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The Spectral Characteristics of Atmospheric Turbulence in an Urban Area of Complex Terrain

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Abstract

There have been very sparse reports on the spectral characteristics of atmospheric turbulence in an urban area of complex terrain. This paper presents an observational study in Lanzhou City, with spectral cospectral analysis of velocity and temperature. It is shown, even though the height at which the probing sensors were mounted was rather low (6.45 meters), the turbulence spectral characteristics still agree well with the results obtained under even and homogeneous conditions. It is concluded, that the requirements for the site and height selection in the direct measurement of turbulent fluxes are not so stringent as here to fore believed.

1. Introduction

There have been many experiments and rather clear theoretical analyses on the turbulence structure of atmospheric boundary layer over uniform terrain (e.g. Kaimal *et al.*[1] (1972)). Based on this research it is commonly recognized, for example, that the spectra of the vertical velocity component obeys Monin-Obuknov similarity theory quite well, while the low frequency region of the spectra of horizontal velocity components are scaled with z_i, the height of the lowest invention, and only the high frequency part obeys Monin-Obukhov and Kolmogolov scaling. Because of its simpler form, Hojstrup.'s spectral model (Hojstrup[2] (1981)) developed on these studies has been referred to widely and used in some practical problems. For the situation of complex terrain, according to the experiments mainly carried out in last decade, even though the spectral characteristics varied somewhat with terrain features, it is still concluded that the turbulence structure of the surface layer is in a state of continuous readjustment as the terrain roughness alters. For the horizontal wind spectra, the high-frequency turbulence is always in a state of quasi-equilibrium and the spectral shape conforms to that over uniform terrain, while the low frequencies of the spectra are affected by the terrain features. In contrast, for the vertical velocity, because most of the spectral energy is continued in high frequencies, the spectral characteristics agree well with the model spectrum over the entire frequency range.

In the literature up to now there have been very sparse reports on this kind of research in urban areas, particularly those with rough terrain conditions. The turbulence structure in any urban surface layer is closely related to the atmosphere-surface interaction and the dispersion of air pollutants. Unfortunately, we still do not have a clear understanding of this aspect. Owing to the development of the

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urban population and economy, and the associated deterioration of the atmospheric environment, this kind of study has attracted the unprecedented attention of meteorologists and environmentalists. There have been boundary layer observations carried out in some cities. However, many practical problems such as the selection of proper sites and heights for observation, the effect of building wakes, etc., are not so clear; there has been no commonly recognized methodological framework to comply with. Recently, Roth *et al.*[3] (1989) analysed the spectral characteristics of velocity and temperature in an unstable suburban atmosphere, based on a boundary layer experiment in Vancouver. It shows that although the observation height is lower than is normally assumed to be required, the results are similar to that for the uniform terrain. This paper presents some results of low level turbulence measurements conducted in Lanzhou, a typical valley-basin city in west China. The project is a part of the program "Boundary layer observation and atmospheric dispersion modelling in complex terrain", and is aimed to measure and analyze the turbulence fluctuations of wind components and temperature, to get a better understanding of the characteristics of the relevant power spectra and cospectra, and to verify the suitability of the similarity scaling and the existing spectral models in this very complicated but quite common situation.

2. Experiment

The experiment was conducted from January 10 to 19, 1989, in the urban area of Lanzhou. The city is located in a valley-basin, about a few kilometers wide and 35 km long. The Yellow River flows through the valley, with mountains along both the north and south sides that are about 300 m to 600 m high above the valley floor (**Fig. 1**). Lanzhou is the industrial center of west China, with a population of over one million. The observation site chosen was in a small open area of about 100 m

