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Measurements of air turbulence in Reading and their relation to Turner's stability categories

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Continuous air turbulence measurements were made near the centre of the town of Reading for a period of one year. These were intended to provide data for deriving diffusion parameters for calculating the dispersion of pollution from chimneys in the town. They were obtained by using a bivane mounted on a 14 m mast, and the intensities of lateral and vertical turbulence for 1 h periods were derived by means of electronic analysers. Similar measurements were made for a period of about 4 weeks on the roof of a building at the B.P. Research Centre, Sunbury-on-Thames. The values of intensity of turbulence were grouped according to Turner's stability categories and the averages within the groups were compared by variance analysis. This showed significant differences in turbulence between the unstable categories and the neutral category, but the stable categories were not distinguished from neutral. The addition of a filter to cut out the high frequency band of the fluctuations showed that a considerable portion of the measured turbulence had been in this band and this is attributed to mechanical turbulence produced by the surrounding buildings. Eliminating the high frequency band also distinguishes the stable categories from neutral. The measurements of intensity of turbulence have been used to estimate the spread of plumes in the town. The lateral spread is greater than that published by other authors but the vertical spread is similar.

Introduction

In calculating the dispersion of a plume from a chimney it is necessary to know the lateral and vertical spread of the plume at various distances downwind. Ideally, these should be calculated from turbulence measurements made near the chimney but, in practice, these are rarely available and it is necessary to use published data. One of the most commonly used sets of data is due to Pasquill (1962), who published graphs of plume widths against downwind distance for six categories of atmospheric stability. These categories of stability were defined in terms of insolation, wind speed, and cloud cover, so that the stability could be determined from standard synoptic observations. However, Pasquill's definition of insolation does not allow for variations of cloud cover during the day, so Turner (1964) has modified the Pasquill categories by including a more precise definition of insolation based on the elevation of the Sun above the horizon, the cloud cover, and cloud height.

Pasquill's data were obtained mainly from diffusion experiments on flat grassland and the stability categories themselves refer to weather conditions in open country, whereas many dispersion calculations have to be done for chimneys in urban or industrial areas. It is of considerable interest, therefore, to know if the diffusion data and the method of defining the categories are valid in these conditions. Some further information on this subject was obtained during a study of the dispersion of the emissions from chimneys in Reading (Marsh & Foster 1957) and the present paper describes the analysis of turbulence measurements made in the course of the experimental work. The primary aim of this study was to develop a dispersion model—based on the dispersion equation for a single chimney—for calculating the pollution in Reading and to compare the predictions with measurements. So the turbulence measurements were made to provide data for these calculations, but the other meteorological observations obtained made it possible to associate the turbulence measurements with Turner's stability categories and to determine how far these categories could be distinguished by differences in turbulence near the ground in a built-up area.

The measurement of air turbulence

Air turbulence was measured with a sensitive bivane mounted on a 14 m mast, placed in an open space near the centre of Reading. The immediate surroundings of the site consisted mainly of two-storey private houses and buildings about 10 m high, and the nearest of these was about 100 m away; the commercial centre of Reading, with taller buildings, lay about $\frac{3}{4}$ km to the west and south-west.

The vertical and lateral deflexions of the bivane were converted into voltage variations and were analysed in separate electronic units. Hay & Pasquill (1959) have shown that the spread of a plume can be determined from the intensity of turbulence measured within a spectral window limited by values s and τ. The high frequency limit, s, is obtained from the time of flight of the plume to the measuring point and can be expressed in terms of distance, x, and wind speed, u, by the relation $s = x/u\beta$, where β is the ratio of Lagrangian to Eulerian time scales; the low frequency limit, τ, is determined by the sampling time of the measurements. The intensity of vertical or lateral turbulence, i, may then be defined in terms of the average deflexion, θ_s, of the vane in a time, s, by the relation

$$i^2 = (\overline{\theta_s^2})_\tau,$$

where the squares of the deflexions are averaged for a time, τ.

For practical purposes, Jones & Pasquill (1959) have shown that this spectral window can be stimulated by using electrical filters followed by an electronic averaging circuit. This method was used for the turbulence measurements described here.

Measurements of turbulence were made continuously for a period of about one year. In the first group of measurements lasting from October 1964 to February 1965, no high frequency filter was used and the high frequency cut off was determined by the inertia of the bivane. This varied with wind speed but was of the order of 1 s. Later, this variable cut off was considered to be unsatisfactory and a high frequency filter was included in the electronic units corresponding to an averaging time of 30 s. A second group of measurements was then obtained for a period lasting from March to September 1965. The comparison of the two sets of measurements therefore provides an indication of the energy contained within the high frequency band which was cut off by the filter.

