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WIND TUNNEL STUDIES OF THE AIR FLOW AND GASEOUS PLUME DIFFUSION IN THE LEADING EDGE AND DOWNSTREAM REGIONS OF A MODEL FOREST

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Abstract—A model forest canopy is designed to simulate meteorological characteristics of a typical live forest. Velocity and gaseous plume behavior are measured. Flow properties are compared with recent field measurements. Ground penetration in the initial fetch region resulted in strikingly different streamline motion when compared to wind motions within the equilibrium regions. Measured values of the vertical eddy diffusion coefficient are shown to predict plume behavior in the equilibrium region if a correction is included for the ratio $K_y/K_z > 1.0$.

Ventilation of an elevated line source into the canopy region is compared with a simple one-dimensional model.

INTRODUCTION

WIND movement within a forest stand and within its boundary region dominates the exchange processes occurring within the vegetative canopy. The structure of the timber stand interacts with prevailing winds to determine the rate of fire spread, snow pack, soil erosion, dispersal of seed for forest regeneration, blow down, and carbon dioxide and water vapor exchange during plant metabolism.

Agricultural meteorologists, atmospheric scientists, and hydrologists are interested in information about the evaporation and exchange processes occurring within these vegetative canopies. Such information facilitates calculating the efficiency of water, energy, and CO_2 transport in plant metabolism and the penetration of foreign additives into or their escape out of the bulk of a canopy. As early as 1937 experimenters measured velocity, temperature, evaporation rate, and energy balance within and above such canopies (PENMAN and LONG, 1960; INOUE, 1963; UCHIJIMA and WRIGHT, 1964; LEMON, 1962). These measurements, however, have provided only a rough sketch of the final picture of a highly complex, turbulent flow field within vegetation.

In the past, measurements of diffusion from point or line sources in forest configurations were limited to measurements of an instantaneous line source by Bendix over a tropical rain forest (BAYNTON, 1963), of point and line source distributions over a deciduous forest by Litton Systems (TOURIN and SHEN, 1966), of instantaneous point sources in a tropical deciduous forest by MELPAR (ALLISON *et al.*, 1968), and of rates of particulate dispersion in a forest canopy at Brookhaven (RAYNOR, 1967, 1969). These measurements are extensive and well documented. However, they must be normalized to some simplified geometry in order to determine universal characteristics and governing parameters of a vegetative penetration by a diffusing plume.

Since field measurements are not easy to obtain because of prohibitive costs of providing a perfect measuring station and the difficulty of obtaining cooperative weather, a laboratory program for modeling flow in and above plant covers was initiated at the Fluid Dynamics and Diffusion Laboratory at Colorado State University. [For previous results see PLATE and QUARISHI (1965), MERONEY and CERMAK (1967), and MERONEY (1968).]

The purpose of this paper, then, is to discuss some measurements of diffusion from a continuous point source, rather than from an instantaneous point source, in and above a model forest canopy. The results include:

(a) a description of the diffusion process in and above the simulated canopy;

(b) a description of vertical dispersion of tracer materials;

(c) a determination of the effect of the initial fetch of the forest canopy on tracer dispersion, and

(d) a determination of the vertical distribution of the eddy diffusion coefficients in and above the modeled canopy.

MODELING OF A FOREST CANOPY

The wind tunnel, traditionally a research tool of the aerodynamicist, also has been used frequently by the forest meteorologist in an effort to understand the climate in a forest as it is generated by the presence of permeable, random shaped, elastic, objects, i.e., trees. Researchers have modeled forest behavior using tree boughs, cotton balls, wooden pegs, plastic strips, and even wire mesh (HIRATA, 1953; IIZUKA, 1956; MALINA, 1941; WOODRUFF and ZINGG, 1952). Obviously, complete modeling of the complex geometry and structural characteristics of a live tree is not practical. However, a recent comparison of velocity, turbulence, and diffusion measurements in model and prototype canopies indicates simulation of dimensionless drag and wake characteristics of the individual canopy elements are sufficient to study general phenomena (MERONEY, 1968).

Model trees chosen after this simulation are specified to have an average height of 18 cm, a stem height of 5 cm, and crown diameter of 7 cm. Thus, 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.

EXPERIMENTAL EQUIPMENT AND PROCEDURES

The experimental data were obtained in the low speed Army Meteorological Wind Tunnel at Colorado State University (CSU) (PLATE and CERMAK, 1963). This tunnel was specifically designed to study fluid phenomena of the 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 cm^2. From above, the arrangement gave the same visual appearance as a moderately dense coniferous forest. The density of this modeled coniferous forest was 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 in. (FIG. 1), (FIG. 2).

The flow field of this model was studied by mapping the diffusion plume of a continuous point source. Helium gas was used as one tracer for the diffusion experiment. The gas was released continuously at a constant rate from a 2 mm nozzle located in and 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 MS12AB of the Vacuum-Electronics Corporation). The output of the mass spectrometer was an electrical

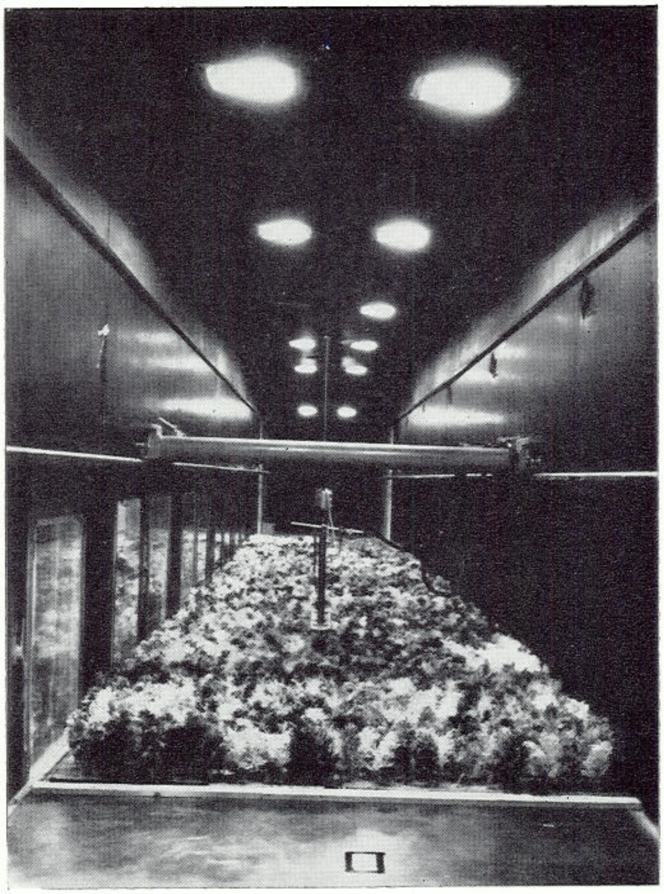

FIG. 2. Model plastic forest.

