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Short-range diffusion experiments in unstable conditions over inhomogeneous terrain

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ABSTRACT

Equipment to measure the dispersion of a release of the tracer sulphurhexafluoride (SF_6) was developed and nine experiments were then performed at the Risø National Laboratory in the period April to July 1976. The tracer was released at 60 m from the Risø meteorological tower, situated on a peninsula in the Roskilde Fjord, Denmark, and was sampled at ground-level positions distributed over a crosswind line about 1 km downwind. During the experiments, the turbulent wind velocity components were measured at the height of release with a three-dimensional ultrasonic anemometer. The experiments were performed in westerly winds, hence the dispersion was influenced by the internal boundary layer developing downwind from the inhomogeneity in surface roughness between the fjord and the site. Five of the experiments, performed in neutral and slightly unstable conditions, were accepted as cases of purely turbulent dispersion of the tracer. Because of wind direction shifts the others were discarded.

The concentration measurements allowed a direct estimate of the lateral dispersion parameter σ_y. The Taylor diffusion formula using the wind velocity measurements at the height of release was found to work well in predicting σ_y, despite the fact that shortcomings in fulfilling the requirements for its application existed. σ_y, predicted by an empirical formula characteristic for an open area (Bultynck and Malet, 1972), was found to be systematically larger than the experimental value. Excellent agreement was found by multiplying the predicted σ_y values by the factor 0.6. This indicates that the effect of surface roughness can be separated from the effect of stability.

Because the estimates of the vertical dispersion parameter, σ_z, were only indirectly inferred from continuity considerations, they could not, although fair agreement was obtained, be used to check the validity of calculating σ_z from Taylor's formula or from the empirical formula mentioned above.

1. Introduction

The ability to predict the dispersion of effluents released from point sources is important in view of the use of the atmosphere as a pollutant depository. Much experimental work has been performed to determine diffusion coefficients and their relationship to meteorological parameters. However, such work is usually carried out over uncomplicated, flat terrain to avoid dependency on special site location effects. Only in a few experiments has the influence of terrain and terrain-modified meteorological conditions been investigated. Pooler (1966), McElroy (1969), Smith (1968a), and Csanady et al. (1968) performed tracer experiments to study dispersion in urban areas. Field tracer experiments designed to investigate the air flow and dispersion of effluents around buildings have been described by Cagnetti (1975) and Drivas and Shair (1974).

The present paper describes a series of experiments performed in a flow field influenced by the inhomogeneity of the surface roughness between water and land. This is one of the least complicated inhomogeneous situations and, hence, is a natural first step from that of flat, uncomplicated

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terrain. Furthermore, in this situation the flow is quite well understood theoretically and, in particular, it has been thoroughly experimentally studied at the actual Risø site.

In nine experiments, the tracer sulphurhexafluoride (SF_6) was released from the Risø meteorological tower at a height of 60 m, and the tracer-loaded air was then sampled at ground-level positions about 1 km downwind.

2. Site description

During these experiments, the tracer-loaded air was sampled at the positions distributed along one or both of the lines shown on the map of the experimental site (Fig. 1). The experiments discussed in this paper were all from situations in which the mean wind direction was in the sector 265–305°. The "west" wind fetch for the Risø peninsula is more than 5 km of Roskilde Fjord water surface.

The experimental site consists of the Risø peninsula and a landward part. At its western tip the coast of the peninsula is a steep slope which rises to about 10 m above sea level. The western half of the peninsula is gently rolling with the meteorological tower located on a 6.5-m hill. The eastern half is a meadow about 1 m above sea level. The landward part rises smoothly from the fjord and the meadow to the sampling positions which were situated at heights varying (gently) from 13 to 17 m above sea level.

Some of the access roads are bordered by rows of trees. Most of the mainly one-storied buildings are gathered in four distinct groups and occupy only a minor part of the site. Those buildings closest to the sampling positions all had a base lower than that of the sampling equipment. The