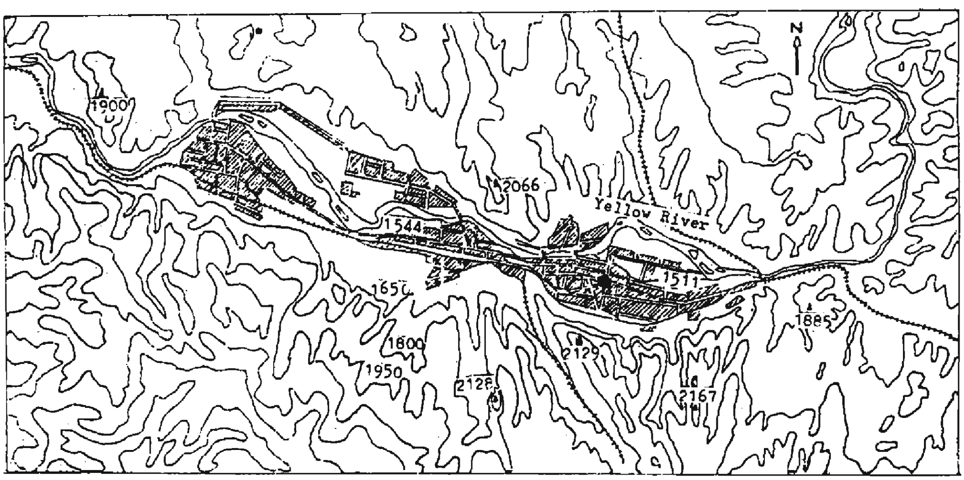

Fig. 1. The topographic map of Lanzhou city. (●: position of the observation site)

by 150 m and had a flat soil surface. A three-dimentional sonic anemometer-thermometer (Kaijo Denki DAT-300) and an attached 12 μm tungsten wire thermometer were mounted on the top of a 6 m mast, and used for the wind and temperature fluctuation measurements. In addition, there were different kinds of radiometers and a tether-balloon system (AIR TS-2A) used to probe the wind and temperature profile of the boundary layer. About 100 m to the south of the 6 m-mast, there is a five-story building approximately 18 m high. To the east, prevailing wind direction about 42 m to 100 m, there are some lower (approx. 3 m–4 m) walls and market houses, but with some high buildings a little farther on.

According to the usual estimation (e.g. Panofsky and Dutton[4], (1984)) the aerodynamic roughness (z_0) for the experimental area is about 0.6 m. The zero-displacement length (d), for sparsely scattered roughness elements, can be approximately taken the same as z_0 (both referring to main wind direction). Based on some observation in rough terrain and some wind tunnel study, for the validity of the Monin-Obukhov similarity theory, Raupach et al.[5] (1980) suggested that the lower height limit for wind variance and covariance measurement might be $z_*=h+1.5D$, where h is the height of the roughness elements and D is the inter-element spacing. Apparently, the height at which turbulence was measured in this study was still in the roughness sublayer. Air flow would be affected by building wakes. We hope to confirm this through the analysis of spectral characteristics.

The observation period was under clear and rather stable weather conditions, with mostly low wind speeds (around 1 m/sec). The sampling frequency for wind and temperature fluctuations was 10 Hz; Each run lasted for 60 minutes. A real-time, low cost microcomputer (IBM PC) controlled system was developed for the data acquisition and processing. A sonic anemometer was carefully installed. Necessary corrections (such as for the shadow effect) have been made in the data processing procedures. The Fast Fourier Transformation was used to calculate spectra and cospectra. Within 10 minutes after each run both variances and spectra could be printed out and stored in the data files. The original data were also stored by a data streamer for later re-analysis.

In the analysis made for this paper we selected in all about 40 observation runs according to the wind direction ($E+45°$) and also a higher wind speed, which, in fact, covered different hours both day and night. The atmospheric stability in the experimental period was mostly in the range of $-1.0<z/L<1.0$, averaging about -0.18 (where $z=6.45$ m, L Monin-Obukhov length). The height of the lowest inversion was mostly under 400 m in daytime, with a daily average about 200 m, which would be used in the model calculations later.

