An Analysis of the Turbulent Structure in the Unstable Surface Layer nearby a Shelter Belt

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ABSTRACT

An analysis was performed of the turbulent data obtained from Yucheng experimental station in the Shandong Province in 1984. It is shown that at variant wind speed, the spectra of streamwise velocity remain similar and the intensity of wind fluctuations is proportional to wind speed in the downwind area of shelter belt. Therefore, we may decide the similarity of wind fluctuations by a speed scale and a length scale which is not correlated with stability. $\sigma_u / V_0 = F(X / H)$. The $-5/3$ power range of temperature spectra extends to lower frequency. The variation of ratio σ_θ / T_* with stability becomes $\sigma_\theta / T_* = C(X / H)(-Z / L)^{-1/3}$. There is not such an extension of *$-5/3$ power range in the humidity spectra.*

I. INTRODUCTION

The investigation of the turbulent flow over nonhomogeneous terrain is important because a flat homogeneous terrain is not met often and the practical problem is always related to a specific terrain. We need not only investigating the local influence of terrain on turbulent flow but also inferring the whole turbulent flow from the measurements obtained at a few points.

The turbulent spectra over flat homogeneous terrain have shown that the inertial range and dissipation range are universal at high frequency but the part of low frequency is variational with stability and can be described by experimental formulas following from Monin–Obukhov similarity (Haugen, 1973). Therefore, we can start from the concept of the equilibrium of turbulent dissipation and generation and then calculate heat and momentum flux by means of the rate of turbulent energy dissipation or the energy of inertial range (Champagne, 1977; Hicks, 1972). We can also measure or calculate these two fluxes with the aid of mean values for profile, radiation and roughness to solve the problem of turbulent structure.

In the case of varying surface roughness the characteristics of velocity fluctuations have already been investigated (Høјstrup, 1981; Beljaars, 1987). There have been many results for the other topography such as mountain, forest, suburb (Neal, 1982; Steyn, 1982; Plate, 1982). It is shown that the inertial range can rapidly reach a new equilibrium with the variation of terrain. It is possible to obtain the results similar to homogeneous terrain under some circumstances. For example, the c_T^2 value measured on the tower in Beijing decreases with height of $-4/3$ power (Zeng, 1983). It is the aim of this paper to describe the local effects of shelter belt on the turbulent structure and put the behavior of this turbulent structure in a kind of flow so that the conclusions can be extended.

II OBSERVATIONS

The observations were made beside a tower at the experimental station of Institute of Geography, Academia Sinica, Yucheng, Shandong Province a thick shelter belt to the north, a line of poplar to the east and a meteorological station surrounded by shrubs to the west. Some of flat houses and a two-storied building are located in the north belt. Any belt is about 100 m away from the tower. There are a bean field southward and a thin shelter belt 200 m away. The site for observations is in the upwind of the north shelter belt when south wind blows and in the downwind when north wind blows. The distance of the site from the north shelter belt is about six times the height of belt.

The temperature was measured with platinum wire thermometer at a height of 2,4,6 m respectively. The diameter of platinum wire is 1 micrometer. Wind speed was measured with DISA 55M01 hot wire anemometer with P81 probe and humidity with a fine wire thermocouple psychrometer, with a frequency response of 0–1 Hz. Only a few data of humidity were obtained for the thermocouple was contaminated. The analysis of spectra was made according to Zeng (1983). The averaging time of spectrum is 5 times the period of lowest frequency component. The variances were calculated with 30 Hz sampling ratio and 300 s averaging time. The error due to the short averaging time was larger than that estimated according to Wyngaard (Haugen, 1973). Practically, in comparison with variance averaged over 1 hour, it is expressed that the error would be larger than 10% and the variance calculated was often lower.