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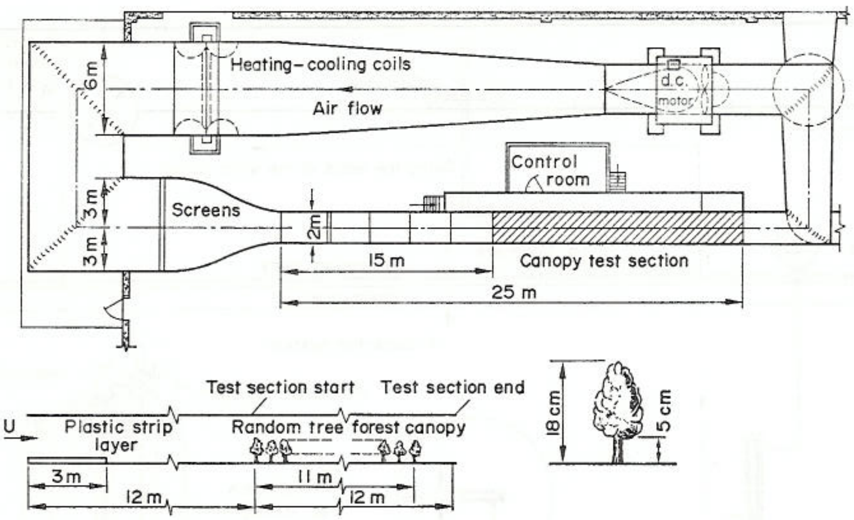

FIG. 1. Wind tunnel arrangement.

voltage proportional to the concentration. The mass spectrometer was calibrated periodically by a set of premixed gases of research grade (FIG. 3).

To investigate the buoyancy character of the helium tracer additional measurements were obtained using a mixture of Kr-85 and air as another tracer. The flow rate of

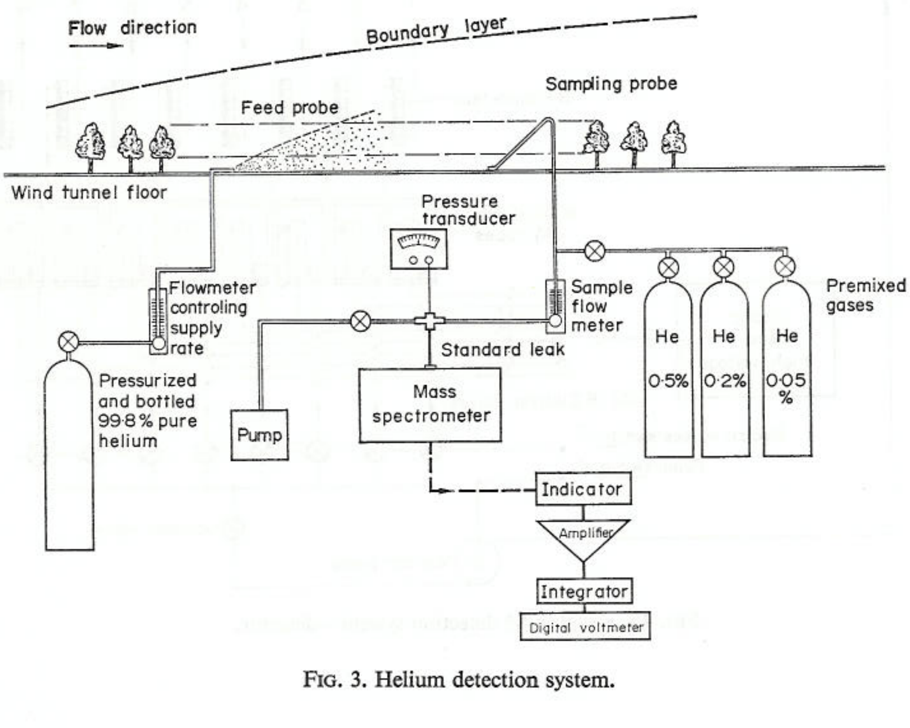

FIG. 3. Helium detection system.

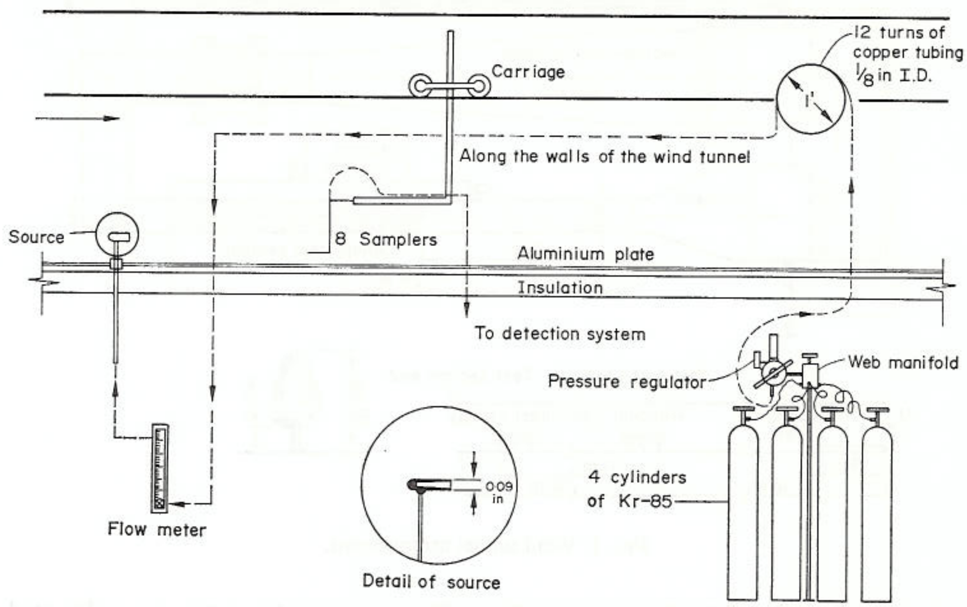

FIG. 4a. Krypton-85 detection system—source.