A further group of measurements with the same equipment was made at the B.P. Research Centre, Sunbury-on-Thames, during a 4-week period in the summer of 1967. The bivane was then mounted on a 13 m mast on the roof of a building about 15 m high surrounded by smaller industrial buildings and private houses; it was then a total of 28 m from the ground. These measurements were made with the 30 s averaging filter and provide an indication of the intensity of turbulence at another location. For all three groups of measurements the low frequency cut-off corresponded to a sampling time of 24 min but the records were averaged for a period of 1 h.

Each hourly value of turbulence was then grouped according to the Turner stability category for that hour, and the average values of the intensities of vertical and lateral turbulence within the groups were found. These averages were then compared statistically by an analysis of variance.

Results

The average values of the intensities of vertical and lateral turbulence for each stability category are given in table 1; in the third set of observations, made at the B.P. Research Centre, there were not sufficient occurrences of categories 6 and 7 for a reliable comparison of the means. The means were compared by a statistical analysis of variance, using a 5 % level of significance. This showed that, in the first set of measurements, the means for categories 4 to 7 did not differ significantly for either the lateral or the vertical turbulence; they have therefore been grouped together. There is then a significant difference between categories 2, 3 and the combined group.

Table 1. Average values of intensity of turbulence (rad) within Turner's stability categories

<table>
<tr><th></th><th colspan="6">lateral</th><th colspan="6">vertical</th></tr>
<tr><td>stability category</td><td>2</td><td>3</td><td>4†</td><td>5</td><td>6</td><td>7</td><td>2</td><td>3</td><td>4†</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td colspan="13">Reading, s = 1 s, τ = 24 min</td></tr>
<tr><td>number of observations...</td><td>16</td><td>85</td><td>250</td><td>5</td><td>22</td><td>13</td><td>14</td><td>69</td><td>261</td><td>7</td><td>19</td><td>11</td></tr>
<tr><td>i</td><td>0.775</td><td>0.374</td><td>0.299</td><td>0.334</td><td>0.324</td><td>0.299</td><td>0.214</td><td>0.212</td><td>0.167</td><td>0.183</td><td>0.186</td><td>0.164</td></tr>
<tr><td></td><td></td><td></td><td colspan="4">0.302</td><td></td><td></td><td colspan="4">0.168</td></tr>
<tr><td colspan="13">Reading, s = 30 s, τ = 24 min</td></tr>
<tr><td>number of observations...</td><td>66</td><td>153</td><td>764</td><td>67</td><td>60</td><td>41</td><td>70</td><td>152</td><td>631</td><td>54</td><td>59</td><td>40</td></tr>
<tr><td>i</td><td>0.379</td><td>0.272</td><td>0.170</td><td>0.150</td><td>0.207</td><td>0.235</td><td>0.124</td><td>0.080</td><td>0.052</td><td>0.049</td><td>0.061</td><td>0.069</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td colspan="2">0.218</td><td></td><td></td><td></td><td colspan="3">0.059</td></tr>
<tr><td colspan="13">B.P. Research Centre, s = 30 s, τ = 24 min</td></tr>
<tr><td>number of observations...</td><td>35</td><td>88</td><td>199</td><td>53</td><td>—</td><td>—</td><td>41</td><td>72</td><td>231</td><td>49</td><td>—</td><td>—</td></tr>
<tr><td>i</td><td>0.298</td><td>0.230</td><td>0.157</td><td>0.123</td><td>—</td><td>—</td><td>0.119</td><td>0.077</td><td>0.066</td><td>0.070</td><td>—</td><td>—</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">0.067</td><td></td><td></td></tr>
</table>

† 4 = neutral stability

In the second set of observations categories 6 and 7 did not differ significantly for lateral turbulence and were grouped together; the differences between categories 2 to 5 and (6+7) were significant. For the vertical turbulence categories 5 to 7 did not differ and were grouped together; the differences between categories 2 to 4 and (5+6+7) were then significant. At the B.P. Research Centre the lateral turbulence means differed significantly for categories 2 to 5; there was a significant difference between the vertical means for categories 2, 3 and the combined group for categories 4 and 5 (which did differ from each other).