3. Results

a. Spectra of wind components and temperature

As mentioned earlier, the variation range of atmospheric stability in this experi-

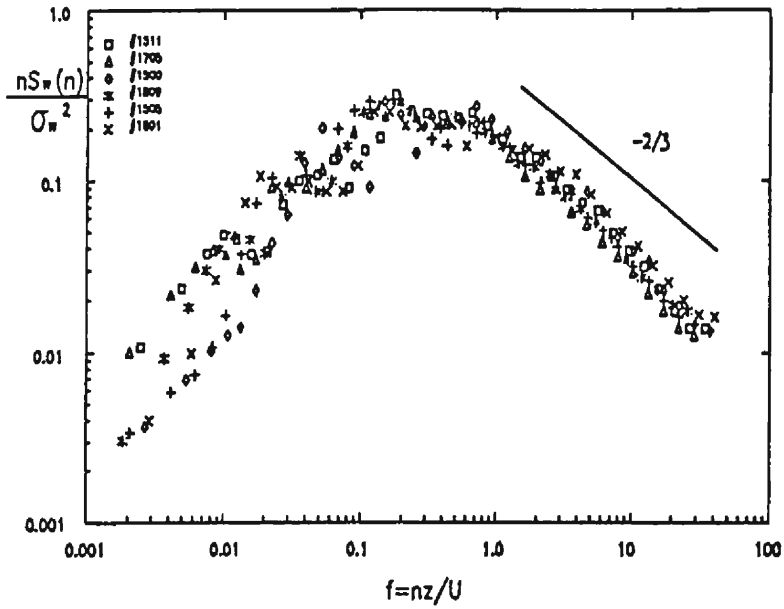

Fig. 2. Spectra of vertical velocity component for six runs.

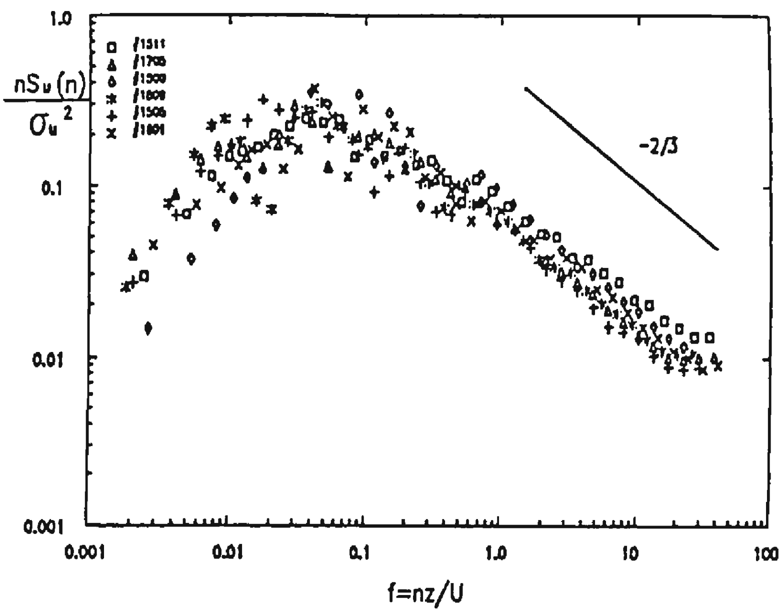

Fig. 3. Spectra of longitudinal velocity component for the same runs as in Fig. 2.

mental period was rather small. The stratification was weakly unstable in the daytime, probably due to weak solar radiation (which related also to the serious air pollution of this city—a smog lid hung over the valley most of the time). At night, because of the heat from the urban surface, it was also in a near neutral state. If we classify the normalized spectra according to stability z/L, some dependence could be observed. However, this was easily obscured by the scattering of the calculated spectra in the low frequencies when the stability had not greatly changed, as can be seen in **Fig. 2** and **Fig. 3**, which show the spectra of vertical and longitudinal wind components for six runs of different stabilities. In these figures the spectra are normalized by relevant variance; $f(=nz/U)$ is the commonly used dimensionless frequency. In any case, the inertial subrange (slope $-2/3$) in the high frequencies are all very clear.

In order to understand the characteristics more clearly, in this experiment, it is better to analize the averages of the spectra and cospectra of different runs. **Fig. 4** through **Fig. 6** are the wind-component spectra so treated. In order to have a better comparison with Hojstrup's spectral model here, the spectral densities are scaled by the squared friction velocity u_*^2.

