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Micrometeorological and atmospheric diffusion studies at nuclear power station sites in India
Part I : Wind profile studies

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ABSTRACT. Micrometeorological and atmospheric diffusion studies were made at Tarapur and Rajasthan, two of the nuclear power station sites in India, in connection with the environmental safety programme. This paper describes the wind profile experiments and the analysis of wind data collected. The results are compared with similar analyses carried out on the published data from various other sites such as O'Neil (Nebraska, USA), Round Hill (Massachusetts, USA), Argonne (USA) and Kerang (Australia).

Using the shear function defined as $(1-S^4)/S^3$ where S is the non-dimensional wind shear $(kZ/U_*)\,(d\bar{U}/dZ)$, it is shown that the analysis is critically dependent upon the value of roughness parameter Z_0. A plot of the shear function *versus* Z/L' does not pass through the origin as required, unless the proper value of Z_0 is chosen. This, in fact, can be considered as a test for the accuracy of Z_0. It has also been observed that the shear function tends to a constant value when plotted against Z/L' in the stable regime indicating that K_H/K_M steadily decreases with increase in stability.

1. Introduction

The profile of wind (variation of mean horizontal wind speed with height) in the earth's boundary layer exhibits a marked dependence on the stability conditions of the atmosphere. A strong wind shear is associated with temperature inversion conditions, while under lapse conditions the variation of mean wind with height is less pronounced. The derivation of an expression for the wind profile under all stability conditions (universal wind profile) is one of the important and as yet not fully solved problems in micrometeorology. A good deal of work both experimental and theoretical has so far been done to evolve a universal wind profile. On the experimental side there are available extensive data collected under all atmospheric conditions at sites in several countries — Rider (1954), Lettau and Davidson (1957), Cramer *et al.* (1958), Stinson *et al.* (1963) and Swinbank (1964). Some of these data, because of their accuracy and volume, are suitable to test the theoretical work or to obtain empirical relationships. The theoretical work has led to considerable insight into the transport mechanisms of heat and momentum in the vertical and has yielded profile expressions which, when tested using experimental data, show a validity over only a part of the stability range.

A number of experiments consisting of profiles of wind and temperature and smoke diffusion studies were carried out at Tarapur and Rajasthan, two of the nuclear power station sites in India, in connection with the environmental safety programme. As the fetch to height ratio for the Rajasthan site is not adequate, wind data collected at this site are not suitable for wind profile analysis. In this paper the analysis of wind profile data collected at the Tarapur site is presented. Data for other sites are also analysed for comparison.

2. Experimental details

The Tarapur Power Station site is a plain level terrain with small ditches evenly distributed in the area. Apart from a sparse distribution of palm trees of about 15 metres height, there is hardly any obstruction within a kilometre radius. The coast is rocky with a gentle slope and the difference between the high and low water lines is about 800 metres. The experiments were conducted at a location about 600 metres from the high water line, thus giving a fetch to height ratio of at least 60. The roughness elements were fairly uniformly distributed. Under such conditions, any change of heat and momentum flux height is not significant within the layer of measurements (Taylor 1962), and data collected at Tarapur meet the requirements for examining the wind profile theories.

For profile measurements a temporary steel mast of height 10 metres was erected with Casella contact type cup anemometers mounted on horizontal arms. Calibrated small bead-thermistors sheltered in louvered housings were mounted at two heights for temperature profile measurements. The anemometer contacts were registered on electromagnetic counters and also on an Esterline Angus operation recorder with a chart speed of 6" to 12" per minute for fast recording of wind speed. A low torque potentiometer type windvane was used for recording wind direction fluctuations on a 0-1 ma E.A. recorder at fast chart speeds. Experimental runs were made periodically and simultaneously with smoke runs (to be described in another paper) to obtain the diurnal variation of micrometeorological parameters.

3. Analysis of data

3. 1. *Determination of roughness parameter Zo*

The basic parameter required to be determined in most of the wind profile calculations is Z_0, which is characteristic of the site. This was obtained from profile measurements made under adiabatic conditions, using the relation —

$$\bar{U} = \frac{U_*}{k} \ln \frac{Z}{Z_0} \qquad (1)$$

where U_* is the friction velocity and k is the Von Karman's constant taken to be 0·41. For Tarapur site Z_0 was found to be 0·14 cm.

3. 2. *Determination of friction velocity U_**

Eq. (1) can be used for the determination of U_* under neutral atmospheric conditions, given the value of Z_0. But under non-neutral atmospheric conditions it cannot be directly determined from the wind profile, since it will involve knowledge of the shape of diabatic wind profile which is exactly what is being investigated. In the absence of any experimental determination of shearing stress by either eddy correlation or drag plate technique advantage can be taken of the fact that, very close to the ground, the wind profile tends to its adiabatic shape and Eq. (1) holds in this region for diabatic conditions. Swinbank (1964) determined U_* by this method using $\bar{U}$ at 0·5 m, claiming that the error in the value may not exceed 3 per cent.

