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Characteristics of Wind and Turbulence in and above Model Forests

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ABSTRACT

A model forest canopy was designed to simulate the meteorological characteristics of typical live forests. Measurements were made of velocity, turbulence, drag, and gaseous plume spread within the simulated canopy. The resulting data compares favorably with prototype field measurements in all cases. Several new aspects of the flow at the upwind edge of a forest are displayed.

Introduction

Wind movement within forest stands and in their undary regions dominates the exchange processes ich occur within the vegetative canopy. The struc-e of the timber stand interacts with the prevailing ıds to determine fire spread rates, snow pack, soil sion, dispersal of seed for forest regeneration, blow wn, and rates of carbon dioxide and water vapor change during plant metabolism.

As early as 1893, a German scientist, Metzger, in-stigated the effects of wind action on trees. Subse-ently, a variety of studies have been made of the ıavior of winds well inside a forest (Bayton, 1963; oper, 1965; Denmead, 1964; Fons, 1940; Huston, 54; Poppendiek, 1949; Tiren, 1927; Tourin and Shen, 56). Some measurements are available for the varia-n of the wind at the edge of a forest (Iizuka, 1952; ifsnyder, 1955). These measurements have provided ough picture of a highly complex and turbulent flow d within the vegetative canopy. There exists a inite need for a sorting out of the basic character-cs and parameters of the flow in order to provide dictions for differing forest stands or species.

Since field measurements are not easy to obtain ause of the cost involved in providing a perfect asuring station and obtaining cooperative weather, program of modeling the flow in and above plant ers has been initiated in the Colorado State Uni-sity Fluid Dynamic and Diffusion Laboratory.[2] It he purpose of this paper to discuss measurements of ıd velocity, turbulence and turbulence spectra over ıodel forest canopy.

2. Modeling of a forest canopy

The wind tunnel has been used repeatedly by the forest meteorologist in his efforts to understand the complex pattern of flow generated by the tree—a permeable, random shaped, elastic object. Tiren, in 1927, attempted to estimate crown drag from conifer branch-drag measurements made in a wind tunnel as part of his study of stem form. Wind-breaks have been studied by models to determine soil erosion and blow down characteristics (Hirata, 1953; Iizuka, 1956; Malina, 1941; Woodruff and Zingg, 1952). These studies were all conducted to deduce the qualitative behavior of tree barriers for specific problems. The investigators apparently made no attempt to scale dynamically the character of a live tree except to compensate intuitively for shape and porosity. To model completely the complex geometry and structural characteristics of a live tree is obviously not practical; however, measurements made on coniferous and deciduous trees in the wind tunnel and in the field suggest that equivalence of drag and wake characteristics between model and prototype trees should be sufficient to study the general flow phenomenon (Lai, 1955; Rayner, 1962; Sauer *et al.*, 1951; Walske and Fraser, 1963).

Correlation of the measurements mentioned above plus additional ones made on live trees at Colorado State University indicates that the drag coefficient C_D may vary with wind speed from 1.0–0.3 (Burgy, 1961) (Fig. 1). These measurements indicate that the flow is inertially dominated (i.e., Reynolds number independent), but that self-streamlining of the tree at high velocities can reduce the effective cross-sectional area for the more flexible species.

Measurements made behind small specimens of Colorado spruce, juniper and pine trees revealed that linear wake growth exists behind all trees, that the wake shadows of individual branches disappear within

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Meroney, R. N., and J. E. Cermak, 1967, Characteristics of usion within model canopies. Paper presented at Symposium he Theory and Measurement of Atmospheric Turbulence and usion in the Planetary Boundary Layer, Albuquerque.

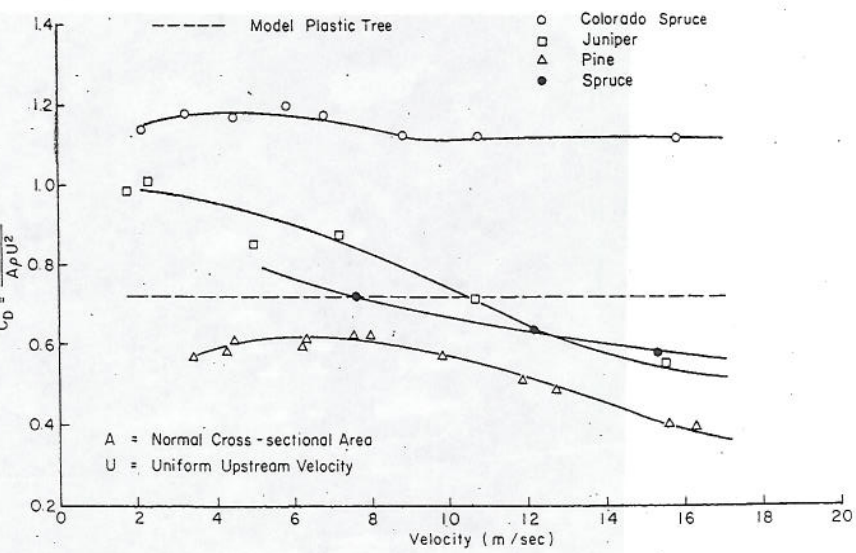

FIG. 1. Drag coefficients of live and model trees: dashed line (after Hsi and Nath, 1968); solid circles (after Rayner, 1962).