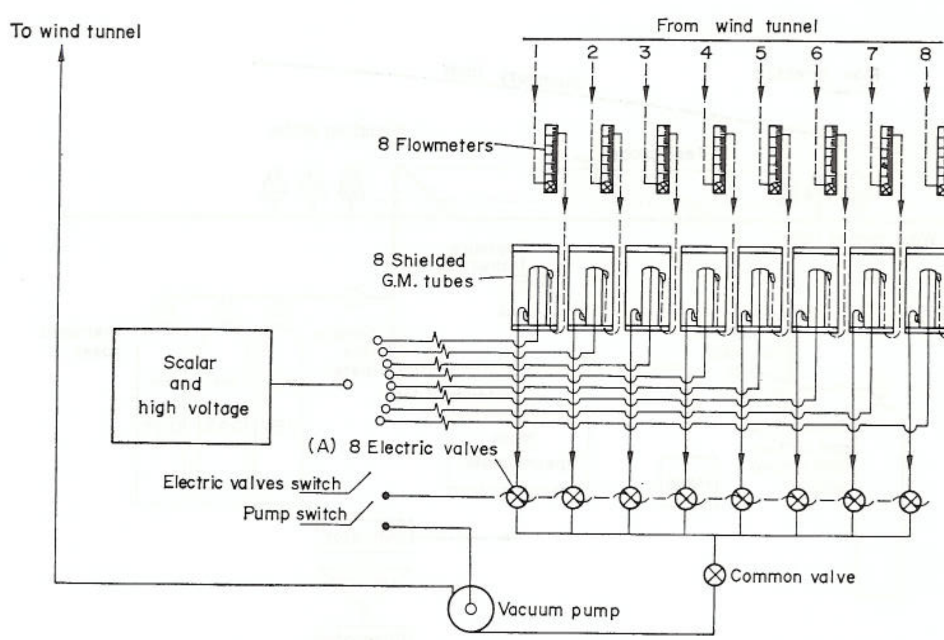

FIG. 4b. Krypton-85 detection system—detector.

Kr-85 mixture was controlled by a pressure regulator at the bottle outlet and monitored by a Fisher and Porter flowmeter. Source concentration was 6·4 μCi cm^{-3} of Kr-85, a beta emitter (half life—10.3 years).

A sampling rake of eight probes was built from 2 mm dia. hypodermic tubing and was mounted on a traversing carriage. The horizontal and vertical position of this carriage was controlled remotely from outside the tunnel. Concentrations were measured at ground levels at various scaled distances from 200 to 400 ft downwind and at vertical elevations centered on plume maximum concentrations. Samples were aspirated at a constant rate of 500 cm^3 min^{-1} into eight TGC-308 Tracerlab Geiger–Mueller side wall cylindrical counters. Samples were flushed through the counting tubes for at least 2 min. Valve A in FIG. 4b was closed, and each sample was subsequently counted for 1 min on Nuclear Chicago Ultra-scaler Model 192A. All samples counted were adjusted for background radiation (see FIGS. 4a and 4b).

EXPERIMENTAL RESULTS

All measurements were taken at a free stream velocity of 6 m sec^{-1}. 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.

a. Typical velocity profile results

A sequence of vertical profiles of mean velocity measurements were made along the tunnel centerline both in and above the forest canopy. The transformation of the wind profiles in the vertical direction are shown in FIG. 5. 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 equilibrium 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

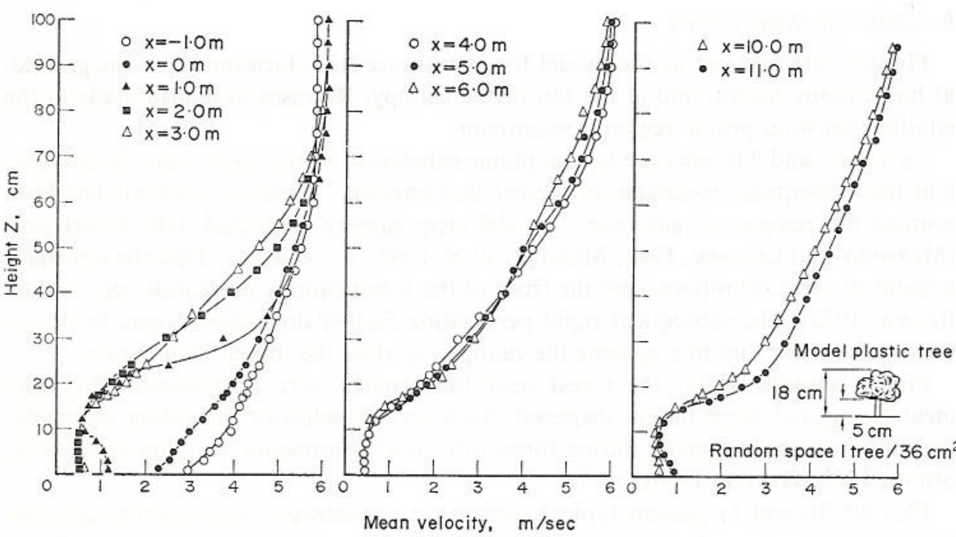

FIG. 5. Velocity profiles.

agrees with previous measurements by MERONEY and CERMAK (1967), and PLATE and QUARISHI (1965), but is greater than that tentatively suggested by REIFSNYDER (1955), whose measurements were for an extremely short forest fetch. The shape of the equilibrium velocity profile agrees qualitatively with prototype measurements for moderately dense conifer forests (COOPER, 1965; DENMEAD, 1964; FONS, 1940; POPPENDIEK, 1949; REIFSNYDER, 1955; TIREN, 1927; TOURIN and SHEN, 1966).

Seasonal wind profile changes can be compared with various model elements. In the winter the Minnesota deciduous forest of TOURIN and SHEN (1966), compares favorably quantitatively with a fairly dense peg arrangement by MERONEY and KAWATANI (1968), (FIG. 6), whereas, the plastic tree canopy simulates summer measurements made by ALLEN (1968), SHINN (1968) and TOURIN and SHEN (1966), (FIG. 7).