Hojstrup's model divides the spectra into high and low frequency parts

$$S(n) = S_L(n) + S_H(n)$$

where the low frequency part $S_L(n)$, for horizontal velocity components, depends on $f_i = nz_i/U$ and z_i/L, and for the vertical components, depends on $f = nz/U$ and z/L. The high frequency part $S_H(n)$ is only a function of f. Specifically, the model contains the following expression,

$$\frac{nSn(n)}{u_*^2} = \frac{0.5 f_i}{1.+2.2 f_i^{5/3}}\left(\frac{Z_i}{-L}\right)^{2/3} - \frac{105 f}{(1+33f)^{5/3}} \tag{2}$$

$$\frac{nSv(n)}{u_*^2} = \frac{0.32 f_i}{1+1.1 f_i^{5/3}}\left(\frac{Z_i}{-L}\right)^{2/3} - \frac{17 f}{(1+9.5f)^{5/3}} \tag{3}$$

$$\frac{nSw(n)}{u_*^2} = \frac{32 f}{(1+17f)^{5/3}}\left(\frac{Z}{-L}\right)^{2/3} - \frac{2 f}{1+5.3 f^{5/3}} \tag{4}$$

The spectral curves calculated from this model (taking the mean values of $z/L = -0.18$ and $z_i = 200$ m) are plotted in the respective figures (solid lines).

The w spectrum shown in **Fig. 4** has the expected typical shape. The agreement between the urban spectrum and the model is excellent. However, the peak frequency (f_m) in the measured spectrum of this study is less well defined and there exists a rather flat peak area at about $0.1 < f < 0.8$. If we take the middle, i.e., let $f_m = 0.2$, then the peak wave length (l_m), the dominant eddy scale in the vertical direction, would be about 30 m ($l_m = U/n_m = z/f_m$). Compared to the model, the measured spectrum drops faster when $f > 10$. (The upward bending part when $f > 20$ is just noise contamination.)

The trend of the along-wind spectrum shown in **Fig. 5** also agrees well with

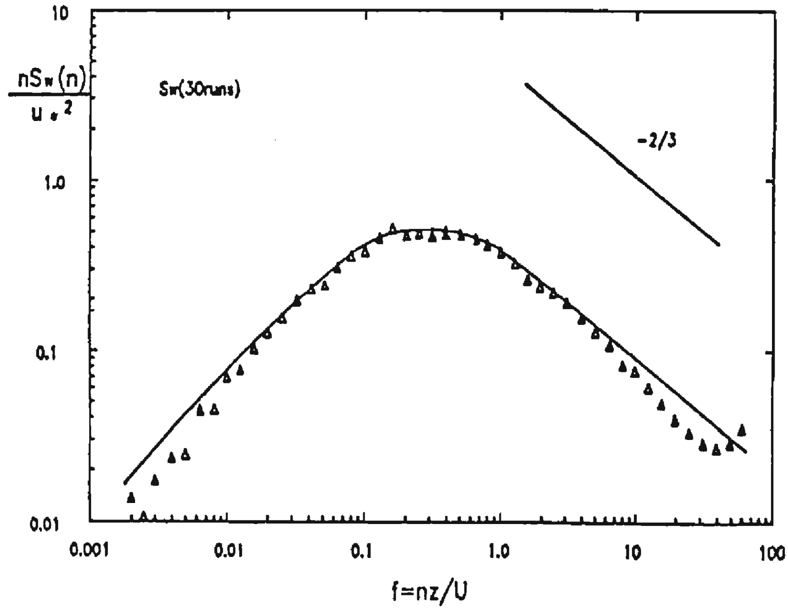

Fig. 4. The composite w-spectra, with the Hojstrup model spectra shown in solid curve.