1–2 tree crown diameters downstream, and that the velocity defect becomes Gaussian within 3–4 crown diameters (Fig. 2).

After studying a variety of plastic, metal and brush model trees, a model made from plastic simulated-evergreen boughs was selected. The model trees chosen have an average height of 18 cm, a stem height of 5 cm, and a crown diameter of 7 cm. The model tree has a drag coefficient of 0.72 over the velocity range studied and a lateral wake growth similar to that measured for live trees (Figs. 1 and 2).

3. Experimental equipment and procedures

The experimental data were obtained in the low speed Army Meteorological Wind Tunnel in the Fluid Dynamics and Diffusion Laboratory at Colorado State University (Plate and Cermak, 1963). This tunnel was specifically designed to study fluid phenomena of the

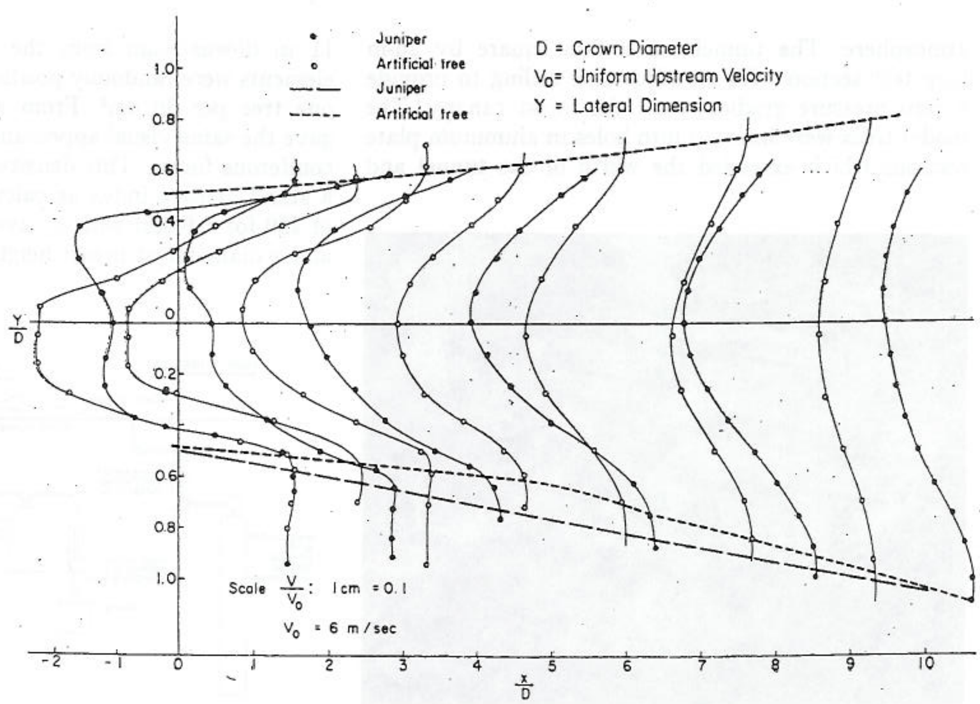

FIG. 2. Wake characteristics of live and model trees.

