ON THE DISPERSION OF LARGE PARTICLES FROM A 15-M SOURCE IN THE ATMOSPHERE[1,2]

K. D. Hage[3]

Department of National Defence, Canada

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ABSTRACT

In a series of nine experiments, embracing a range of wind speeds and stability conditions, fluorescent-dyed glass microspheres of nominal diameter 100μ were emitted continuously from a point source at 15 m over gently rolling prairie. The particles were collected on flat-plate adhesive sampling surfaces at ground level along arcs between the source and a distance of 800 m. The observed crosswind-integrated deposits are compared with the predictions of Rounds' solution to the K theory of eddy diffusion and with Godson's modification of Rounds' solution. The results indicate that Rounds' solution tends to overemphasize the effects of vertical diffusion on large particles. Godson's modified solution improves the predictions in stable cases but results in excessive dispersion of the particles in the direction of the wind under lapse conditions. Some evidence is provided to suggest that, in certain cases, measurements of vertical temperature gradient and wind-speed profiles between ground level and emission height are not sufficient to provide unique or reliable indicators of the intensity of vertical turbulence for the purpose of predicting the dispersion of particles.

1. Introduction

In recent years, the problem of predicting the ground deposit or low-level concentration of particles which are emitted from elevated sources in the atmosphere has attracted the attention of several authors — for example, Baron, Gerhard, and Johnstone (1948), Chamberlain (1953), and Csanady (1955, 1957). In most instances, attempts have been made to adapt or to modify Sutton's (1947) equation for the diffusion of gas or smoke from elevated sources to the problem of particle dispersion. An alternate approach based on the so-called *K* theory was adopted by Rounds (1955) as the basis for a theory of particle dispersion under neutral stability conditions. Subsequently, the solution was modified in an approximate way by Godson (1958) to include all stability conditions.

Since all parameters in Rounds' solution to the *K*-theory equation are inherent in the wind profile, it is possible, in principle, to predict the behaviour of particles without recourse to the observed deposit data. The purpose of this report is to compare the predictions of Rounds' solution and Godson's modification of the solution with the observed deposits in a series of experiments involving point source emission of glass microspheres.

Godson (1958) also adapted Sutton's (1947) equation for diffusion from an elevated source to the falling particle problem. This model is not considered in the present report, however, because of uncertainties in determining the required parameters n and C_z.

2. Theory

Rounds' solution satisfies the two-dimensional diffusion equation

$$U\partial\chi/\partial x = \partial/\partial z(K_z\partial\chi/\partial z) + v_s\partial\chi/\partial z \qquad (1)$$

where U is horizontal wind speed, χ represents crosswind-integrated concentration, K_z is the eddy coefficient for vertical diffusion, v_s is particle settling speed, and the x axis is oriented downwind from the source and the z axis is vertical. It is assumed that the vertical turbulent flux of matter is proportional to the concentration gradient and that the eddy coefficient for vertical diffusion varies linearly with height. Consequently, the relative crosswind-integrated deposit D_K at ground level is given by

$$D_K = v_s\chi_0/Q \qquad (2)$$

where χ_0 is surface crosswind-integrated concentration and Q is the source strength. Rounds' solution takes the form

$$D_K = \gamma v_s/hU_h \frac{\mathrm{Exp} - A/x}{\Gamma(1-p)}(x/A)^{p-1} \qquad (3)$$

if the wind profile is approximated by a power function of the form

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[2] A condensation of this paper was presented at the 187th National Meeting of the American Meteorological Society held in Eugene, Oregon, 14 to 16 June, 1960.

[3] Seconded to Suffield Experimental Station from the Department of Transport, Meteorological Branch.

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$$U = v_* q (z/z_0)^\alpha. \tag{4}$$

In eq (3) and (4), α and q are constants, z_0 is the roughness parameter, v_* is the friction velocity, h is emission height, U_h is wind speed at emission height and

$$A = hU_h/\gamma^2 k v_* \qquad p = -v_s/kv_*\gamma \qquad \gamma = 1 + \alpha. \tag{5}$$

In Godson's modified solution, eq (5) are replaced by

$$\begin{aligned} A &= hU_h/\gamma^2 \epsilon k v_* \qquad & p &= -v_s/\epsilon k v_* \gamma \\ \gamma &= 1 + \alpha & \epsilon &= 2/1 + \beta(z_0/h)^{1-\beta}. \end{aligned} \tag{6}$$

Variations in stability are introduced by means of the parameter β which appears in Deacon's (1949) wind profile.

3. Experimental procedure

Discussion of the experimental procedures will be limited to a brief outline since detailed descriptions and data summaries may be found in separate reports (Hage, Diehl, and Dudley, 1960a, 1960b).