The profiles above the canopy are logarithmic and can be plotted to follow the displacement law $u/u^* = k^{-1}\ln[(y-d)/z_0]$ as shown by PLATE and QUARISHI (1965). However, it should be noted that the popular regression technique first suggested by Lettau to solve for u^*, d, and z_0 could not be used unless it was modified (ROBINSON, 1961). This program (a version of which is known as the "Three Bears" program) unfortunately assumes u^*, d, and z_0 are independent; as a result, some investigators have obtained the physically suspect result that d is negative (KUNG, 1961). In our computations d was assumed equal to the canopy height; thus $z_0 \simeq 2.2$ cm, and $u^* \simeq 1.4$ m sec^{-1}. In addition, measurements over the peg canopy suggested that the velocity profiles may be dominated by the canopy top wake until $z \simeq 2.5$ to 3 h; hence, it would appear that forest micro-meteorologists should not attempt a log-law analysis unless they utilize fairly tall towers. Moreover, recent analysis of data for above canopy flows suggests that the friction velocity and roughness length are not local quantities but vary with height in the leading edge region; perhaps because the assumption of a constant shear stress region is invalid (SADEH *et al.* 1969).

Turbulence and drag measurements for the model forest discussed herein have been previously presented by MERONEY (1968).

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.

FIGURES 8 and 9 display the typical plume exhalation by the forest near the entrance and the subsequent re-inhalation further downstream. A similar behavior has been noticed for releases of gas over a model crop canopy simulated with dowel pegs (MERONEY and CERMAK, 1967; MERONEY *et al.* 1968; YANO, 1967). This phenomena is a result of vertical motions near the front of the forest canopy previously reported by IIZUKA (1952). The subsequent rapid penetration further downstream may be due to the intense shear and mixing near the canopy top over the initial fetch region.

Plume releases within the forest near the ground were characterized by wide meandering and large lateral dispersal. Such erratic behavior, including plume bifurcation, occurs frequently during forest diffusion experiments (ALLISON *et al.* 1968; SHINN, 1969; GEIGER, 1950).

FIGURES 10 and 11 present typical vertical-isoconcentration sections through continuous point source plumes released at various heights above the ground (i.e., 0 and

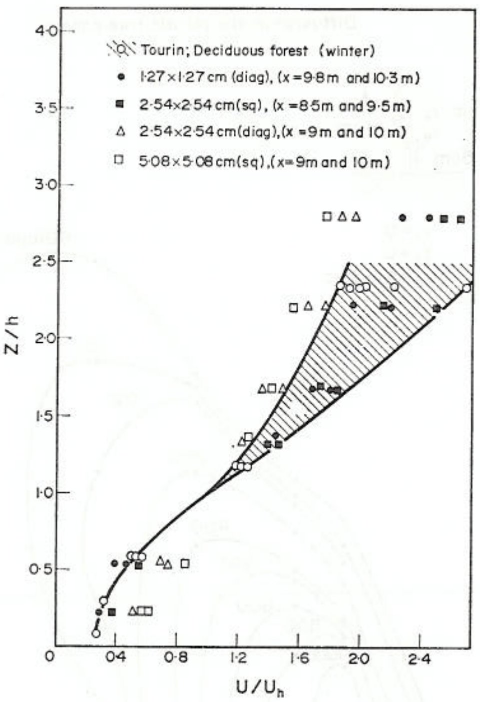

Fig. 6. Comparisons with winter forests.

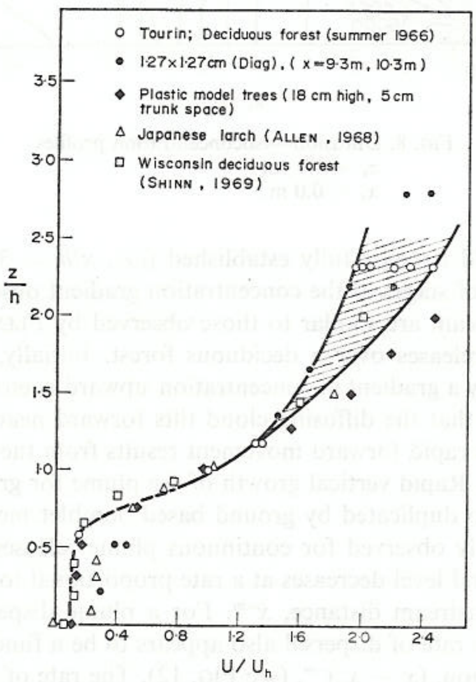

Fig. 7. Comparisons with summer forests.

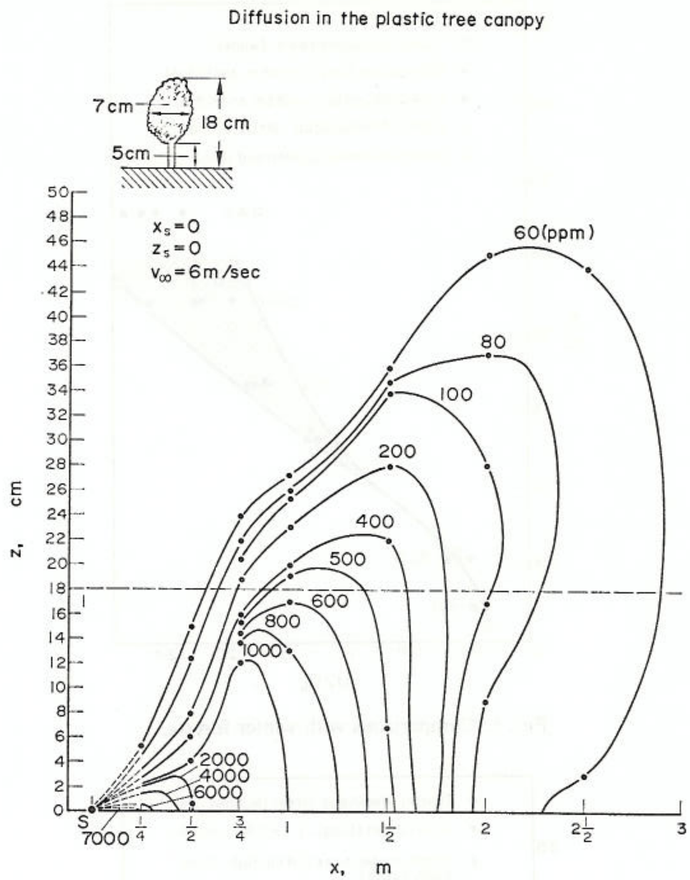

FIG. 8. Diffusion—Isoconcentration profiles
$z_s = 0.0$ cm
$x_s = 0.0$ m.

h) where the flow field appears fully established (i.e., $x/h = 33$). For the elevated releases the sequence of stages of the concentration gradient observed on penetration of the plume downstream are similar to those observed by FLEMMING (1967) during elevated line source releases over a deciduous forest. Initially, there is a gradient downward followed by a gradient in concentration upward even further downstream.