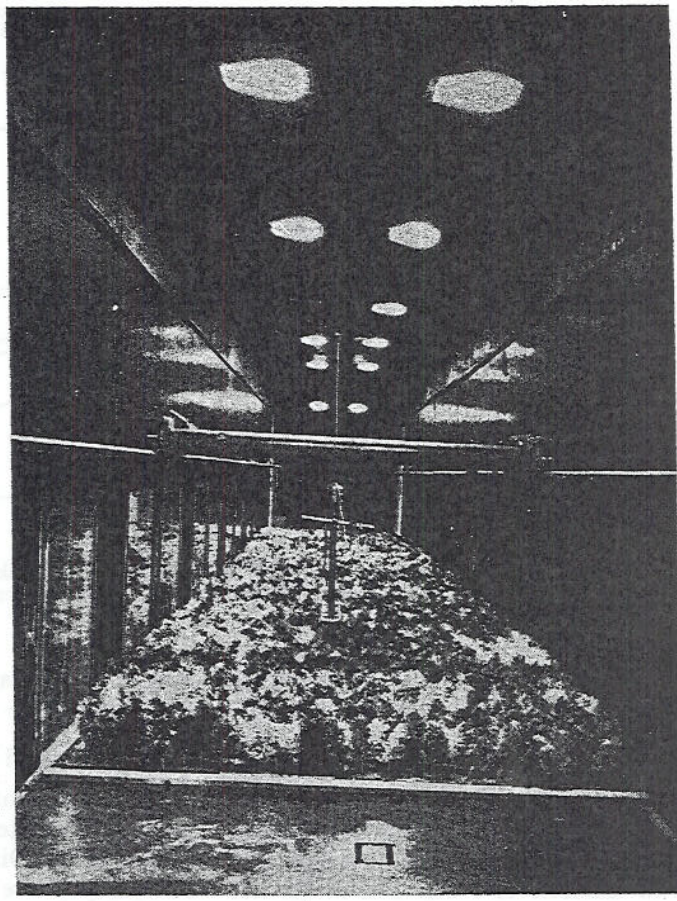

FIG. 3. Meteorological wind tunne and artificial tree canopy.

atmosphere. The tunnel has a 2-m square by 26-m long test section with an adjustable ceiling to provide a zero pressure gradient over the forest canopy. The model trees were inserted into holes in aluminum plate sections which extended the width of the tunnel and 11 m downstream from the tunnel midsection. The elements were randomly positioned with approximately one tree per 36 cm². From above, this arrangement gave the same visual appearance as a moderately dense coniferous forest. This density would be equivalent to a stand density index as calculated by Reinke (1933) of 250 for a forest with an average tree height of 40 ft and a diameter at breast height of 10 inches.

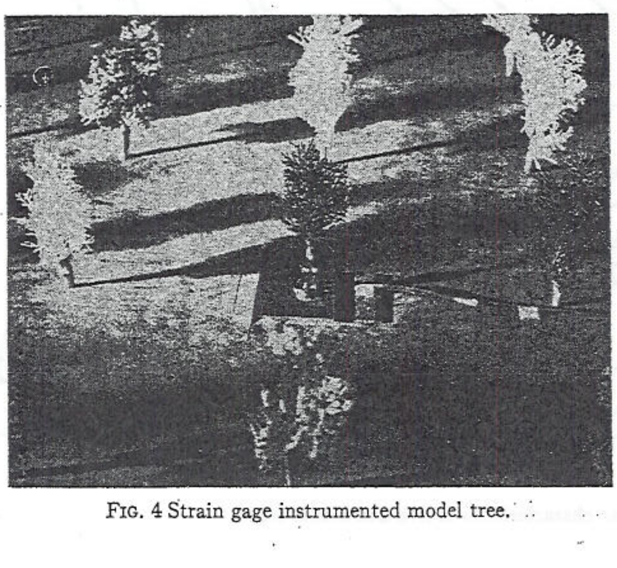

FIG. 4 Strain gage instrumented model tree.

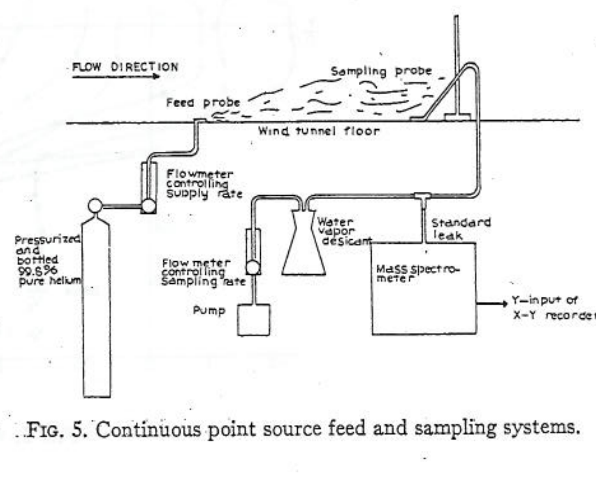

FIG. 5. Continuous point source feed and sampling systems.