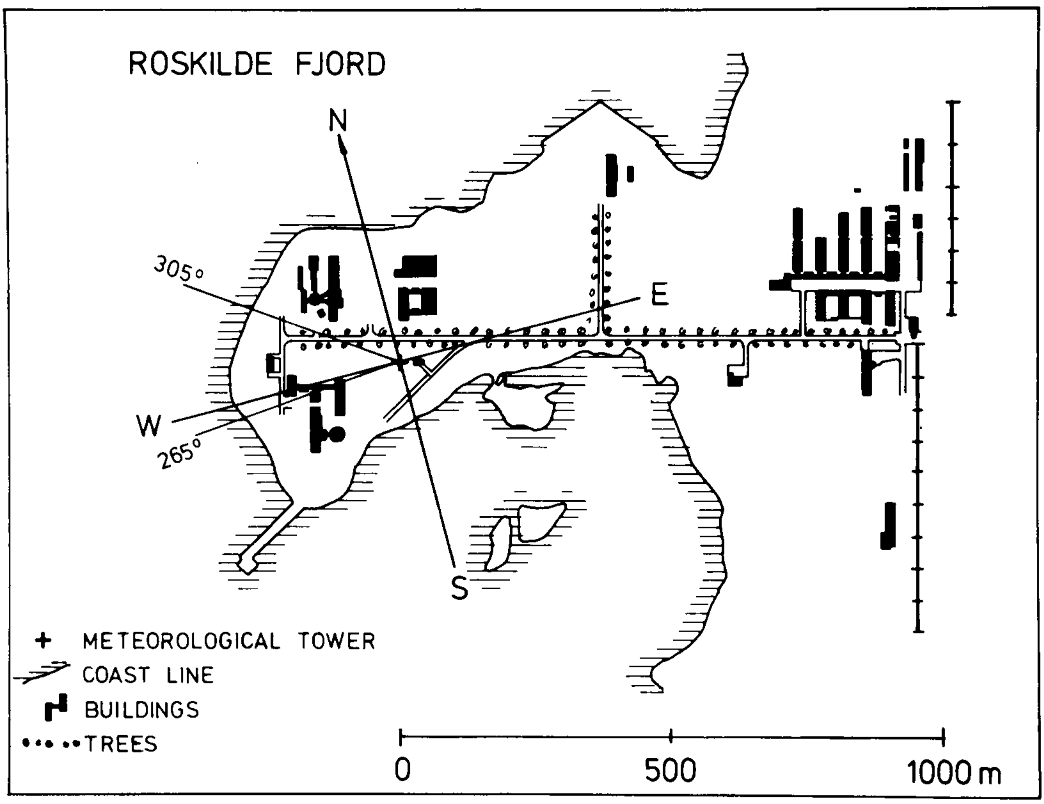

Fig. 1. The Risø site. The experiments were performed with a mean wind direction inside the sector shown. The sampling network is indicated by bars.

height of the buildings was generally about 4 m and varied up to 6 m.

3. Experimental equipment and procedure

Various meteorological parameters are routinely measured at the 123-m meteorological tower. Only those of particular importance to these experiments are briefly described here. Wind speed and direction are obtained from cup anemometers and wind vanes, and temperature is measured by quartz thermometers. Wind speed and temperature are measured at the following heights above the base of the tower: 11, 27, 43, 76, and 117 m and temperature alone at 2 m. Wind directions are obtained at 11, 43, 76, and 117 m. The instruments are mounted 2–4 m from the lattice of the tower on booms directed to the southwest. The measurements are recorded digitally as consecutive 10-min averages. Some are continuously recorded on strip charts for visual display. Among these are the wind speed and direction at the top of the tower, which were used prior to each experiment to estimate the direction of the tracer plume and the amount of tracer to be released.

During the experiments, turbulent wind velocity component fluctuations were also measured at the height of release with a three-dimensional ultrasonic anemometer (Kaijo Denki). Before each experiment the instrument was zero adjusted by placing the probe in an anechoic box. During operation, the signals were recorded digitally with a sampling frequency of 100 Hz.

The tracer was released at rates ranging from 0.9 to 1.8 g/s in the various experiments. A constant flow rate was secured by observing a flowmeter. The tracer was discharged from a cylinder placed in a building near the tower and piped through nylon to the 60-m-high point of release.

An automatic air-sampling unit based on sampling in plastic bags was developed for this work. A small diaphragm pump inflates three bags consecutively with a flow rate of about 300 ml/min. The sampling procedure is controlled by an electronic timer based on CMOS circuit components and a quartz 100 kHz oscillator. Pulses from the oscillator are counted and the sampling period (i.e. the time for each air sample) can be preselected as 2^{26}, 2^{27} or 2^{28} pulses, corresponding to approximately 11, 22 or 45 min, respectively. The waiting time (i.e. the time from the initial triggering of the timer to the moment that the pump starts) can be selected in a multiple (1 to 9) of the sampling period. The inflation of the bags is controlled by magnetic valves and the power is supplied by rechargeable batteries. The sampling unit, weighing about 1.5 kg, was placed on a portable rack during experiments, thus making it completely self-contained.

Analysis to determine the SF_6 content of the air samples was carried out by means of a Perkin Elmer F 11 gas chromatograph equipped with a d.c. electron capture detector. The column consisted of a 1-m long $\frac{1}{8}$-in stainless steel tube, packed with 30–60 mesh molecular sieves, operated at room temperature. Prepurified nitrogen was used as carrier gas. Calibration was accomplished by means of test dilutions of SF_6 kept for the whole series of experiments. The test dilutions were prepared by exponential dilution and the SF_6 concentrations were measured by means of a coulometric electron capture detector. The uncertainty is estimated to be 30%. The short-term reproducibility was about 2% and the detection limit for SF_6 with a signal-to-noise ratio of 2 was $5 \cdot 10^{-11}$ ppp (parts of SF_6 per parts of air) corresponding to approximately $3 \cdot 10^{-7}$ g SF_6 m^{-3}.

Dilute concentrations of SF_6 were stored in plastic bags. Bags of Saranex®, a Dow Chemical trade name, were used in these experiments. Prior to use of the bags, dilutions of SF_6 in the concentration range about 10^{-9} ppp were prepared and stored for a period of a week, and there were no noticeable losses of SF_6.