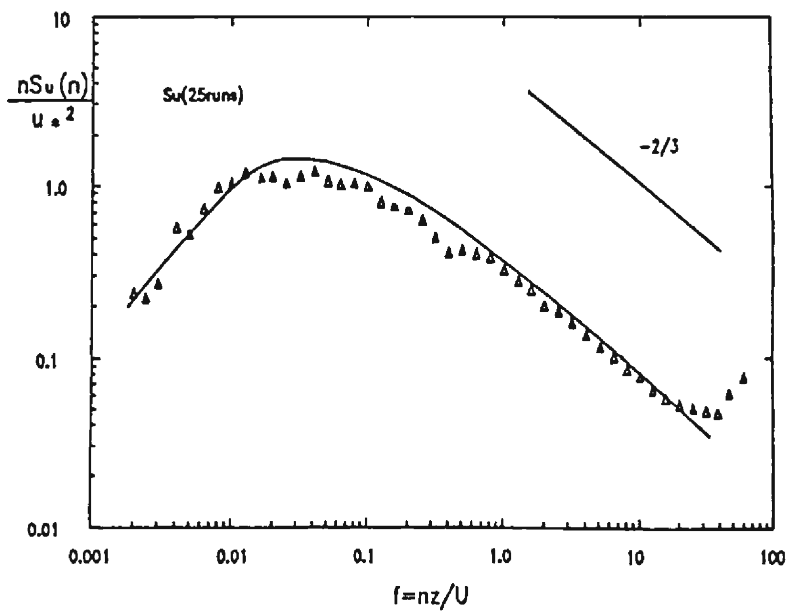

Fig. 5. As Fig. 4 but for u-spectra.

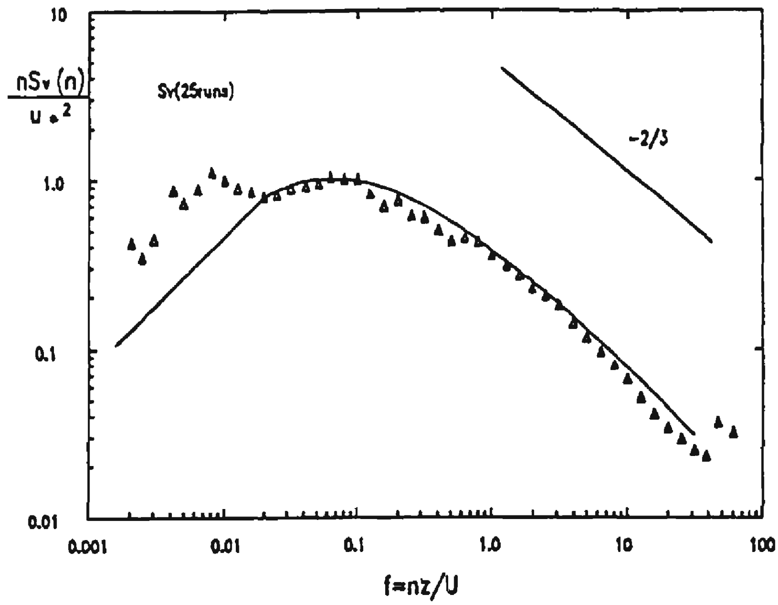

Fig. 6. As Fig. 4 but for v-spectra.

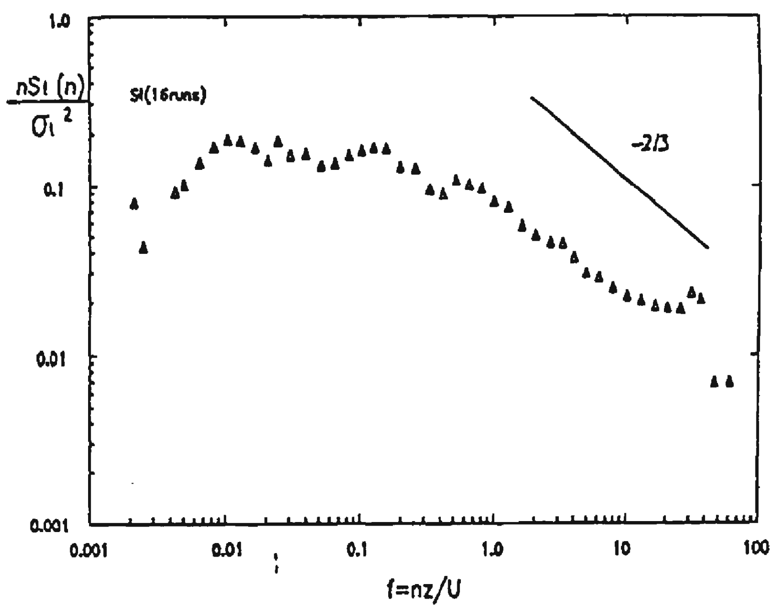

Fig. 7. The composite temperature spectra.