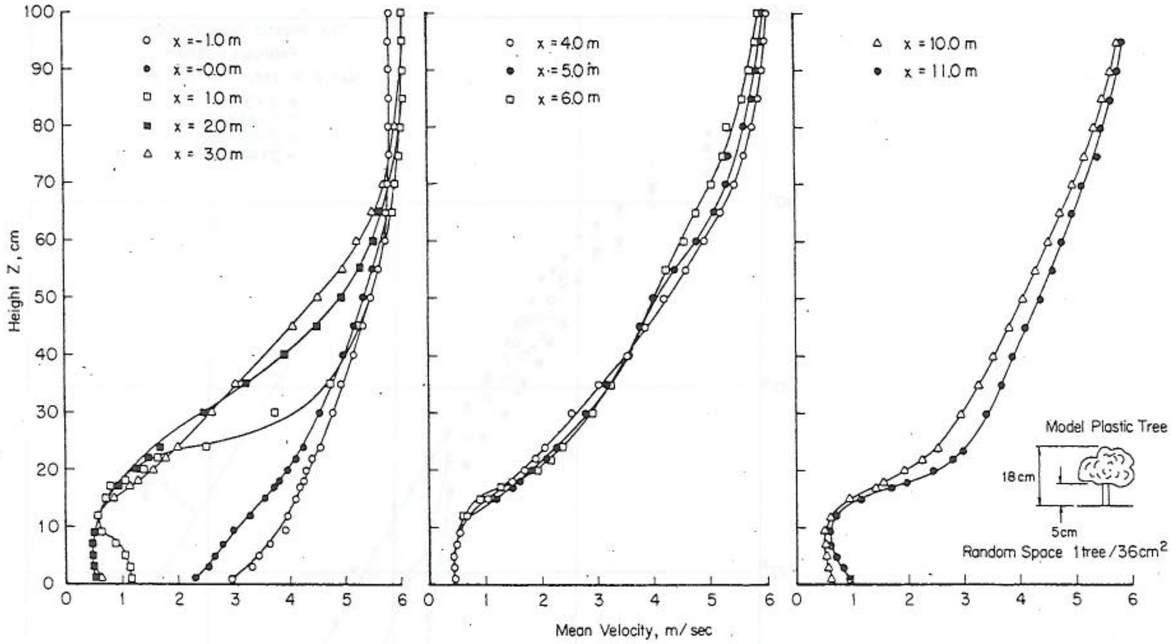

Fig. 6. Velocity profiles in and above model forest canopy.

Single-wire constant temperature anemometers were used to measure velocity and turbulent intensity. In addition, pitot-static tube measurements were made at each section. The sensing elements of the anemometer circuit were platinum wire 0.2 mil in diameter and approximately 0.25 cm long. The bridge circuit utilized was a CSU Solid State Anemometer and the pitot tube output went to a Transonic Model A, Type 120, electronic pressure meter. Turbulence signals were recorded on a Mincom tape recorder and interpreted with a Bruel and Kjær RMS meter, Model 2416, and a set of Bruel and Kjær one-third octave filters ranging from 16–10,000 Hz.

Drag measurements were made on individual model tree elements utilizing a specially designed strain gage balance independent of the center of pressure point (Hsi and Nath, 1968). The shear exerted on sections of the model forest canopy were studied by means of a shear plate, 0.6×0.6 m in area, also instrumented with strain gages as shown in Fig. 4.

Finally, the character of the flow field was studied by mapping the diffusion plume of a continuous point