The observations lasted six days from 21 August to 2 September. Measurement was made once every two hours and continued 40 minute. Only one group of variance and spectrum were calculated in a measurement usually. 35 samples under the unstable condition in daytime were used. It was warm and wet, blowing south wind below 3 m / s in the first 3 days. The cold air passed through the area. The wind was north and increased to more than 4 m / s in the other 3 days. The temperature decreased continuously till 2 September. The states of south and north wind will be discussed respectively because the number of sample was not plentiful and there was not synchronous registration of wind direction.

III RESULTS

Fig. 1 and Fig. 2 represent spectra of streamwise velocity and temperature, in which dimensionless frequency $f=nz/U$, n–frequency (Hz), z–height (m), U–mean velocity (m / s). $S_u(n)$–spectrum of streamwise velocity, $S_\theta(n)$–spectrum of temperature, and σ_u^2–the variance of streamwise velocity and σ_θ^2–the variance of temperature. It is shown that there are an inertial range with $-5/3$ power law in the spectra of streamwise velocity as well as temperature. But the normalized spectra are separated from each other and specially at the state of north wind. This is related to the behavior of fluctuations at low frequency. The solid curves of velocity spectra are obtained from Højstrup's formula(Højstrup, 1982) and the temperature spectra, from Kaimal's formula of neutral stratification (Kaimal, 1972). The calculated methods will be explained later. The low frequency of velocity spectra increases obviously as north wind blows and there is a maximum value at $f=0.1$. The enhancement is more obvious in the temperature spectra. The range of $-5/3$ power law extends to $f=0.01$. There is not such a phenomenon in the humidity spectra (Fig. 3).

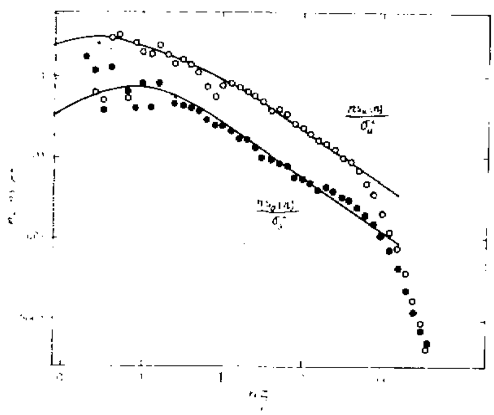

Fig. 1. The turbulent spectra in south wind. the solid curves are calculated according to Høјstrup and Kaimal, respectively, $-z/L=0.03$

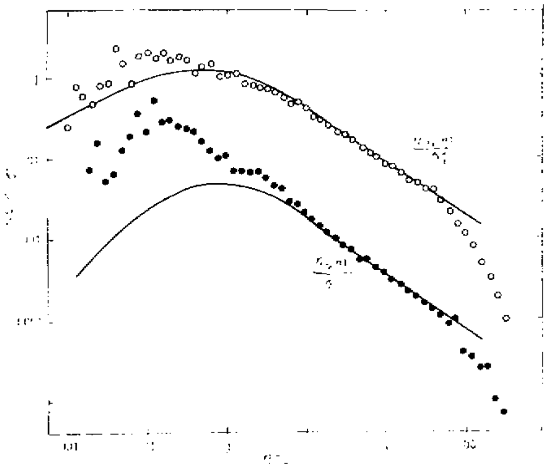

Fig. 2. The turbulent spectra in north wind, the solid curves are calculated according to Høјstrup and Kaimal, $-z/L=.02$.

A linear relationship of the energy of high frequency component (h=4Hz) in the streamwise velocity spectra of north wind with variance has been well revealed. It has been shown that the spectra of streamwise velocity remains similar at the variant wind speed and does not vary with stability ($-z/L<0.1$, L–Monin–Obukhov length). The data in stable state at night are also quoted in the Fig. 4.