At Tarapur the lowest height of observation was as high as 1·2 metres. Before determning U_* from wind speeds at 1·2 metres, the error involved in assuming adiabatic conditions upto this height has to be examined. Swinbank's Kerang data were used for this purpose. Values of U_* were estimated from wind speeds at 1 metre and 2 metres assuming adiabatic profile upto these heights. These were compared with the values calculated from wind speeds at 0·5 metre. It is found that calculation of U_* from wind speed at these heights involves a maximum error of 3 and 4·5 per cent respectively. Panofsky's (1963) method for determination of U_* is not used here since it assumes the validity of KEYPS profile (*cf* Eq. 5).

3.3. *Determination of vertical wind and temperature gradients*

The graphical method of determining the gradients in a diabatic profile is not sufficiently accurate for numerical analysis. In such a case, the finite difference method is preferable.

The finite difference relation $d\bar{U}/dZ=(\bar{U}_2-\bar{U}_1)/(Z_2-Z_1)$ is strictly valid only for a linear relationship between $\bar{U}$ and Z, seldom observed in the atmosphere except in highly stable cases. In the correct application of the finite difference formula would involve the knowledge of the profile function.

Bernstein and Young (1962) have discussed at length the appropriate relations to be used and the percentage errors involved in adopting a particular function.

Throughout the calculations presented in this paper the gradient has been determined from the relation for a logarithmic profile

$$\frac{d\bar{U}}{dZ} = \frac{\bar{U}_2 - \bar{U}_1}{\sqrt{Z_1 Z_2}\ln (Z_2/Z_1)} \qquad (2)$$

applicable at the geometric mean height $\sqrt{Z_1 Z_2}$.

Panofsky (1965) in his calculations has shown that the use of the above form introduces a maximum error in $d\bar{U}/dZ$ of 1 per cent during unstable conditions although this involves an assumed profile form. The use of the above relation (strictly valid for neutral cases only), throughout the unstable region is a good approximation but the application of the same to the stable regime, though not well justified, is usually made. Since no particular universal diabatic profile can be assumed, this error is inevitable and reflects the undesirability of examining profiles in differential form rather than the integral form.

The potential temperature gradient is also estimated from the similar relation —

$$\frac{d\bar{\theta}}{dZ} = \frac{\bar{\theta}_2-\bar{\theta}_1}{\sqrt{Z_1 Z_2}\ \ln (Z_2/Z_1)} \qquad (3)$$

3.4. *Profile analysis*

For the non-neutral atmosphere where the thermal stratification introduces bouyancy forces a new length scale L was first introduced by Monin and Obukhov (1954) as —

$$L = - \frac{U_*^3 C_p \rho\theta}{k g H} \quad (4)$$

where, H is the turbulent heat flux, also assumed invariant with height in the boundary layer considered and the other symbols carry their usual meaning. The generalization of the profile equation for the non-neutral conditions is represented by the relation—

$$S = f(Z/L) \quad (4)$$

where, $S=(kZ/U_*)(d\bar{U}/dZ)$ is known as the non-dimensional wind shear, and its value is unity for neutral conditions.

An interpolation formula, now known as the KEYPS profile between neutral and extremely unstable cases (free convection regime) was given independently by various authors (Ellison 1957, Yamamoto 1959 and Panofsky 1961) as,

$$S^4 + \gamma \frac{Z}{L} S^3 = 1 \quad (5)$$

where, γ is an empirical constant, whose value has been determined to be 14 (Blackadar *et al.* 1960). Since the experimental determination of L is rather difficult, Panofsky (1960) has introduced a modified length scale L' such that —

$$L' = \frac{K_H}{K_M} L = \frac{U_* \theta \, d\bar{U}/dZ}{kg \, d\bar{\theta}/dZ} \quad (6)$$

where K_H and K_M are the eddy diffusivity of heat and momentum respectively. Using L', Eq. (5) becomes —

$$S^4 + \gamma' \frac{Z}{L'} S^3 = 1 \quad (7)$$

where, $\gamma' = \gamma K_H/K_M$ whose value has been estimated to be 18 by Blackadar *et al.* (1960) assuming K_H/K_M to be independent of stability, an assumption which has been shown not to be correct (Panofsky *et al.* 1967).

4. Discussion

It will be convenient to use the derived quantity $(1-S^4)/S^3$ (hereinafter called shear function) in the subsequent discussion. This function will pass through the origin when plotted against Z/L. If the KEYPS profile is valid then, as can be seen from Eq. (5), the plot would also be linear, the slope of which would be equal to γ.