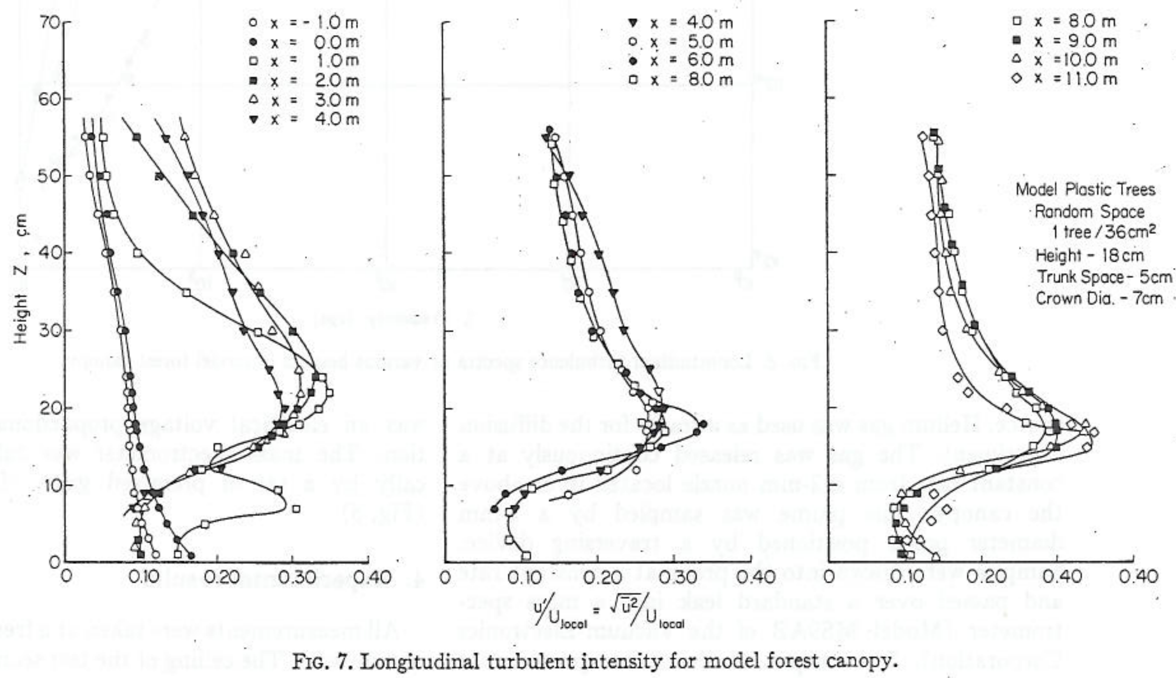

Fig. 7. Longitudinal turbulent intensity for model forest canopy.

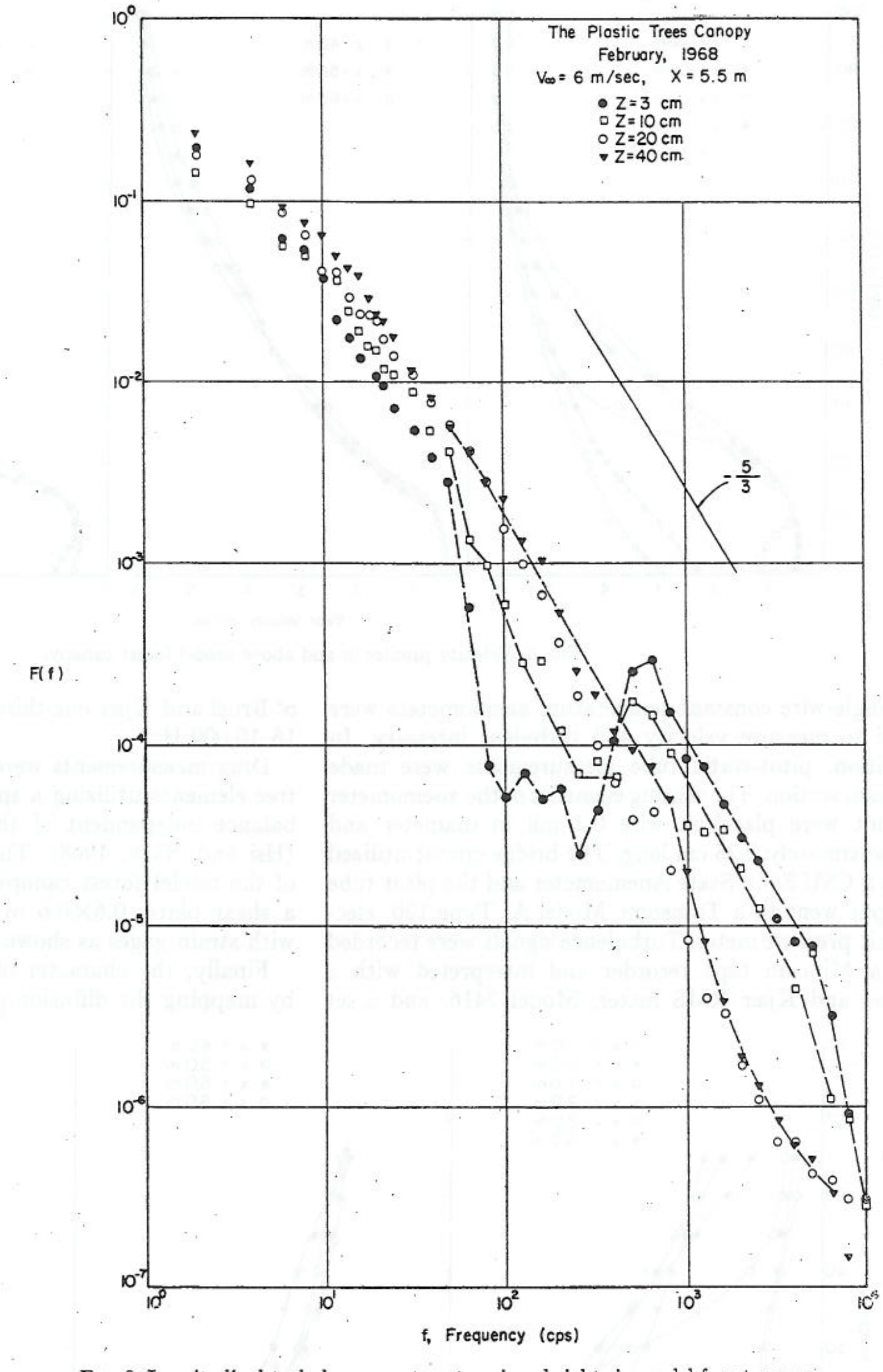

FIG. 8. Longitudinal turbulence spectra at various heights in model forest canopy.

source. Helium gas was used as a tracer for the diffusion experiment. The gas was released continuously at a constant rate from a 2-mm nozzle located in or above the canopy. The plume was sampled by a 2-mm diameter probe positioned by a traversing device. Samples were drawn into the probe at a constant rate and passed over a standard leak into a mass spectrometer (Model MS9AB of the Vacuum-Electronics Corporation). The output of the mass spectrometer was an electrical voltage proportional to concentration. The mass spectrometer was calibrated periodically by a set of premixed gases of research grade (Fig. 5).