In order to facilitate a rapid experimental procedure, positions 60 m apart were marked out in advance along selected fences and roads located about 1 km from the tower. The experiments were accomplished with 11–13 sampling units adjusted to a waiting time of 45 min and a sampling period of 22 min. Prior to an experiment, the units were mounted with the plastic bags in the laboratory and connected to a central electronic box for the initial triggering of the timer. Further preparations were necessary to secure the proper functioning of the ultrasonic anemometer and to plan the setup of the sampling units according to the actual wind direction and stability. After the initial triggering by a pulse from the central box, thus fixing the experiment in time, the units were disconnected and transported together with the racks to the planned positions. Last moment corrections of the setup were made possible by radio contact with the meteorological tower. No alterations of the setup were made during the three consecutive sampling periods even if windshifts occurred. Immediately after an experiment, the bags were disconnected and taken to the laboratory for analysis. The time involved in the practical part of an experiment was typically 6 h. The bags were used several times. After each experiment they were flushed with filtered air and tested for leaks. The efficiency of the flushing procedure was proved by analysing the air from a flushed bag.

4. Analysis of experimental data

The measurements of tracer concentrations at positions on a crosswind line primarily allowed an estimation of the standard deviation of the concentration distribution at ground level in the lateral directon, $(\sigma_y)_{\text{mea}}$. The latter was calculated by use of the standard formula:

$$(\sigma_y)^2_{\text{mea}} = \frac{\sum(\chi_i \cdot y_i^2)}{\sum \chi_i} - \left(\frac{\sum(\chi_i \cdot y_i)}{\sum \chi_i}\right)^2$$

where χ_i is the measured tracer concentration and y_i the corresponding crosswind distance. The vertical equivalent can only be inferred indirectly from continuity considerations.

For comparison, the lateral and vertical standard deviations, σ_y and σ_z, are derived:

(1) according to formulae, $(\sigma_y)_{\text{Sm}}$ and $(\sigma_z)_{\text{Sm}}$, given by the ASME's *Recommended guide for the prediction of the dispersion of airborne effluents*, edited by Smith (1968b), which used a qualitative classification of the atmospheric stability;
(2) according to a method given by Bultynck and Malet (1972), $(\sigma_y)_{\text{B}}$ and $(\sigma_z)_{\text{B}}$, using a quantitative description of the atmospheric stability; and
(3) by a statistical treatment of the wind fluctuation measurements, $(\sigma_y)_{\text{tur}}$ and $(\sigma_z)_{\text{tur}}$, following an appropriate mathematical model.

Smith's (1968b) formulae for σ_y and σ_z are considered to be valid for elevated sources and a sampling period of 1 h. Atmospheric stability is classified as stable, neutral, unstable and very unstable, and formulae are given for each class. To determine the stability class, we chose to put Smith's unstable class equal to B and C, and his neutral class equal to D in the Pasquill (1962) classification. We determined the latter using sunshine data.

Formulae for σ_y and σ_z as a function of the parameter $S = (\partial\theta/\partial z)/\bar{u}^2$ are given in Bultynck and Malet (1972), $\partial\theta/\partial z$ is the vertical potential temperature gradient and $\bar{u}$ the mean wind velocity at the height of release. The S parameter is a quantity often used to characterize the atmospheric stability conditions (Hanna, 1977). The conditions that affect the dispersion of plumes at the site, including roughness and special site features, will, though indirectly described through S, be reflected in the functional relationships between S, σ_y and σ_z. Consequently, the formulae are site-specific. The Bultynck and Malet (1972) formulae are for an elevated source, 69 m high, and are derived by application of the Taylor diffusion formula to wind fluctuation measurements at the release height. The formulae apply to the Belgium S.C.K./C.E.N. nuclear site at Mol, an area sparsely covered with buildings. $(\sigma_y)_{\text{B}}$ and $(\sigma_z)_{\text{B}}$ are calculated for a sampling period of 1 h and conditions in which the wind direction does not change significantly. Results were confirmed by a number of fluorescent particle dispersion experiments. In the present study, calculations of S are performed by means of the temperature measurements at 2 and 117 m and the wind velocity at the release height, 60 m, at the meteorological tower at Risø.

σ_y and σ_z were basically estimated from wind velocity measurements, according to Taylor (1921) who showed that, during the time T, the diffusion of a passive effluent in stationary homogeneous turbulence results in a Gaussian concentration distribution with the variance

$$\sigma_i^2 = 2\overline{u_i'^2} \int_0^T \int_0^t R_{L,i}(\tau) d\tau dt \quad i = y,z \tag{1}$$

where subscript y, as usual, denotes the lateral components and z the vertical components, and where $\overline{u_i'^2}$ is the wind velocity variance and $R_{L,i}(\tau)$ the Lagrangian autocorrelation function of lag τ. The diffusion time T is, in this case, estimated as $T = x/\bar{u}$, where x is the downwind distance from the release point. The calculation of σ_y and σ_z from the ultrasonic anemometer measurements is made feasible through replacement of the

Lagrangian autocorrelation function by the Eulerian under the assumption (Hay and Pasquill, 1959) that

$$R_{L,i}(\beta_i t') = R_{E,i}(t') \quad i = y,z \tag{2}$$

By means of this assumption, (1) may be expressed (Hay and Pasquill, 1959) as

$$(\sigma_i)_{\text{tur}} = T\sqrt{\overline{(u_i')^2_{\tau_i}}} \quad i = y,z \tag{3}$$

where subscript τ_i denotes low-pass filtering with the characteristic time scale $\tau_i = T/\beta_i$, and the averaging, denoted by the overbar, is performed over the sampling time ξ, which is assumed larger than the travel time, $T < \xi$. In (3) it is also assumed that the averaging time is large compared to the characteristic spectral-energy-containing time scales. To ensure this, $\overline{(u_i')^2_{\tau_i}}$ was estimated for the entire period of the actual tracer runs, in most cases 2 to 3 times 22 min. This corresponds to a high-pass filtering of the variance with the characteristic time scale ξ. β_i is calculated following the theory of Wandel and Koefoed-Hansen (1962)

$$\beta_i = \frac{\sqrt{\pi}\cdot\bar{u}}{4\cdot\sqrt{\overline{u_i'^2}}} \quad i = y,z$$