The present data is not suitable for determination of L. Hence Z/L' or the related quantity R_i would have to be used as a stability parameter.

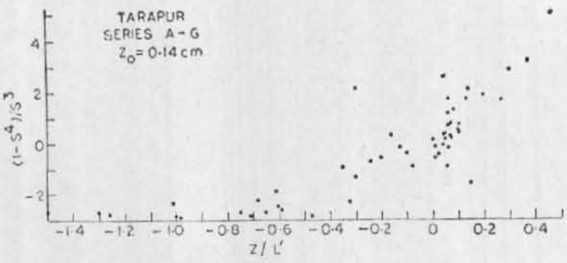

Fig. 1. Variation of shear function $(1-S^4)/S^3$ with Z/L'

In this analysis, we shall use Z/L' as the stability parameter. One advantage with using Z/L' is that L' involves wind speed and temperature gradients in single powers. This, therefore, reduces the error in determination of L' as compared with R_i. In addition, the correct determination of gradients at a given height requires the knowledge of profile form (Bernstein and Young 1962) and the errors due to this are likely to be cancelled in the case of L' and not in R_i.

The slope of graph between shear function and Z/L' will depend upon K_H/K_M. In the following we shall avoid making assumption of constancy of K_H/K_M with stability. Such assumptions are often made (*e.g.*, Blackadar *et al.* 1960) for facilitating the analysis, though the fact that it leads to gross unreality, appears to have been conveniently ignored. The value of K_H/K_M increases with decrease in stability and is approximately taken as unity near neutral conditions.

In Fig. 1, Tarapur data are plotted. Two aspects are prominently noticeable in the plot : (*i*) the scatter is very considerable in the unstable regime, (*ii*) the curve tends to flatten in the stable regime for large negative values of $Z/L' (< -0\cdot3)$. Using KEYPS and $\gamma=14$, we get $K_H/K_M=0\cdot2$ at $Z/L' = -1$ and thereafter K_H/K_M steadily decreases with increase in stability. The latter behaviour is in conformity with the deduction made by Ellison (1957) in deriving the functional form what is now known as KEYPS profile.

A comment may be made here on the scale used in the graph. It has been customary to plot S and Z/L on linear and log scale respectively. Such a scale is suitable in studying the behaviour of the variables in the near neutral zone where the scale spreads out the points. For higher values of Z/L, however, the scale contracts making it appear that S scatter is high. In this region it is preferable to use a linear scale as in Fig. 1.

Figs. 2 to 5 show similar graphs for O'Neil (data taken by the Johns Hopkins group), Kerang,

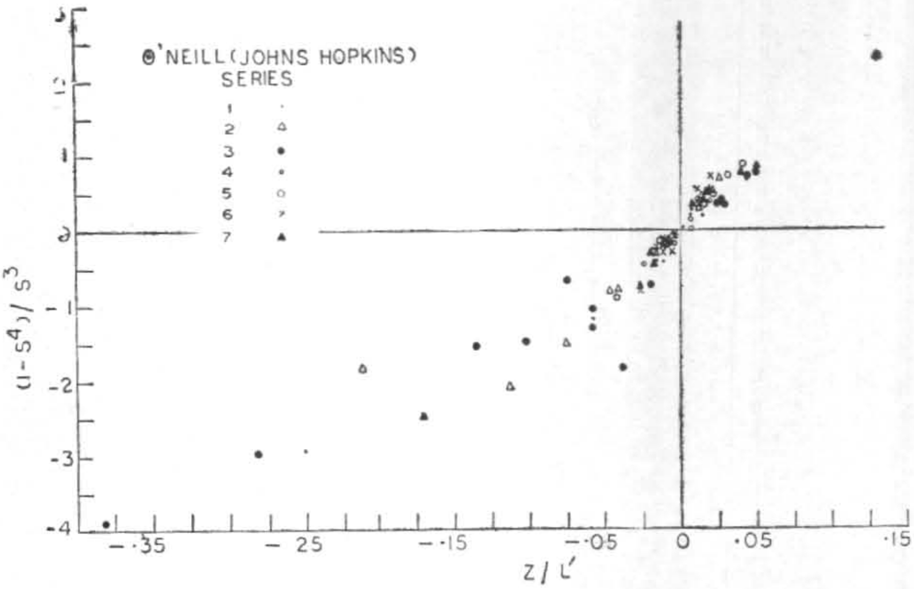

Fig. 2. Variation of shear function $(1-S^4)/S^3$ with Z/L'

Fig. 3 (a & b). Variation of shear function $(1-S^4)/S^3$ with Z/L'