According to Høјstrup and $Z_i=1000$m, $n=4$Hz

$$\frac{n(S_u)(n)|n=4Hz}{\sigma_u^2}=\frac{0.307U^{2/3}}{[38(\frac{-z}{L})^{2/3}+4.8](4z)^{2/3}}. \tag{1}$$

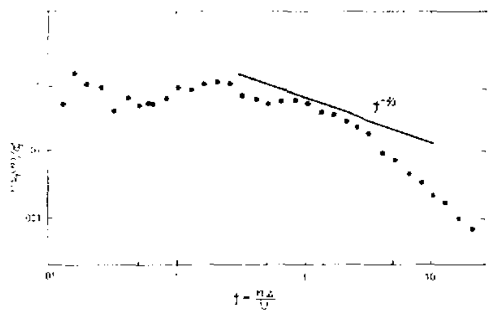

Fig. 3. The humidity spectra in north wind. $-z/L \sim 0.0$.

Obviously, the ratio should be dependent on stability $-z/L$. There is no longer linear relationship between $nS_u(n)$ and σ_u^2 under the south wind condition.

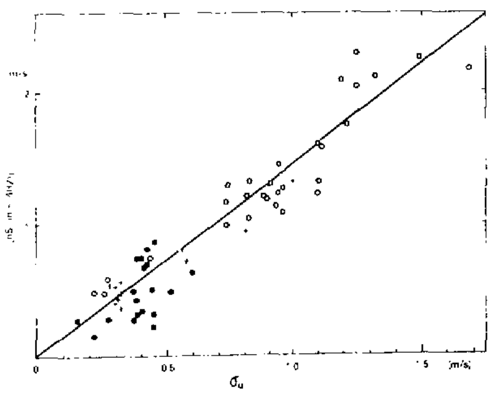

Fig. 4. The intensity of high frequency component in streamwise velocity spectra vs. σ_u. ○ — in the north wind ● — in the south wind. - — in the north wind at night.

In Fig. 5, it is shown that the variance of streamwise velocity fluctuations is independent of wind speed. U/σ_u is close to a constant under the north wind condition and tends to the value over the flat homogeneous terrain with increasing wind speed under the south wind condition (Wyngaard, 1977).

Therefore, under the north wind condition, we may find the similarity of streamwise velocity fluctuations with a speed scale and a length scale (such as the wind speed above shelter belt and the height of belt) independent of stability in the downwind area of shelter belt.

$$\frac{\sigma_u^2}{U_o^2} = F(x/H). \tag{2}$$

Where U_o–the speed undisturbed. H–the height of shelter belt. X–the distance from shelter belt.

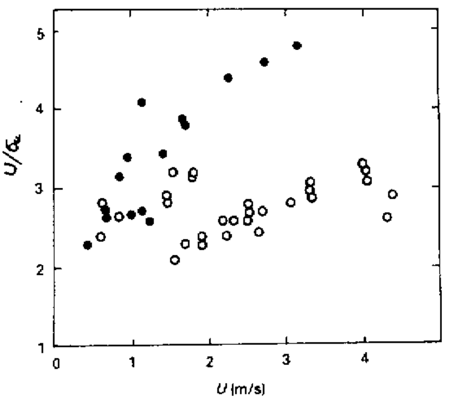

Fig. 5. Ratio of mean velocity and standard deviations as a function of mean speed. ○ -- in the north wind, • -- in the south wind.

It is much different and complicate in the upwind. We do not discuss this state, let us analyse the temperature fluctuations.

The fine scale fluctuations are usually isotropic for the surface layer in the unstable stratification (Haugen, 1973). We may expect that the fine scale structure measured is isotropic. The Kolmogorov constant α and Obukhov constant β measured by dissipation method (Williams, 1977) are 0.49 ± 0.053 and 0.80 ± 0.285, respectively, and close to the value over the flat homogeneous, which is an evidence for the isotropic surface turbulence. Therefore, we can obtain the characteristic velocity U_{*1}, and temperature T_{*1}, which is determined by the rate of dissipation of turbulent Kinetic energy and dissipation of temperature.