It should be noted that the diffusing cloud tilts forward near the tree top due to wind shear and that a rapid forward movement results from the relatively high wind speed at the tree tops. Rapid vertical growth of the plume for ground source releases is another feature also duplicated by ground based bomblet measurements.

It has been generally observed for continuous plume releases that the maximum concentration at ground level decreases at a rate proportional to a power function of the longitudinal downstream distance, x^{-m}. For a plume dispersing in or above a vegetative canopy, the rate of dispersal also appears to be a function of the distance from the release position, $(x - x_s)^{-m}$, (see FIG. 12). The rate of dispersion, however, is much larger than for plumes dispersing over a smooth surface (MALHOLTRA and

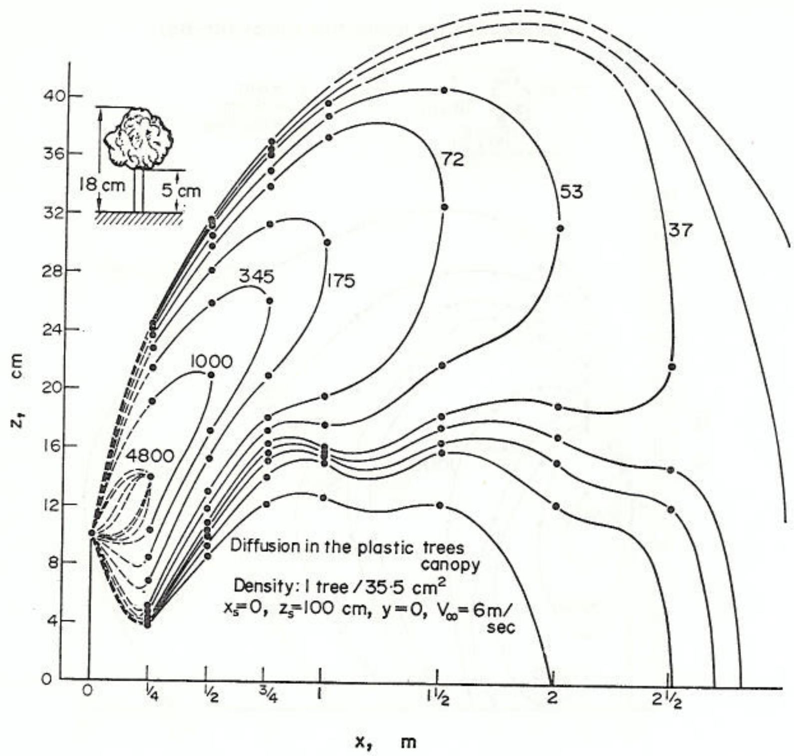

FIG. 9. Diffusion—Isoconcentration profiles
z_s = 10.0 cm x_s = 0.0 m.

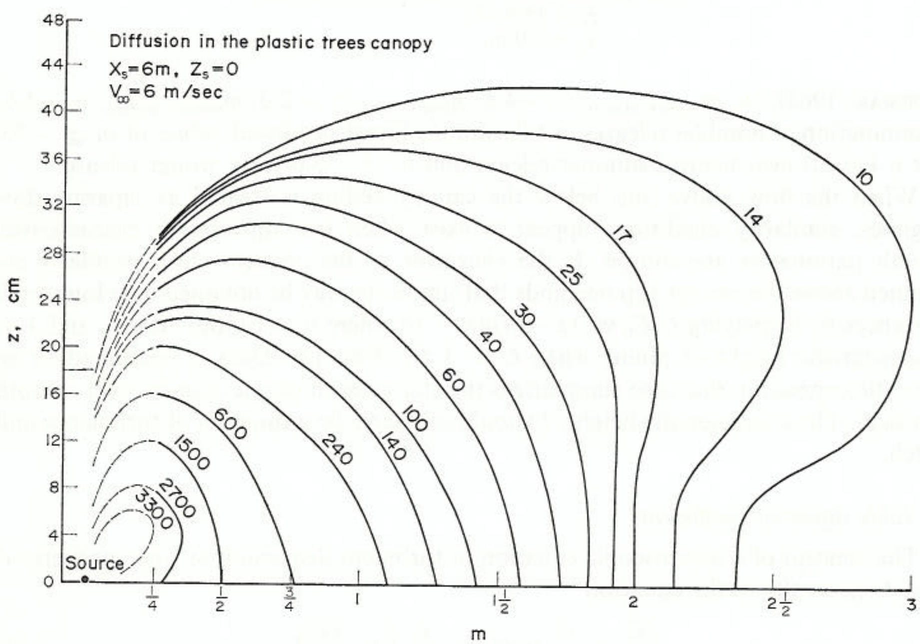

FIG. 10. Diffusion—Isoconcentration profiles
z_s = 0.0 cm x_s = 6.0 m.

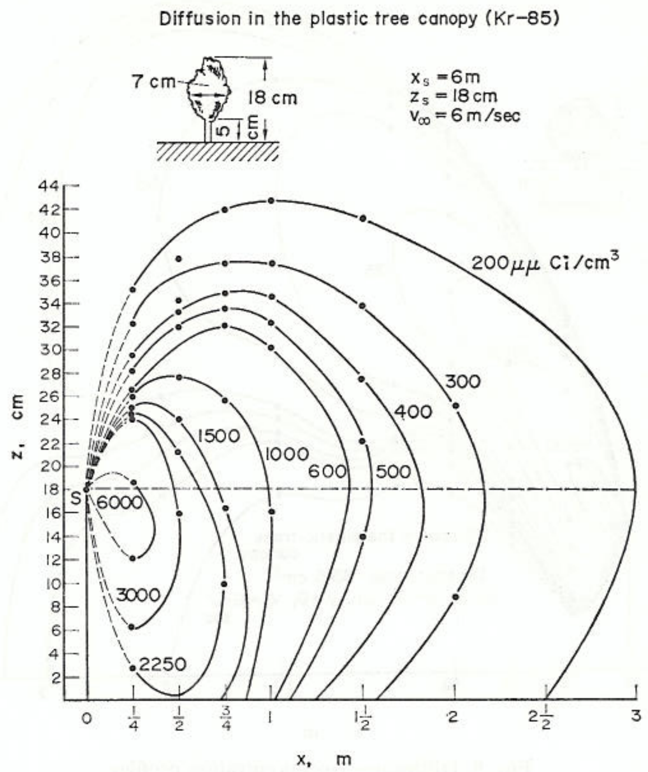

FIG. 11. Diffusion—Isoconcentration profiles
$z_s = 18.0$ cm
$x_s = 6.0$ m.