4. Experimental results

All measurements were taken at a free stream velocity of 6 m sec^{-1}. The ceiling of the test section was adjusted

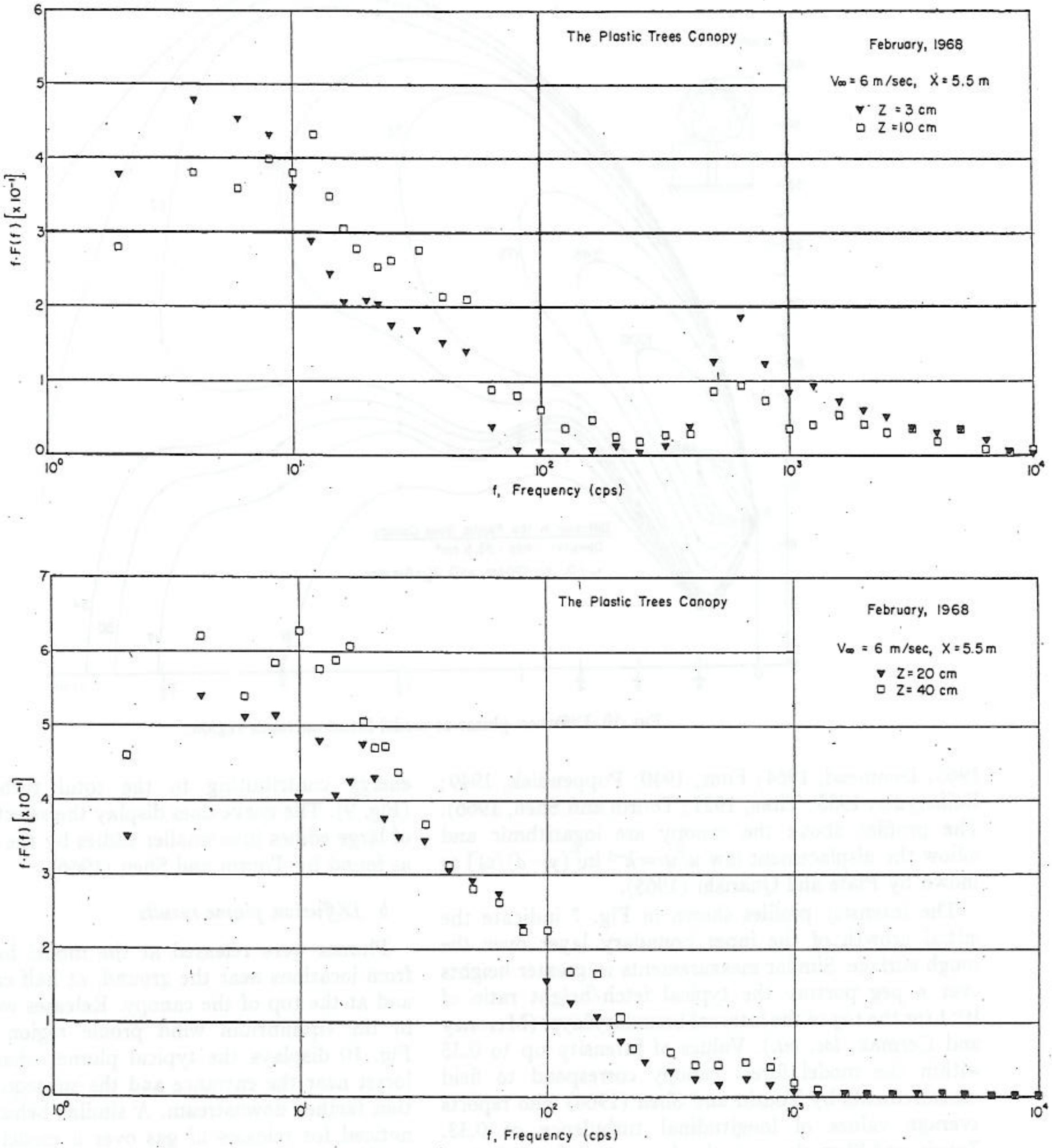

FIG. 9. Turbulent energy distributions in model forest canopy for various heights above the ground.