model. However, there are several depressions evident in the high energy region (f=0.02, 0.4, etc.). The peak frequency is difficult to determine as well. This characteristics of the u spectrum is also typical for unstable conditions in the surface layer over a relatively smooth surface. The unstable low frequency part of Kaimal *et al.*[1] (1972) u-spectra is not as organized as other parts. At near neutral conditions it even presents a so-called "excluded region". Hojstrup's model shows that a little deviation from neutral to unstable would induce remarkable increases in the frequency energy. Most data collected in the Lanzhou were in this stability range. Therefore, small peaks or dips appearing in the high energy region could have no special meaning. Panofsky et al.[6] (1982) concluded that in unstable conditions the influence of terrain features to the spectra of velocity components is relatively unimportant. z_i expressed in the model would be the main length scale in the low frequency region of the u-spectra. From **Fig. 5** if we take the peak frequency as the middle value of the peak region, about f_m=0.03, then the predominant eddy scale would be about 200 m, which coincides with the height of the inversion layer.

In **Fig. 6** the measured composite lateral spectrum is compared with the model. In the inertial subrange the agreement is quite good. However, in the low frequency part, the measured spectrum shows higher energy content and there are apparently two peaks. These features have also been reported in other studies. The low frequency parts of the v-spectra of different runs normally show obvious differences. Particularly, in this observation z/z_i is rather small. The eddies of shear production and buoyant production would be farther apart in the spectral frequencies. This feature has not yet been reflected in Hojstrup's model.

The composite temperature spectrum is shown in **Fig. 7** (normalized with variance). There is also an obvious $-2/3$ slope in the inertial subrange. Its low frequency feature is similar to the v-spectrum. A wider peak region and a slower drop-down at low frequency end. The two apparent peak frequencies appear near f=0.01 and 0.1. These characteristics are also found in the result of Kaimal et al. The spectrum of Roth *et al.* shows a flat region at $0.01<f<0.06$ and other parts are similar to this experiment.

b. Cospectra of momentum flux and heat flux

Vertical momentum flux and sensible heat flux in the surface layer are important parameters in the study of urban micrometeorology and the development of urban boundary layer models. The analysis of the cospectra of the vertical velocity component with the horizontal component and temperature is conductive to the understanding of the eddy scale distribution in transfer processes, as well as to the determination of sensor response and average time in those flux measurements.

Fig. 8 and **Fig. 9** show respectively the cospectra of $u'w'$ and $w'T'$ calculated in this experiment. Compared to the power spectra of single parameters described earlier the fall-off is obviously faster in both high and low frequencies. In the higher frequency part ($f>0.2$ for $u'w'$, $f>0.7$ for $w'T'$) the inertial subrange feature is very clear, with a slope near the theoretical value of $-4/3$. Compared to momen-

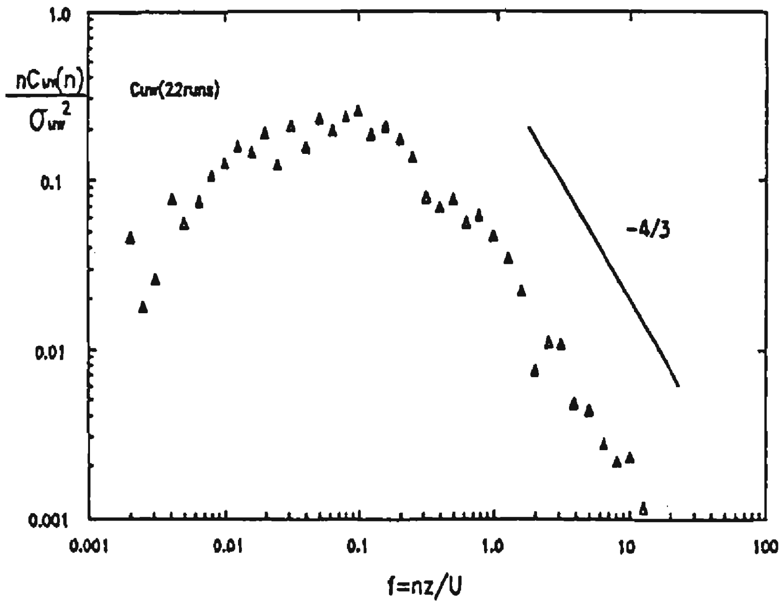

Fig. 8. The composite *uw*-cospectra.