CERMAK, 1964), i.e. $m_{\text{canopy plastic}} = -4.8$, $m_{\text{peg canopy}} = -2.5$, $m_{\text{smooth surface}} = -1.5$. Examination of bomblet releases in a deciduous forest produced values of $m \cong -7.0$ for a typical near-neutral summer release and $m \cong -3.0$ for a winter release.

When the flow above and below the canopy ceiling is treated as separate flow regimes, similarity conditions appear to exist when the appropriate characteristic length parameters are chosen. If the character of the concentration profile is examined above the canopy top one finds that similarity may be obtained over long fetch distances by displaying C/C_h vs. $(z - h)/(\lambda - h)$ where h = canopy height, and λ = characteristic height of plume when $C = \frac{1}{2} C_h$ (FIG. 13). Data is compared to an analytic expression that also summarizes the character of plume releases over smooth surfaces. The characteristic height, λ should of course be a function of turbulence and fetch.

c. Eddy diffusion coefficient

The concept of a macroscopic equation of turbulent dispersion of some property C results generally in the equation

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x_i}(u_i C) = \frac{\partial}{\partial x_i}\left(K_{x_i}\frac{\partial C}{\partial x_i}\right), \tag{1}$$

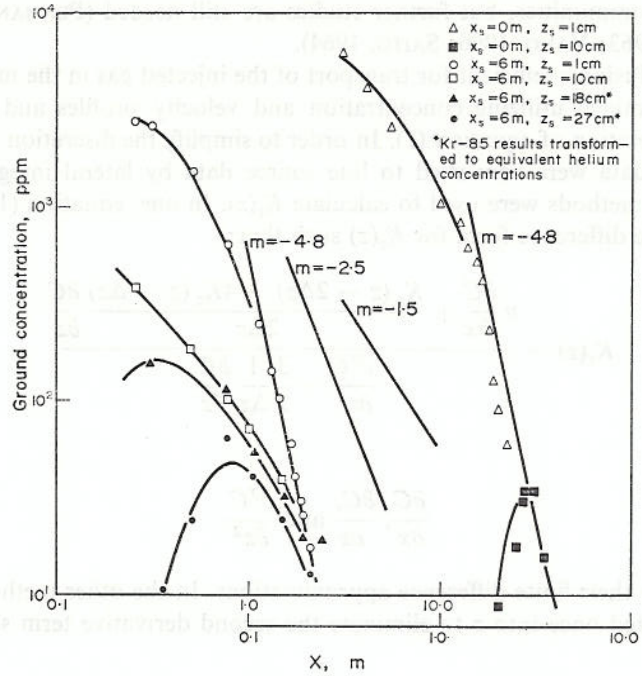

FIG. 12. Ground concentration vs. downstream distance.

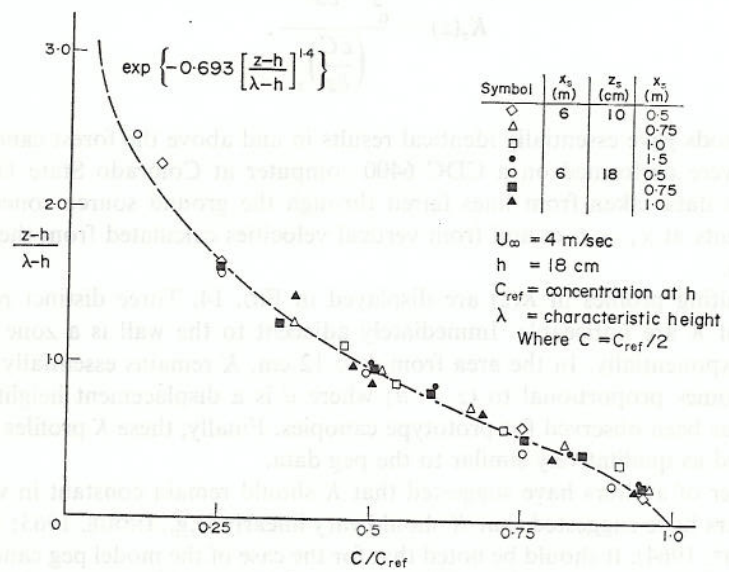

FIG. 13. Dimensionless above canopy profiles.

where K_{x_i} is the coefficient of turbulent diffusion. The coefficient K_{x_i} incorporates within itself the complexities of the actual transport process. Hence, most analytical studies of fluid mechanics require some theoretical or empirical expression for the variation of K_{x_i} with other parameters. Several scientists have studied the nature of

K_{x_i} for plant communities, but further studies are still needed (PENMAN and LONG, 1960; INOUE, 1963; YANO, 1966; SAITO, 1964).

The eddy diffusion coefficient for transport of the injected gas in the model canopy has been determined utilizing concentration and velocity profiles and a finite difference interpretation of equation (1). In order to simplify the discretion analysis, the concentration data were converted to line source data by lateral integration. Two computational methods were used to calculate $K_z(z)$. In one, equation (1) was solved directly in finite difference form for $K_z(z)$ such that:

$$K_z(z) = \frac{u\dfrac{\partial C}{\partial x} + \dfrac{K_z(z - 2\Delta z) - 4K_z(z - \Delta z)}{2\Delta z}\dfrac{\partial C}{\partial z}}{\dfrac{\partial^2 C}{\partial z^2} + \dfrac{3}{2}\dfrac{1}{\Delta z}\dfrac{\partial C}{\partial z}} \tag{2}$$

where

$$\frac{\partial C}{\partial x}, \frac{\partial C,}{\partial z} \text{ and } \frac{\partial^2 C}{\partial z^2}$$

are replaced by their finite difference approximations. In the other method, equation (1) was integrated once into z to eliminate the second derivative term such that

$$K_z(z) = \frac{\int_0^z u \dfrac{\partial C}{\partial x} \, \mathrm{d}z}{\left(\dfrac{\partial C}{\partial z}\right)_z}. \tag{3}$$

These methods gave essentially identical results in and above the forest canopy. Calculations were performed on a CDC 6400 computer at Colorado State University using input data taken from lines faired through the ground source concentration measurements at $x_s = 6$ m and from vertical velocities calculated from the slope of streamlines.