$(\sigma_y)_{\text{tur}}$ and $(\sigma_z)_{\text{tur}}$ are used to calculate the expected value of the dilution factor χ/Q, where χ is the tracer concentration and Q the release rate. The expected centerline maximum value at the downwind positions of the air samplers, $(\chi/Q)_{\text{cal}}$, is calculated by use of an equation, e.g. (Turner, 1970), that implies a Gaussian distribution of the tracer concentration, total reflection at the ground, and conservation of mass. The equation is used in the form

$$\left(\frac{\chi}{Q}\right)_{\text{cal}} = \frac{1}{2\pi\bar{u}(\sigma_y)_{\text{tur}}(\sigma_z)_{\text{tur}}}\left\{\exp\left(-\frac{1}{2}\left(\frac{z-h}{(\sigma_z)_{\text{tur}}}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z+h}{(\sigma_z)_{\text{tur}}}\right)^2\right)\right\} \tag{4}$$

where z is the height of the sampling unit intakes (z = 2 m), and h is the release height. The dilution factor is also derived from the measured concentrations, $(\chi/Q)_{\text{mea}}$, where the measured maximum concentration has been inserted for χ. We have compared the ratio $(\chi/Q)_{\text{cal}}/(\chi/Q)_{\text{mea}}$ in the evaluation of the experiments. The numerator in this ratio is derived solely from meteorological data, and the denominator is based only on information on tracer abundance.

If consecutive runs were usable, the concentration distributions were ensemble averaged. An example of a tracer distribution is given in Fig. 2. The corresponding wind velocity and temperature profile are shown in Figs. 3 and 4. In

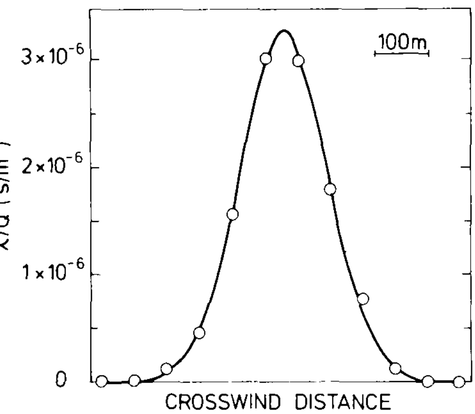

Fig. 2. Measured tracer concentrations (O) and fitted Gaussian distribution for the experiment on July 6 1976.

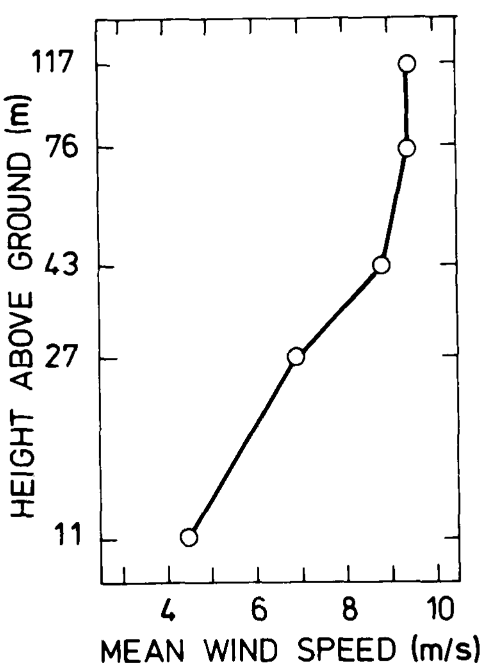

Fig. 3. Mean wind profile for the experiment on July 6 1976.

experiments performed on June 3 and July 6, the average of all three runs gave a proper tracer concentration distribution. The April 30 experiment allowed only the use of runs 2 and 3, and symmetry around the wind direction was assumed. In the experiments on June 11 and 18 only one run was usable. Results from the experiments are shown in Tables 1 and 2.

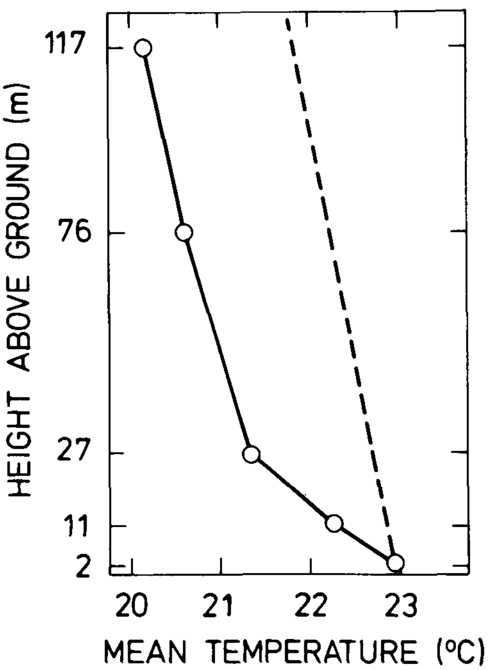

Fig. 4. Mean temperature profile for the experiment on July 6 1976. The dashed line indicates the dry adiabatic lapse rate.