: zero pressure gradient and the upstream velocity ofile was measured and found to be logarithmic. The nperature condition was constant and hence neutral ıbility existed.

a. Typical velocity and turbulent intensity profile results

A sequence of vertical profiles of mean velocity meas- ɜments were made along the tunnel centerline both and above the forest canopy. The transformation of ɜ wind profiles in the vertical direction are shown in ʒ. 6. Jetting of the wind flow beneath the canopy is observed for at least the first 3 m (or 15 canopy heights); subsequently, the wind profile reaches an equilibrium state at about 4 m (or 20 canopy heights). Finally, accelerations of the wind are observed during the last 2 m of the canopy as the wind adjusts to the smooth surface downwind. The extent of the entrance region agrees with previous measurements by Meroney and Cermak (*loc. cit.*) and Plate and Quarishi (1965), but is greater than that tentatively suggested by Reifsnyder (1955). The shape of the equilibrium velocity profile agrees qualitatively with prototype measurements for moderately dense conifer forests (Cooper,

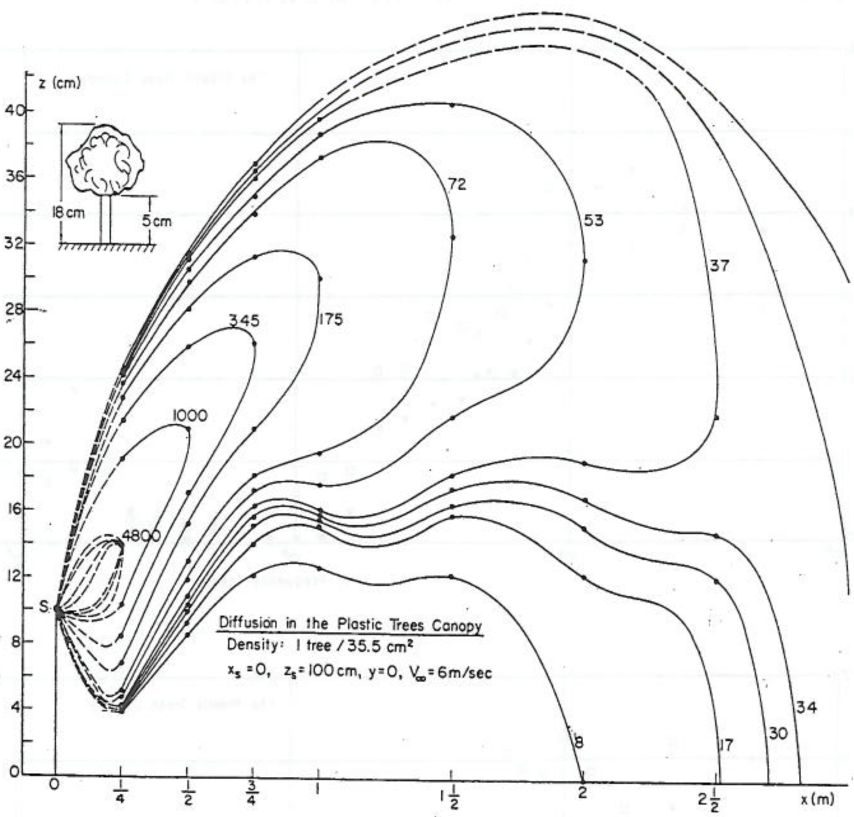

Fig. 10. Diffusion plume at model forest entrance region.

1965; Denmead, 1964; Fons, 1940; Poppendiek, 1949; Reifsnyder, 1955; Tiren, 1927; Tourin and Shen, 1966). The profiles above the canopy are logarithmic and follow the displacement law $u/u_* = k^{-1}\ln[(y-d)/z_0]$ as shown by Plate and Quarishi (1965).

The intensity profiles shown in Fig. 7 indicate the initial growth of the inner boundary layer over the rough surface. Similar measurements to greater heights over a peg portray the typical fetch/height ratio of 10:1 for the top of the internal boundary layer (Meroney and Cermak, *loc. cit.*). Values of intensity up to 0.35 within the model forest canopy correspond to field measurements by Tourin and Shen (1966) who reports average values of longitudinal turbulence of 0.33. Tourin and Shen also note the decrease of the turbulent intensities as one moves downward into the forest cover.