The resulting profiles in $K(z)$ are displayed in FIG. 14. Three distinct regions of variation of K are noticeable. Immediately adjacent to the wall is a zone where K increases exponentially. In the area from 4 to 12 cm, K remains essentially constant and K becomes proportional to $(z - d)$ where d is a displacement height. Similar behavior has been observed for prototype canopies. Finally, these K profiles may also be described as qualitatively similar to the peg data.

A number of authors have suggested that K should remain constant in vegetative cover, others have suggested that K should vary linearly (e.g., INOUE, 1963; UCHIJIMA and WRIGHT, 1964). It should be noted that for the case of the model peg canopy, both conditions of K exist, although in different regions. FIGURE 15 compares the distribution of the modeled K within the canopy with typical results of the distribution of K for a pine forest as measured by DENMEAD, 1964.

The experimental data mesh used to obtain the estimates of $K_z(z)$ was fairly coarse, hence, to verify the results it was decided to recompute the concentration distributions numerically for the elevated release conditions for a continuous point source situation.

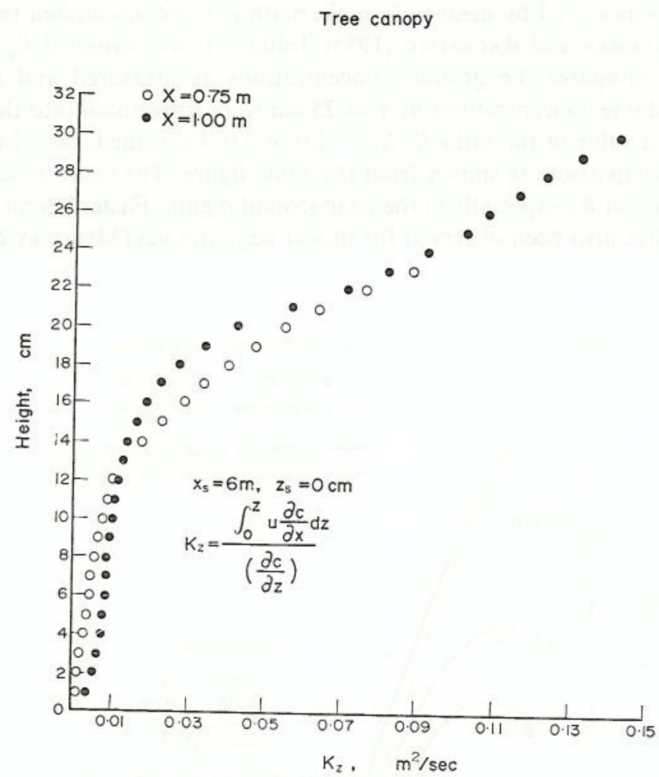

FIG. 14. Eddy diffusion coefficient—mass.

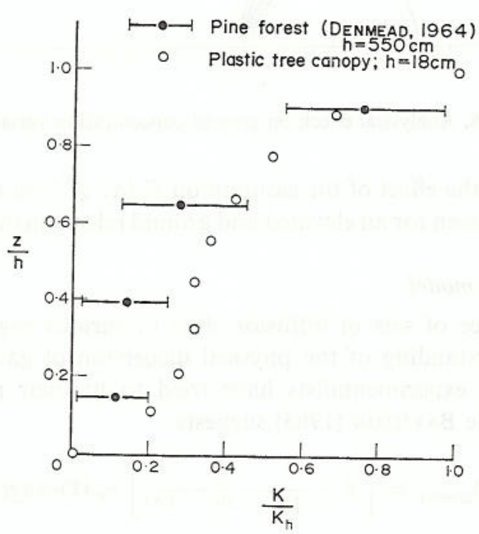

FIG. 15. Below canopy dimensionless eddy diffusion coefficient profiles.

Equation (1) was solved by means of an alternating-direction-implicit technique described by PEACEMAN and RACHFORD (1955). Initially it was assumed $K_y \equiv K_z(z)$.

FIGURE 16 compares the ground concentrations as measured and as calculated when initial plume concentrations at $x = 25$ cm were substituted into the calculation procedure. If a value of the ratio $K_y/K_z = 2.0$ or 4.0 is assumed, one obtains a somewhat better comparison as shown from the same figure. The value of K_y is normally expected to exceed K_z, especially in the near ground region. Faster lateral dispersion at ground level has also been observed for model peg canopies (MERONEY and CERMAK, 1967).

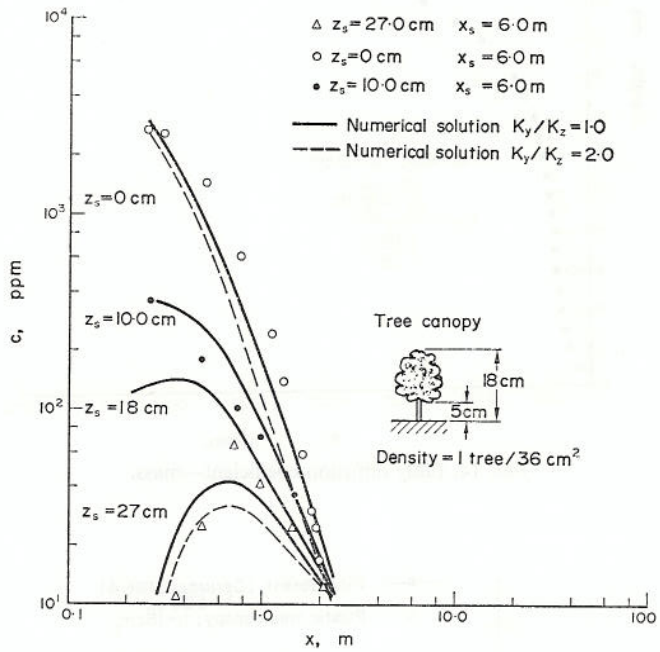

FIG. 16. Analytical check on ground concentration variation.