Discussion

A comparison of the two sets of measurements of Reading shows that, for both lateral and vertical turbulence, the average intensity of turbulence for each stability category is considerably reduced when an upper frequency limit equivalent to 30 s is introduced. This indicates that there is a significant proportion of the turbulent energy in the high frequency band of the energy spectrum between the limits equivalent to 1 and 30 s (*ca.* 0.4 to 0.02 Hz). It is significant that the

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reduction is as marked for the unstable category 2 as for the neutral category 4. A spectral analysis of turbulence measurements made at a height of 100 m at Brookhaven National Laboratory (Panofsky & McCormick 1954) showed that, although the energy in the high frequency band (*ca.* 0.05 Hz) did not differ greatly with atmospheric stability, there was a marked increase in energy with unstable air in the low frequency band (*ca.* 0.005 Hz), due to large thermal air movements. Eliminating a high frequency band of the spectrum would therefore have had much less effect on the total energy in unstable conditions. In the measurements at Reading, made at only 14 m above the ground, the relative contribution of the high frequency band is roughly similar for all the stability categories; this suggests that, for all the categories, mechanically induced turbulence makes a significant contribution which increases proportionally with the total turbulence. The roughness due to the houses may be regarded as reducing much of the large thermal movements to small scale eddies.

It is satisfying to find that stability categories defined in terms of wind speed, insolation, and cloud cover reflect significant differences in the low level turbulence in a town. Turner suggests that urban areas do not become as stable in the lower layers as non-urban areas and that stability categories 6 and 7 should be grouped with 5 in towns. The first set of turbulence measurements confirms this, but it shows further that the combined stable category 5 cannot be distinguished from the neutral category 4. In the second set of measurements the elimination of the high frequency band from the turbulence measurements leads to a greater distinction between the categories and the stable categories can be distinguished from the neutral category 4. This again indicates that the high frequency energy makes a significant contribution to all the categories and has blurred the distinction in the first set of measurements. Other measurements (M. Parry & M. Hough, private communication) of turbulence and vertical temperature difference up to 10 m in Reading have shown that a stable atmosphere is rare in the lower air layers of the centre of the town even when stable air is indicated in the surrounding countryside; there is usually some air circulation within the town due to the effect of its ‘heat island’.

The measurements on the roof of a building in the B.P. Research centre indicate less lateral turbulence in categories 2 to 5 than at Reading but the vertical turbulence is roughly similar. This shows the variation which can occur at different sites but it must not be concluded that the reduced lateral turbulence is due to the elevation of the bivane (28 m above the ground) because the short term exposure of the bivane on the roofs of two buildings in Reading had indicated that both lateral and vertical turbulence were then slightly higher than the turbulence at the main measuring site.

Since the aim of the turbulence measurements was to predict the spread of chimney plumes it is of interest to use the average values of turbulence in each category to calculate the corresponding plume widths. It was assumed that the plume width equalled the product of distance and intensity of turbulence when the latter was measured within the appropriate spectral range defined by s and τ (Klug 1962). These calculated plume widths are compared with those published by other authors, using a downwind distance of 500 m, and the standard deviations of lateral and vertical plume spread are given in table 2. This compares data published by Pasquill (1962), Smith & Singer (Brookhaven) (1966), and the Verein Deutsche Ingenieur (V.D.I. 1963); the two former are based on experimental observations in open country. It shows that the lateral spread of a plume predicted by the turbulence measurement is roughly twice the spread indicated by Pasquill or Brookhaven, and that the spread predicted by the V.D.I. method is unusually small. On the other hand, the predicted values of vertical spread fall roughly between those indicated

Table 2. Comparison of predicted standard deviations of plume spread at 500 m

	σ_y/m, lateral						σ_z/m, vertical					
stability category	1	2	3	4	5	6	1	2	3	4	5	6
Pasquill	134	96	62	41	31	20	105	50	32	18	13	8
Brookhaven	—	114	75	41	26	—	—	117	69	28	5	—
V.D.I.	—	—	—	18	—	—	—	—	—	15	—	—
Reading	—	190	136	85	75	109	—	62	40	26	30	—
B.P. Research Centre	—	149	115	79	62	—	—	60	39	33	—	—

by Pasquill and Brookhaven, except in the stable category 5 where a much larger spread is predicted. The higher values of lateral spread may well reflect the different dispersion conditions between town and country, and Pooler (1966) has shown from tracer dispersion experiments in St Louis that the dispersion at short distances (less than 1 km) is greater than that indicated by Pasquill for unstable conditions. An alternative reason for the greater predicted spread could be that it does not increase as the first power of distance but at some lower power—this could be between 0.5 and 1—but it is difficult to determine the value without a detailed knowledge of the scale of turbulence within each category. However, the rough agreement in the values for vertical spread suggests that a linear increase is a good approximation. On this basis it may be concluded that the lateral dispersion of plumes in an urban area is greater than that in the open country, and that the vertical spread is similar.

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