5. The lateral diffusion parameter

The measured ground-level-concentration distributions were all with acceptable accuracy found to be symmetric and Gaussian distributed. Three of the experimental conditions were determined to be stability class Pasquill B. In unstable stratification $(\sigma_y)_{Sm}$ = 137 m at a distance of 1000 m. For these three experiments, the values of $(\sigma_y)_{mea}$ ranged from 80 to 123 m. They are thus somewhat less than $(\sigma_y)_{Sm}$ and, furthermore, exhibit variations up to 50% in the same bulk stability class. Additionally, some measured σ_y values were found to be nearly equal even though the measurements were made in conditions which were assigned different Pasquill stability classes.

It is desirable to be able to predict σ_y with greater accuracy. This requires careful measurement of either stability or wind vector fluctuations. In the following, both methods of predicting σ_y are applied, and the special effects due to the transitional (internal boundary layer) flow at the Risø site are discussed.

5.1. *σ_y calculated from turbulence measurements*

Application of the Taylor diffusion formula (1) assumes the existence of stationary and homogeneous turbulence. Under such conditions, the Lagrangian and Eulerian variances are equal (Lumley and Panofsky, 1964). The conditions

Table 1. *Meteorological conditions and result of the data analysis for σ_y*

Experiment 1976	No. of runs*	Meteorological conditions: Wind direction at 117 m (degrees)	Wind velocity at 60 m (m/s)	Pasquill stability class	Stability index $S \times 10^4$ (°C s²/m³)	Lateral dispersion parameter (m): $(\sigma_y)_{mea}$	$(\sigma_y)_B$	$(\sigma_y)_{tur}$
April 30	2	285	9.8	D	−0.49	68	113	58
June 3	3	305	3.5	B	−10.3	123	200	109
June 11†	1	300	—	B	−2.88	86	154	—
June 18	1	265	10.5	C	−1.35	84	131	88
July 6	3	295	9.8	B	−1.51	80	134	77

* One run took approximately 22 minutes.
† Without sonic measurement.

Table 2. *Result of the data analysis for* σ_z

Experiment 1976	Vertical dispersion parameter (m) $(\sigma_z)_{tur}$	$(\sigma_z)_{est}$* Upwind of χ_{max}	Downwind of χ_{max}	$(\sigma_z)_B$	$\frac{(\chi/Q)_{cal}}{(\chi/Q)_{mea}}$
April 30	27	26	375	77	1.4
June 3	43	26	349	129	3.5
June 11†	—	—	—	93	—
June 18	45	30	222	83	2.1
July 6	33	38	118	84	0.8

* Indirectly estimated from $(\chi/Q)_{mea}$ and $(\sigma_y)_{mea}$.
† Without sonic measurement.

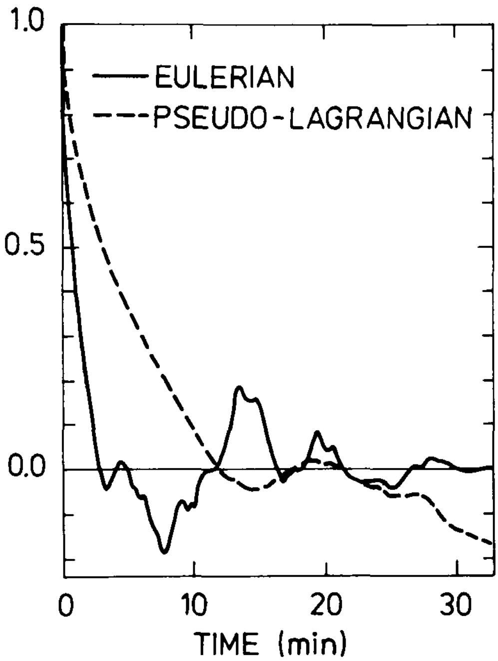

Fig. 5. Measured Eulerian and computed Lagrangian autocorrelation function of u_y, $\beta_y = 4.9$, for the experiment on July 6 1976.

under which our experiments were performed were fairly stationary. However, the energetic scales of turbulence in a shear flow can never fulfil the requirement of homogeneous turbulence. In the present case, the heterogeneous surface conditions are a further complication.

The expression (3) used for practical application of the Taylor diffusion formula assumes that the Lagrangian autocorrelation function is uniquely determined by the Eulerian, as in (2). An example of a computed pseudo-Lagrangian autocorrelation function is shown in Fig. 5 for the July 6 experiment. Comparison with actually measured Lagrangian autocorrelation functions (Sato, 1975) indicates that the pseudo-Lagrangian autocorrelation for small time-lags underestimates the true Lagrangian autocorrelation function. In the case of stationary and homogeneous turbulence this would cause $(\sigma_y)_{tur}$ to be underestimated.

Despite these shortcomings in fulfilling the requirements for application of the modified Taylor diffusion formula (3), it is found to work well in practice. Bultynck and Malet (1969) found favourable agreement between actually measured and computed lateral spread estimates. In our experiments the values of $(\sigma_y)_{tur}$ are within 15% of $(\sigma_y)_{mea}$. This agreement is fine; hence, we have interpreted the effects of spatial inhomogeneities on atmospheric diffusion according to (3).