FIGURE 17 displays the effect of the assumption $K_y/K_z \geq 1$ on the cross-section isoconcentration lines as seen for an elevated and ground release in the plastic tree canopy.

d. Forest penetration model

Despite the existence of sets of diffusion data in various vegetative canopy configurations, the understanding of the physical dispersion of gases in forests is very simple-minded. Most experimentalists have tried to fit their results to regression equations; for example BAYNTON (1963) suggests

$$(\text{Dosage})_{\text{ground}} = \left[A + \frac{B}{10^{C + DU + E\Delta T}}\right] \sigma_\theta \, (\text{Dosage})_{\substack{\text{above}\\ \text{canopy}}} .$$

where U is the velocity, ΔT is the temperature difference above and below canopy, and σ_θ is the standard deviation of wind direction above forest. As Baynton notes, such a

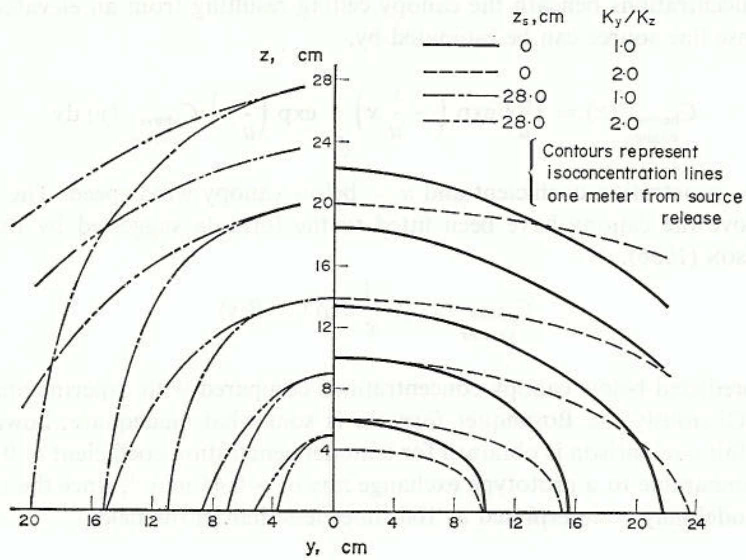

FIG. 17. Cross-section-isoconcentration profiles.

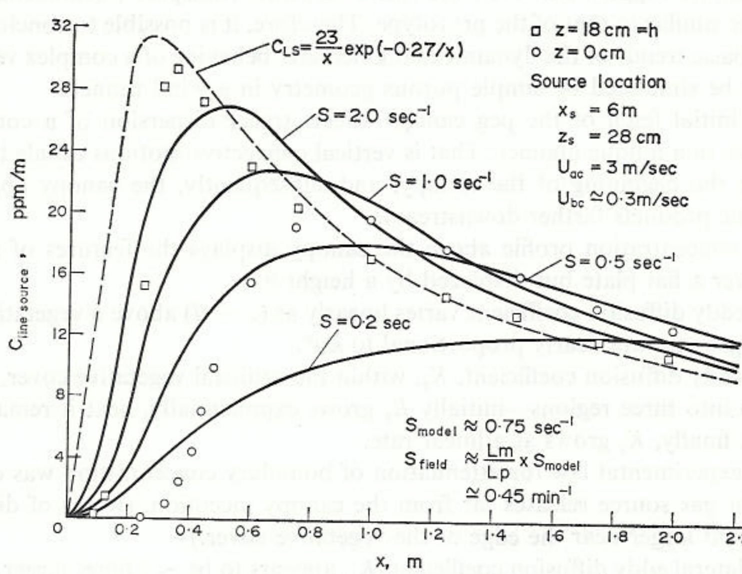

FIG. 18. One dimensional penetration model.

formula applies specifically to the forest where the data were collected. In addition to modifications of simple Gaussian plume models (TOURIN and SHEN, 1969; ALLISON *et al.* 1968), one may also appeal to a simple-minded, one-dimensional model for canopy penetration first suggested by CALDER (1961).

The concentrations beneath the canopy ceiling resulting from an elevated continuous release line source can be estimated by,

$$C_{\substack{\text{below}\\ \text{canopy}}}(x) = \left(\frac{s}{u}\right) \exp\left(-\frac{s}{u}x\right) \int_0^x \exp\left(\frac{s}{u}y\right) C_{\substack{\text{above}\\ \text{canopy}}}(y)\, \mathrm{d}y$$

where s = penetration coefficient and u = below canopy wind speed. The measurements above the canopy have been fitted to the formula suggested by BOSANQUET and PEARSON (1936).

$$C_{\substack{\text{above}\\ \text{canopy}}}(x) \cong \frac{A}{x} \exp(-B/x)$$

and the predicted below canopy concentrations compared with experimental data in FIG. 18. Obviously the Bosanquet formula is somewhat inadequate; however, it is apparent fair comparison is obtained for a model penetration coefficient of 0·75 sec^{-1}. This is comparable to a prototype exchange rate of $\sim$0.45 min^{-1}, since the time scale for the model may be interpreted as 100 times less than in the field.

CONCLUSIONS

The general character of flow in and above vegetative canopies may be satisfactorily simulated in the meteorological wind tunnel. In addition, new data derived for this experimentation suggest that even the micro-structure transport phenomena behave in a manner similar to that of the prototype. Therefore, it is possible to conclude that:

(1) The basic trends of the dynamic and kinematic behavior of a complex vegetative cover may be simulated by simple porous geometry in a wind tunnel.

(2) The initial fetch of the peg canopy affects tracer dispersion of a continuous point source in a unique manner. That is vertical convective motions exhale the gases released at the beginning of the canopy, and subsequently, the canopy appears to re-inhale the products farther downstream.

(3) The concentration profile above the canopy displays the features of a plume released over a flat plate but displaced by a height h.

(4) The eddy diffusion coefficient varies linearly as $(z - d)$ above a vegetative cover and has a growth rate nearly proportional to ku^*.

(5) The eddy diffusion coefficient, K_z, within the artificial vegetative cover, appears to develop into three regions—initially K_z grows exponentially, next it remains constant, and, finally, K_z grows at a linear rate.

(6) The experimental law for attenuation of boundary concentration was obtained as $x^{-4.8}$ for gas source releases far from the canopy inception. (Rates of dispersion are somewhat larger near the edge of the vegetative cover.)

(7) The lateral eddy diffusion coefficient, K_y, appears to be $\sim$2 times larger than the vertical transport rate as an approximation. However, it is expected that $K_y \neq 0$ at ground level.

(8) Considering the similarity of plume behavior, when considered separately above and below the top of the canopy, it would appear that models directed to treat the physics of these two layers separately are justified.

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