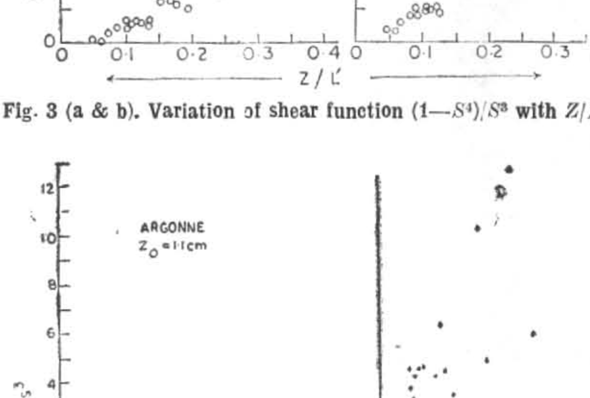

Fig. 4. Variation of shear function $(1-S^4)/S^4$ with Z/L'

Argonne and Round Hill data respectively reported in the literature and are presented for comparison. The data were analysed in the same manner as for Tarapur. O'Neill (*loc. cit.*) and Kerang (Swinbank, *loc. cit.*) data are considered as two of the most carefully collected data. Argonne data (*loc. cit.*) indicated a number of low level jets whereas Round Hill data (*loc. cit.*) are taken very near the coast and, therefore, offer proper fetch only in some directions.

In Fig. 3, Kerang data are plotted for $Z_0 = 0 \cdot 20$ cm as given by Swinbank, and for $Z_0 = 0 \cdot 31$ cm as given by Panofsky (1965) after making reanalysis of the Kerang data. A linear extrapolation of the curve in Fig. 3(a) would intersect the ab s

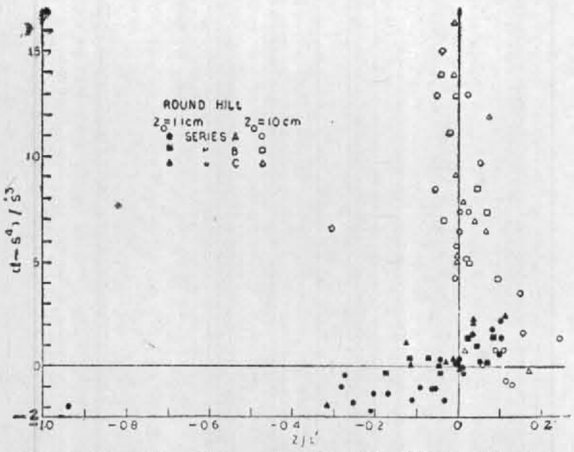

Fig. 5. Variation of shear function $(1-S^4)/S^3$ with Z/L'

cissa at $Z/L'=0 \cdot 05$. If the curve is made to pass through the origin this will imply based on KEYPS profile that $K_H/K_M \rightarrow 0$ near neutral conditions. In Fig. 3(b), because the points are uniformly raised, the linearly extrapolated curve passes nearer origin and perhaps with a somewhat higher value of Z_0, it is possible to pass it actually through origin still keeping $K_H/K_M \sim 1$ in near neutral regime. Data are not available in the near neutral regime to get a suitable value of Z_0. This approach in obtaining Z_0 does not strictly assume the KEYPS profile. It may be noted in passing that Panofsky, correction to Z_0 for Kerang data was based on the assumption of validity of KEYPS profile.

The trend of behaviour of O'Neill, Argonne and Round Hill data is similar. Of the three the behaviour of O'Neill data is much more regular and the scatter is low as in the case of Kerang data. However unlike the reported Kerang data, points are also available in stable regime. The near neutral data from O'Neill (Fig. 2) gives $\gamma'=24$. In this set of data unlike at Tarapur, very high negative values of Z/L' are not observed, hence, though the tendency to flatten is seen to commence as Z/L' at $-0 \cdot 075$, complete flattening cannot be observed. In this analysis the zero plane displacement $d=-9$ cm was used. In the case of Argonne and Round Hill data ($Z_0=1 \cdot 1$ cm) the values of S and Z/L', where the curves flatten in the stable regime differ. A considerable number of points fall in the "wrong" quadrants, *i.e.*, top left and bottom right.

A comparison of Figs. 3(a) and 3(b) shows that Z_0 requires to be estimated very accurately in order to satisfy the criterion (irrespective of the validity of KEYPS or any other profile function) that the graph should pass through the origin. In fact this can be considered as a test for the accuracy of Z_0. This is further illustrated from Fig. 5 for the Round Hill data. For this site the reported value of Z_0 is 10 cm (Cramer *et al.* 1958). From the careful examination of the data, however, it was found that the neutral profiles gave a value of $Z_0=1 \cdot 1$ cm. In Fig. 5, shear function has been plotted both for $Z_0=10$ cm and $Z_0=1 \cdot 1$ cm. The behaviour of points for lower value of Z_0 is in much better conformity with those at the other sites.

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