As a result of the step change in surface roughness some distance upstream of the release point, an internal boundary layer is created. In a detailed study of average wind profiles at the Risø site, Panofsky and Petersen (1972) found the height of the internal boundary layer to be 38 m in the wind direction sector within which the present diffusion experiments were carried out. The wind profile shown in Fig. 3, in which a kink is observed at 43 m height, is a good example. According to

Elliott (1958), the height of the internal boundary layer is proportional to $x^{4/5}$, where x is the fetch from the change of terrain. Downwind from the tower the surface roughness varies (Fig. 1). For some directions we may therefore expect other internal layers to develop from below and the growth of the primary layer to temporarily cease. For other directions, we expect only one internal boundary layer developing according to the 4/5 rule.

Jensen (1975) carried out detailed measurements of the turbulence characteristics at different heights on the Risø tower. Based on 11 22-min unstable runs, the average ratio $(\overline{u_y'^2})_{60\,m}/(\overline{u_y'^2})_{27\,m}$ was determined as 0.55. The average value of the S parameter for the 11 runs was $-0.94 \cdot 10^{-4}$ and the mean wind speed at 60 m height was 7.5 m/s. The power spectra of the lateral wind variance at the two heights showed that the near doubling of the variance from 60 to 27 m takes place at frequencies above $4 \cdot 10^{-2}$ Hz, while the low frequency portion is left unaltered. With the wind speed in question this corresponds to an increase in variance from wavelengths of less than about 200 m. The difference in lateral variance between the two heights is augmented by the development of the internal boundary layer. We expect, however, this difference to be lessened downwind from the meteorological tower because of the increase in lateral variance at 60 m height caused by the flow being gradually embedded in the internal boundary layer. But from the vertical variation of the lateral variance at the tower we may infer that this increase takes place at wavelengths of less than about 200 m.

In the unstable regime a substantial portion of the lateral variance lies in the low frequency part of the spectrum (Lumley and Panofsky, 1964; Kaimal et al., 1972). This is exemplified in Fig. 6, which shows the spectrum of lateral variance for the July 6 experiment. In the low frequency part of the spectrum there are two distinct peaks, in the interval $6 \cdot 10^{-4}$ to $2 \cdot 10^{-3}$ Hz and $2 \cdot 10^{-3}$ to $6 \cdot 10^{-3}$ Hz. The latter interval is characteristic of the average time between large convective systems in the surface layer in unstable conditions (Kaimal et al., 1972), while the peak in the former interval is probably caused by some process(es) associated with convective instability. As the mean wind speed was 9.8 m/s, the eddies of these two low frequency peaks are both greater than about 200 m and will

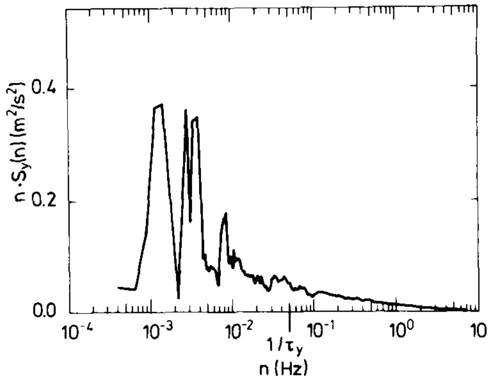

Fig. 6. Power spectrum of lateral wind variance based on a 66-min record from the experiment on July 6 1976, $\beta_y = 4.9$, $\tau_y^{-1} = 5 \cdot 10^{-2}$ Hz.

probably not be affected by the internal boundary layer.

The good agreement between $(\sigma_y)_{mea}$ and $(\sigma_y)_{tur}$ shows that the lateral diffusion at 1000 m is rather insensitive to the development of the internal boundary layer. We interpret this as a consequence of the fact that the increase in variance inside the internal boundary layer takes place at frequencies above β_y/T, so that it will be eliminated to a large extent by the low-pass filtering implied in (3). In the July 6 experiment the low-pass filtering eliminated contributions to the variance from frequencies above $5 \cdot 10^{-2}$ Hz ($1/\tau_y$ in Fig. 6). This insensitivity to the internal boundary layer is pronounced in the unstable range, where the greater part of the variance is in the low frequency part of the spectrum.

The above considerations of the spectral composition of the lateral wind variance thus show, that even in heterogeneous terrain like that at Risø, the modified Taylor diffusion formula (3) provides a good estimate of the lateral diffusion parameter for diffusion in slightly unstable and neutral stratification at distances of approximately 1000 m.

5.2. *σ_y calculated from stability measurement*

The σ_y values calculated from stability measurements by the formula proposed by Bultynck and Malet (1972), $(\sigma_y)_B$ in Table 1, are systematically too high. Multiplying these values by the factor 0.6 gives σ_y's that are within 7% of those measured.

The terrain at the Mol site, as described in Bultynck and Malet (1969), resembles the landward terrain at the Risø site. We should thus expect similarity of spread conditions at the two sites. As described above, the lateral diffusion at the Risø site at distances up to 1000 m is, however, unlikely to be affected by the increased wind variance due to the local terrain, but rather determined by the upwind conditions. At longer diffusion distances, local conditions will eventually determine the lateral diffusion.

The variation of σ_y in the neutral to unstable regime is predicted well by the Bultynck and Malet (1972) formula. Keeping in mind the modified Taylor diffusion formula, this is equivalent to a good prediction of the low-pass-filtered lateral variance by the S parameter. This is notable because a substantial portion of the lateral variance is of meso-scale type. In the July 6 experiment, for example, more than 40% of the total variance is from the frequency interval $6 \cdot 10^{-4}$ to $2 \cdot 10^{-3}$ Hz.