The energy spectrum function F for the longitudinal component of turbulence has been reduced for heights of 3, 10, 20 and 40 cm above the ground (~1/6, 1/2, 10 and 20 times canopy height). Fig. 8 displays the results for a neutral atmosphere in the fully established wind profile region. It is observed that the $-5/3$ law appears to exist for all heights. In addition, the ratio of vertical to longitudinal intensities measured were from 0.8–1.0, indicating a high degree of local isotropy; hence, the dissipation rate may be estimated from Kolmogorov's similarity theory. The spectra were also replotted as $fF(f)$ vs $\log f$ to represent the distribution of the energy contributing to the total turbulent energy (Fig. 9). The curve does display the selective reduction of large eddies into smaller eddies by the tree branches as found by Tourin and Shen (1966).

b. Diffusion plume results

Plumes were released at the model forest entrance from locations near the ground, at half canopy height, and at the top of the canopy. Releases were also made in the equilibrium wind profile region downstream. Fig. 10 displays the typical plume exhalation by the forest near the entrance and the subsequent re-inhalation farther downstream. A similar behavior has been noticed for releases of gas over a model crop canopy simulated with dowel pegs (Meroney and Cermak, *loc. cit.*). This phenomena is a result of vertical motions near the front of the forest canopy previously reported by Iizuka (1952). The ramification of this effect on fire spread and parasite control by spray is obvious. Plume releases within the forest near the ground were characterized by wide meandering and large lateral dispersal. The sequence of stages of the concentration gradient observed upon repenetration of the plume downstream are similar to those observed by Tourin and Shen (1966) during elevated line source releases over a deciduous forest. Initially, there is a gradient downward followed by a gradient in concentration upward even farther downstream.

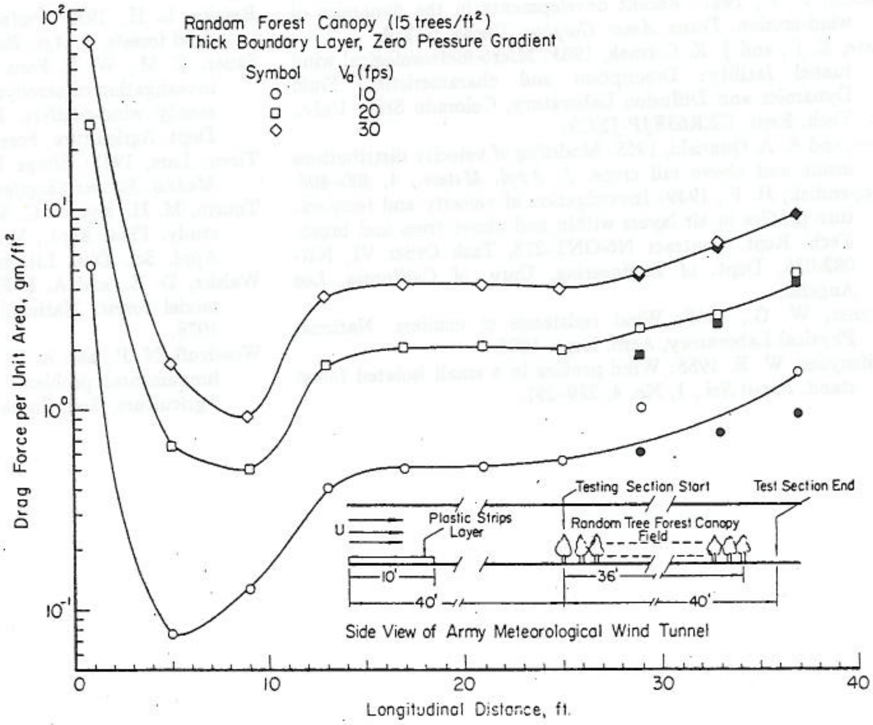

FIG. 11. Shear plate drag for model forest canopy.

c. Drag and shear characteristics of model forest

Results of extensive single tree drag measurements ıade within regular geometric arrays of the model :e (an orchard arrangement) are reported by Hsi and ıth (1968). The drag profiles measured show a nilar behavior to the bending moment measurements ıade by Walske and Fraser (1963); that is, there is a arp decrease in drag on the trees with distance downnd followed by a slight rise to an asymptotic constant .lue.

Shear plate measurements made within the random nopy array under discussion herein display the same aracteristics as the regular arrangements. Fig. 11 ɔts local shear force vs distance downwind from the nopy inception. The minimum observed within the st 2 m is evidently the result of a relatively stagnant gion inside the canopy which also explains the be.vior of the diffusion plume discussed in Section 2. ıis same phenomenon was found for flow over a odel peg canopy (Meroney and Cermak, *loc. cit.*).

Conclusions

It is apparent that the general character of the wind ɪw in and above forests may be satisfactorily simuted in the meteorological wind tunnel. In addition, ese new data suggests that even the microstructure intensity and energy spectra behave in a similar anner to a prototype tree canopy. Hence, it should : economically feasible to determine the effects of nsity variation, vegetative understructure, selective cropping or logging, etc., on forest fire control, on watershed management, or on other aspects of silviculture.

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