According to the Dyer's method (Dyer, 1982) we introduce a length scale L_1 analogous to Monin–Obkhov scale

$$L_1 = \frac{U_{*1}^2 T}{K g T_{*1}}, \quad U_{*1} \approx \left[nS_u(n) / \alpha (U / 2\pi K z n) \right]^{1/2},$$

$$T_{*1} \approx \left[nS_\theta(n) / \beta (U / 2\pi K z n)^{2/3} \right]^{1/2} \tag{3}$$

Where K–Karman constant, g–acceleration due to gravity, T–mean temperature. In taking account of influence of shelter belt, the gradient of temperature and velocity in the X direction, the equation for the conservation of temperature variance can be written as

$$\frac{\partial}{\partial t}\left(\frac{\overline{\theta'^2}}{2}\right) + U\frac{\partial}{\partial x}\left(\frac{\overline{\theta'^2}}{2}\right) - \frac{\partial}{\partial x}\left(\frac{\overline{\theta'^2}}{2}u'\right) - \frac{\partial}{\partial z}\left(\frac{\overline{\theta'^2}}{2}w'\right)$$

$$+ \overline{w'\theta'}\frac{\partial T}{\partial z} + \overline{u'\theta'}\frac{\partial T}{\partial x} - N = 0 \tag{4}$$

The first term on the left hand side of (4) can be neglected at a steady process. The second is an advection term, the third and the fourth are divergence terms. Assuming the horizontal as well as the vertical divergence may be negligible, the sixth term is the production one due to horizontal gradient of temperature which is zero for the homogeneous terrain.

In order to estimate the importance of the second and sixth terms, we have measured the ratios of temperature variances at different height $\sigma_\theta^2(z=6m)/\sigma_\theta^2(z=2m)$ and $\sigma_\theta^2(z=4m)/\sigma_\theta^2(z=2m)$. The figures are 0.57 and 0.76, respectively, slightly larger than $3^{-2/3}$ and $2^{-2/3}$ over homogeneous terrain. It follows that the influence of nonhomogeneous is not distinct. In addition, horizontal influence on the definition of stability may not be essential under unstable condition, because horizontal temperature gradient is always an unstable factor and both horizontal and vertical gradient should be correlative due to the sun's heating. Summarizing, we may assume

$$L \approx L_1, \quad T_* \approx T_{*1}, \quad U_* \approx U_{*1}. \tag{5}$$

Evidently, the relationship of C_T^2 and z/L is well known since the Hick's method was used to decide L. But σ_θ^2/T_*^2 is different due to the behavior of low frequency. In Fig. 6 σ_θ^2/T_*^2 is plotted against $-z/L$. Although the dispersion is large the general trend satisfies

$$\sigma_\theta^2/T_*^2 \quad \propto \quad (-z/L)^{-2/3}. \tag{6}$$

The coefficient of proportion is considerably different in the north wind. We may postulate

$$\sigma_\theta/T_* = C\left(X/H\right)\left(-z/L\right)^{-1/3}. \tag{7}$$

The value of C depends on the feature of shelter belt and is a function of the distance from shelter belt but is independent of stability. Far from shelter belt or considerably distant away from the upwind $C\left(\frac{X}{H}\right)=0.95$ same as Wyngaard's figure (Haugen, 1973).In Fig. 6 there are three dots separated farther probably due to the disturbance of the tower.

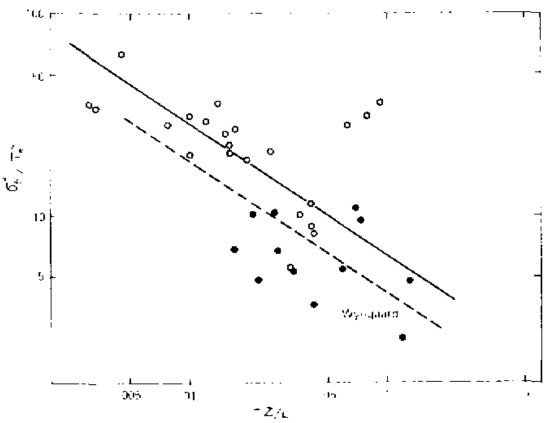

Fig. 6. Dimensionless variances of temperature as a function of $-z/L$.