The Bultynck and Malet (1972) diffusion formula is based on separation of the variables in the form

$$\sigma_y(x, S) = F_1(x, 0) \cdot F_2(S),$$

where x is the diffusion distance and 0 symbolizes neutral stability. For the stability range covered in the present experiments, $F_2(S)$ adequately describes the stability variation. The dependence of σ_y upon stability in the form proposed by Bultynck and Malet (1972), i.e. the function $F_2(S)$, thus seems to be site independent. The site dependence of σ_y therefore only needs to be incorporated into F_1.

The numerical value of F_1 (1000,0) at Risø is only 60% of the value at the Mol site. The reason for this reduction is found in the fact that the release takes place above the internal boundary layer and thus into an air mass, the turbulence characteristics of which are determined by the upwind conditions over the Roskilde Fjord. From this we can conclude that the lateral diffusion in neutral to unstable stratification at a distance of about 1000 m over a water body such as the Roskilde Fjord should not amount to more than 60% of that over a rural area like the Mol site.

As surface roughness is only indirectly described through a stability parameter, it is believed that in general F_1 will exhibit a roughness dependence. The present experiments furthermore show that the roughness distribution upwind of the release also must be incorporated into F_1 if the formulation is to be applied to a situation involving changing surface boundary conditions.

6. The vertical diffusion parameter

The measurements did not provide any means for a direct determination of σ_z. On the basis of $(\chi/Q)_{\text{mea}}$ and $(\sigma_y)_{\text{mea}}$, an equation similar to (4) may give an indirect estimate of the standard deviation of the vertical concentration distribution, $(\sigma_z)_{\text{est}}$. There are two solutions of $(\sigma_z)_{\text{est}}$ in this equation corresponding to measuring either upwind or downwind of the position of the ground-level maximum concentration, χ_{max}. The values are listed in Table 2. In the experiments on April 30 and July 6, good agreement is found between $(\sigma_z)_{\text{tur}}$ and the upwind values of $(\sigma_z)_{\text{est}}$, whereas in the experiments on June 3 and 18 these values deviate more than 30%. The agreement between $(\sigma_z)_{\text{tur}}$ and the downwind values of $(\sigma_z)_{\text{est}}$ is always poor. We conclude, that the ground level concentration measurements took place upwind of the location of the ground level concentration maximum.

The σ_z values predicted by the Bultynck and Malet (1972) formula from stability measurements, $(\sigma_z)_{\text{B}}$ in Table 2, are systematically higher than $(\sigma_z)_{\text{tur}}$. On the average, $(\sigma_z)_{\text{tur}}$ is 0.4 of $(\sigma_z)_{\text{B}}$.

The ratio between the calculated and the measured dilution factors $(\chi/Q)_{\text{cal}}/(\chi/Q)_{\text{mea}}$ is shown in Table 2. This ratio varies from 0.8 to 3.5. In a series of diffusion experiments performed at the Mol site, Bultynck and Malet (1969) found that the minimum values of the ratio of the measured and calculated dilution factors generally varied from 1.5 to 3, whatever the weather conditions. The variation found in the present experiments is thus in good agreement with the values reported from the Mol site.

6.1. *Internal boundary layer in relation to σ_z*

The vertical wind velocity spectra in the form $n \cdot S_z(n)$, where n denotes frequency, more precisely obey similarity laws than the lateral wind velocity spectra. The frequency, n_m, where $n \cdot S_z(n)$ has its maximum can be made non-dimensional through $f_m = n_m \cdot z/\bar{u}$, $\bar{u}$ being the mean wind speed at the height z. Estimates of f_m vary from 0.2 to 0.6 in neutral stratification, and f_m decreases with decreasing stability (Busch, 1973). Kaimal et al. (1972) found f_m for vertical spectra to decrease from · 2.0 in strongly stable stratification to a lower limit of 0.17 in free convection, with a value of 0.5 in neutral stratification. Jensen (1975) found that an average value of 0.6 was a good fit to slightly unstable spectra at the Risø site for the height 27 m, while f_m was found to decrease to 0.3 at 60 m. The corresponding average frequencies at maximum were $1.3 \cdot 10^{-1}$ Hz at 27 m and $4.2 \cdot 10^{-2}$ Hz at 60 m. For unstable conditions other authors have found f_m to be nearly invariant or to slightly increase with height (Kaimal et al., 1972; Busch and Panofsky, 1968). The sharp decrease of f_m with height which was observed at Risø must therefore be ascribed to the existence of the internal boundary layer.

From the measurements by Jensen (1975), the ratio $\overline{(u_z'^2)}_{60\,m}/\overline{(u_z'^2)}_{27\,m}$ was determined to be 0.28. This strong decrease of vertical variance with height is caused by the internal boundary layer. Contrary to the case of the lateral spectrum, the shape of the vertical spectrum was observed to be more nearly conserved with height. The increase in variance from 60 to 27 m height, thus takes place with approximately equal weight for all frequencies.