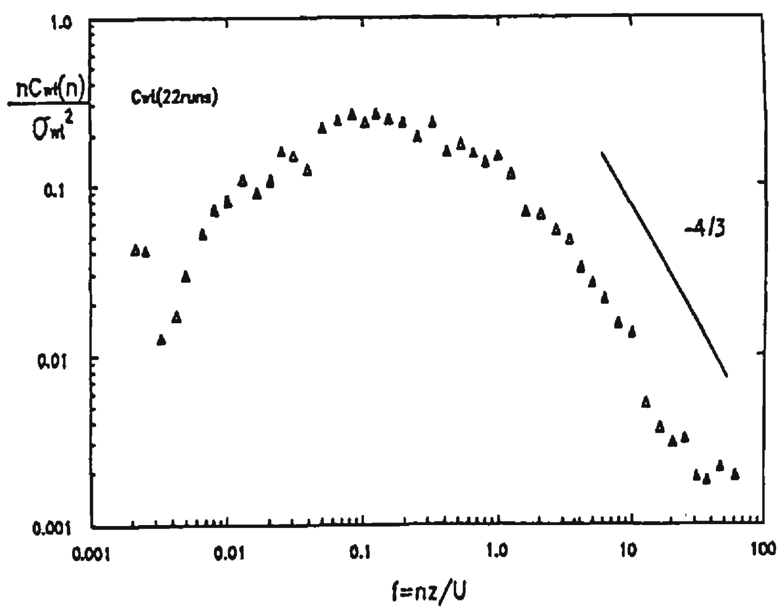

Fig. 9. The composite *wt*-cospectra.

tum flux cospectrum, the peak part of the cospectrum of heat flux is wider. However, the peak frequencies are all about $f_m=0.1$, similar to the result of Kaimal *et al.*[1] (1972). Panofsky *et al.*[4] (1984) concluded that, for the cospectra of the vertical velocity component with other scalars (including u), there would be no significant difference. This seems also true in urban conditions. **Fig. 8** and **Fig. 9** are also similar to the results of Roth *et al.*[3] (1989). According to their analysis, for momentum and heat flux measurement, the averaging time of 30 min. to 40 min. (corresponding to a cut off frequency of $f_c=0.004$ to 0.003, as shown in the figures, the cospectra apparently falling off from here) is enough; 60 min. seems not to be necessary as some authors have declared[3]. This is conductive to more practical observations.

4. Conclusion

This experiment was carried out in an urban area of a large city in a valley-basin complex terrain. The height of the turbulence measurements were quite lower than some authors indicated i.e., the observation was conducted in the, so called, roughness sublayer. However, the results of the spectral analysis shown in figures 2 through 9 are mostly similar to the references of uniform terrain. Hojstrup's spectral model for velocity components under neutral and unstable conditions seems mostly suitable for this situation. The cospectra of momentum flux and heat flux of this experiment also agree well with the result of Panofsky *et al.* Combined with research work of Roth *et al.*, it is concluded that the turbulence structure in the urban area of complex terrain would be no significant difference with that over a rather smooth surface. The requirement for the observational site and mounting height of the equipment for turbulent flux measurement is also not so stringent as formerly believed. This observation was carried out in a small, open area of the city. Probably, the scattered high buildings (or the so called roughness elements, most being higher than the observation height) had not enough influence on the turbulent spectra. There are also some differences between the measured spectra and the commonly recognized references. For example, the energy of the v spectrum in the low frequency part is higher than Hojstrup's model. Some power spectra in the high frequency end roll-off more rapidly. The atmospheric stability in this experiment varied not so largely. More comprehensive comparison and analysis require more observational data at different seasons or weather conditions. This is just what we are planning to do.

Acknowledgements

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