Since

$$\frac{nS_u(n)}{\sigma_u^2} = \frac{nS_u(n)}{U_*^2}\cdot\frac{U_*^2}{\sigma_u^2}, \qquad \frac{nS_\theta(n)}{\sigma_\theta^2} = \frac{nS_\theta(n)}{T_*^2}\cdot\frac{T_*^2}{\sigma_\theta^2}. \tag{8}$$

The solid curves may be calculated from Højstrup's $nS_u(n)/\overline{U_*^2}$ multiplied by the

U_*^2, σ_u^2 measured and Kaimai's $nS_u(n)/T_*^2$ by T_*^2/σ_u^2. The mean values of σ_u/U_* are listed in Table 1.

Table 1. The mean values of σ_u/U_* and T_*/σ_θ

wind direction	σ_u/U_*	T_*/σ_θ
N	2.53 ± 0.55	2.7 ± 0.35
S	1.81 ± 0.34	3.5 ± 0.76

Measured σ_u/U_* is close to the value for homogeneous terrain in the north wind and slightly smaller in south wind which is probably related to the short averaging time of σ_u.

IV DISCUSSIONS

The flow over shelter belt area is complicated (Fig. 7). A part of air penetrates through shelter belt (Lin, 1987) others climb along the windward side and flow over the shelter belt. There is a wake stream behind the belt. Zhan Yi (1984) exploited the model of free jet boundary layer to calculate the distribution of velocity. Practically, both wake streams and jet are some kinds of free turbulent shear flow (Hinze, 1975) and are similar in the character. Therefore we may utilize some results and methods of free turbulent shear flows to investigate this kind of complicated flow. The curve of decreasing windspeed behind a shelter belt obtained by Lin Wei (1987) demonstrates the similarity of flow. We have obtained the similarity of frequency spectra and velocity fluctuations. Although the eddy convection velocity may not be equal to the mean velocity we can obtain the similarity of wave number spectra if only their relationship does not vary with speed. Therefore the flow may be self-preservation and the formula (2) may be obtained. In a word, due to the disturbance of shelter belt, the velocity fluctuations are more intensive than that over homogeneous terrain and dominate the whole streamwise velocity spectra. The thermal effect is obscured under the weak unstable condition (for example $-z/L<0.1$).

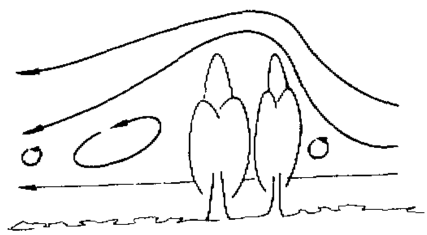

Fig. 7 Schematic of the flow over shelter belt

For this reason we find out a simple similarity that would be extended to a kind of wake stream such as the leeward side of building and hill.

On the contrary temperature fluctuations remain to show the relationship similar to that over homogeneous terrain. It is pointed out that horizontal gradient and vertical stability are correlative in unstable state and disturbances of shelter belt can considerably change the behavior of temperature fluctuations. The range of $-5/3$ power law has been extended to very low frequency. Silversides(1974) correlated this behavior with heat flux but σ_θ^2 was independent of heat flux. Temperature fluctuations are always dependent on velocity fluctuations. According to Fulachier (1983) temperature spectra and total kinetic energy spectra are similar in the low frequency. But the streamwise velocity spectra same as transverse velocity spectra can not bring about the extension of $-5/3$ range of temperature spectra. The low frequency of vertical velocity spectra would be weakened because of the restriction of ground (Evanov, 1973). Finally this extension is attributed to the eddy convection velocity of low frequency which is likely much smaller than mean velocity. This inference is not so satisfactory because there is not this extension in the humidity spectra.

These conclusions obtained from the data measured at one point for few days should be demonstrated further and the indefinite facts should be investigated further, although this paper is a good beginning.

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