The cut-off frequency for the low-pass filtering in (3), $1/\tau_z$ in Fig. 7, is seen to be nearly coincident with the spectral peak. As both $1/\tau_z$ and n_m are proportional to the wind velocity, this coincidence is independent of velocity. It is, of course, not independent of diffusion distance, nor is it independent of height. $(\sigma_z)_{tur}$ is therefore very sensitive to variations in $1/\tau_z$ and thus equally sensitive to the determination of β_z.

When the dispersing plume intercepted the internal boundary layer, we could expect an increase of vertical diffusion because of the greater vertical variance inside the internal boundary layer. However, the effect of the greater variance is expected to be partially counteracted by the increase of n_m, which causes a greater part of the variance to be excluded by the low-pass filtering. We therefore expect the modified Taylor diffusion formula (3) to be applicable, with fair accuracy, for determining σ_z for diffusion over inhomogeneous terrain, although with less apparent accuracy than in the case of lateral spread, σ_y. The comparison in Table 2, however, rests heavily on the use of (4), which at best may only give an estimate of σ_z in the real plume. It cannot be concluded whether the difference between $(\sigma_z)_{est}$ and $(\sigma_z)_{tur}$ results from

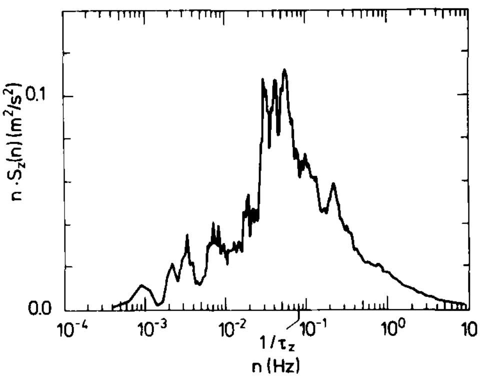

Fig. 7. Power spectrum of vertical wind variance based on a 66-min record from the experiment on July 6 1976, $\beta_z = 7.8$, $\tau_z^{-1} = 8 \cdot 10^{-2}$ Hz.

the inapplicability of the Taylor method, or if it is just caused by the Gaussian formula being a poor approximation (the vertical concentration distribution not being Gaussian (Monin and Yaglom, 1971; Elliott, 1961)). The influence of induced wake perturbations on the measured concentrations, created by those buildings near the sampling positions, should be negligible. As the tracer was released so far upwind at a height so much greater than that of the buildings any concentration gradients for the actual values of σ_z over distances comparable to actual building dimensions would have been, according to (4), rather small.

7. Conclusions

The lateral diffusion parameter, σ_y, estimated from ground-level tracer concentration measurements, was found to agree well with σ_y calculated using Taylor's diffusion formula based on wind velocity measurements at the height of tracer release. This agreement was found during four experiments with slightly unstable to neutral conditions, in spite of the shortcomings in fulfilling the requirements for application of the formula.

The variation of σ_y at the Risø site was found to be well described by an empirical formula determined in an open area. The σ_y values obtained from the formula were systematically too high, but excellent agreement with measured values was found by multiplying by the factor 0.6. This indicates that, for slightly unstable and neutral conditions, the effect of surface roughness can be separated from the effect of stability.

Because of the absence of directly measured values of σ_z, we were unable to check the validity of calculating σ_z from wind velocity fluctuations or from stability measurements.

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ЭКСПЕРИМЕНТЫ ПО ДИФФУЗИИ НА БЛИЗКИЕ РАССТОЯНИЯ В НЕУСТОЙЧИВЫХ УСЛОВИЯХ НАД НЕОДНОРОДНОЙ МЕСТНОСТЬЮ

Была разработана аппаратура для измерений дисперсии трассера шестифтористой серы (SF_6) и в период с апреля по июль 1976г. в Национальной лаборатории и Рисё было проведено 9 экспериментов.

Трассер выпускался с метеорологической башни в Рисё, расположенной на полуострове во фьорде Роскильде, Дания. Высота выпуска была 60 м, а пробы воздуха отбирались на уровне земли в точках на линии поперек направления ветра на расстоянии около I км по ветру. Во время экспериментов скорость ветра измерялась на высоте выпуска трехмерным ультразвуковым анемометром. Эксперименты проводились при западных ветрах, поэтому на дисперсию влиял внутренний пограничный слой, развивающийся по ветру от неоднородностей шероховатости поверхности между фьордом и местом наблюдений. В качестве случаев чисто турбулентной дисперсии трассера было принято пять экспериментов, проводившихся в нейтральных и слегка неустойчивых условиях, другие не рассматривались из-за изменений направления ветра.

Измерения концентрации позволили прямо оценить параметр поперечной дисперсии σ_y. Было найдено, что формула Тэйлора для диффузии при использовании измерений скорости ветра на высоте выпуска работает хорошо в предсказании величины σ_y несмотря на недостатки в выполнении требований для ее применения. Найдено, что величина σ_y, предсказываемая эмпирической формулой, полученной для открытых местностей (Бултинк и Мале, 1972), оказывается систематически больше, чем измеренное значение. Отличное согласие было найдено умножением предсказанных величин σ_y на 0,6. Это указывает, что влияние шероховатости поверхности может быть отделено от влияния устойчивости.

Поскольку оценки параметра вертикальной дисперсии σ_z оценивались косвенным образом из условия непрерывности, их нельзя было использовать для проверки справедливости вычислений σ_z из формулы Тэйлора или из упомянутой выше эмпирической формулы, хотя было получено удовлетворительное согласие с данными измерений.