o. No direct measurements of the transition distance x_o are available. However, some indication of the length of x_o can be obtained from results of measurements of the effectiveness of shelterbelts. The extensive work on shelterbelts has been summarized recently by van der Linde (1962). The length x_o can be compared to that distance downwind from a shelterbelt where the velocity distributions have the same shape as the velocity distribution in the undisturbed boundary layer. The data quoted by van der Linde (1962) indicate effects of open shelterbelts to extend from 10 to 25 h, and of dense shelterbelts to about 60 h. These distances are quite comparable with the wind tunnel values of Table 1.

c. The velocity distributions above the canopy. The validity of Eq. (1) for field data is well established, and has also been verified for large crops by Tan and Ling (in Lemon, 1963). They found d to be of the order of the crop height, and u_* values about of the same magnitude as the values found in the wind tunnel. Significant is that the z_o values found in the field are usually small quantities, of the same magnitude as found in the wind tunnel model crop. Tan and Ling (in Lemon, 1963) calculated values of z_o for corn which ranged from 0.2 cm to 4.2 cm for wind ranging from 3 to 6 m sec^{-1}. For wheat they obtained z_o-values from 3 to 4.8 cm for the same range of velocities. These compare with a laboratory value of about 1.4 cm.

Modeling of the flow above a canopy by using a velocity distribution inside the canopy which is modeled to correspond to the flow inside the actual crop, thus appears difficult. One may have to separately study the modeled flows inside and above the crop.

d. Recommended improvements in field experiments. The need for doing experiments in the field downwind from x_o suggests that measuring stations in the canopy be equipped with two towers, the second at a known distance downwind, preferably diagonally behind the first tower. If during a particularly steady wind similar velocity profiles are observed on both towers, then assurance is obtained that the towers are located downwind from x_o. If the two profiles are significantly different, then the towers should be moved further downwind from the edge of the crop plot.

An interesting result can be obtained with the two towers if the turbulent shear τ_l can be measured at height l above the ground. With modern bi-vane instruments this is entirely feasible. Then the ground shear τ_o for the field situation can be evaluated from a modification of the momentum equation. It can be shown that in zero pressure gradient flow the boundary layer equation in conjunction with the continuity equation integrates to

$$\tau_o-\tau_l=u_l^2\frac{d\theta_l}{dx}+u_l\frac{du_l}{dx}\left(2\theta_l-\int_0^l\frac{u}{u_l}dy\right), \tag{9}$$

where τ_o is the shear stress at the ground, u_l is the velocity at the height l, and θ_l is a type of momentum thickness

$$\theta_l=\int_0^l\frac{u}{u_l}\left(1-\frac{u}{u_l}\right)dy. \tag{10}$$

Eqs. (9) and (10) can be of use, in the case where the ground cover changes in the wind direction, to obtain an estimate of the average surface shear stress between two adjacent stations if the gradients are replaced by differences. Eq. (9) does not depend on the assumption of a similarity profile or on the existence of a logarithmic profile; it only depends on the validity of the boundary layer approximations.

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