Ground-deposit data are available for 9 experiments involving the emission of glass microspheres of mass mean diameter 106.7 μ (S.D. $\pm$ 6.8 μ) from a continuous point source at 15 m. The source was mounted on a slim steel mast over gently rolling prairie in an area devoid of buildings or trees. Deposit densities downwind from the source were estimated from particle counts on flat-plate adhesive sampling surfaces distributed laterally along arcs between the source and a distance of 800 m. In general, the samples were below grass-top level in a region of stagnant air, and it is believed that erosion effects which would lead to pickup and redeposit of particles from the surrounding terrain were negligible. The particles were coated with fluorescent dye prior to emission, and assessment was carried out visually under ultraviolet light. The counts were converted to mass deposit densities on the assumption that all particles were of uniform size. Values of observed crosswind-integrated ground deposit D_0 were obtained from the relation

$$D_0 = NldM/Q \tag{7}$$

where N = total number of particles per square meter per arc
l = spacing between samples
d = width of a lateral strip (1 meter)
M = mass per unit particle.

In each trial the area under the curve of crosswind-integrated deposit as a function of distance from the source provided an estimate of total recovery or the ratio of mass accounted for by the sample network to the mass emitted at the source. Estimates of recovery to the most distant sampling arc in 7 trials ranged from 0.85 to 1.05. In the remaining 2 trials, deposit curves could not be constructed with confidence due to lack of data.

Meteorological measurements were carried out on a portable 16-m tower placed 30 to 50 yd away from the particle source in a direction normal to the wind. Wind speeds were measured by Sheppard-Casella cup anemometers mounted at $\frac{1}{2}$, 1, 2, 4, 8 and 16 m. Vertical temperature gradients between 8 m and $\frac{1}{2}$, 1, 2 and 4 m were measured with shielded copper-constantan thermocouples. Gustiness records were obtained from light vanes of the type described by Clink, Bannister and Styles (1959) mounted at the height of emission.

4. Evaluation of parameters

In order to compute ground deposits according to eq (3), it was necessary to evaluate the parameters U_h, v_*, α, z_0, β and ϵ from measured wind profiles. Average profiles of duration 30 min to 60 min equal to the duration of particle emission were available for each trial. Additional profiles measured over similar terrain under approximately neutral stability conditions (negligible vertical temperature gradient) were also available.

Corrections which were based on the results of calibration tests were applied to the original wind-speed data in order to compensate for overestimation in turbulent flow and for tower effects. The integration constant z_0, often referred to as the roughness parameter, was calculated from the relation

$$U = v_*/k \ln z/z_0. \tag{8}$$

Ratios of the mean wind speed between 7.5 m and 15 m to the mean wind speed between 0.5 m and 7.5 m were computed from average observed wind-speed profiles under neutral stability conditions and equated to the theoretical ratio based on eq (8) to obtain z_0. Reasonable agreement between calculated values and a previously published value of $z_0 = 0.7$ cm (Deacon, 1949, p. 100) for Suffield terrain was found for wind speeds at $\frac{1}{2}$ m in excess of 4 m sec^{-1}. However, larger values of z_0 were found for wind speeds below 4 m sec^{-1} at $\frac{1}{2}$ m. The results are listed in table 1.

If z_0 is interpreted as a physical constant such as roughness length, a decrease in z_0 with increasing wind speed as shown in table 1 can be attributed to the bending of vegetation in high winds. However, such an explanation appears to be improbable in the present case because of the sparseness and short length of the natural vegetation.

The wind speed U_h at emission height and the mean wind speed $\bar{U}$ between ground level and emission height were obtained from graphs of wind speed as a

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TABLE 1. Calculated values of z_0.

Wind speed at 0.5 m (m sec^{-1})	z_0 (cm)
1.00	7.4
2.37	3.5
2.98	3.0
3.09	3.4
3.62	1.5
3.82	1.4
4.11	0.7
6.08	0.3
6.54	0.7

TABLE 2. Cumulative mass-diameter distribution.

Diameter (μ)	75	80	85	90	95	100	102	104	106
Mass (%)	0.1	0.2	0.4	0.9	4.3	13.4	22.2	33.5	45.3
Diameter (μ)	108	110	112	115	120	125	130	135	140
Mass (%)	57.0	67.9	77.8	86.9	95.5	98.3	99.3	99.7	99.9

function of height. Values of the friction velocity v_* were obtained from the logarithmic wind profile eq (8) for neutral stability conditions ($\beta = 1$) and from the Deacon wind profile

$$U = v_*/k(1 - \beta)\{(z/z_0)^{1-\beta} - 1\} \tag{9}$$

under lapse and inversion conditions ($\beta \neq 1$). In the computation of α and β, the observed wind profiles and the theoretical profiles were matched at height h and for the mean wind speed over h has suggested by Godson (1958) so that

$$\bar{U}_h/\bar{U} = 1 + \alpha = \frac{1 - (z_0/h)^{1-\beta}}{1/(2 - \beta) - (z_0/h)^{1-\beta}}. \tag{10}$$

Again following Godson, the parameter ϵ was calculated from the relation

$$\epsilon = 2/(1 + \beta)(z_0/h)^{1-\beta}. \tag{11}$$

The mass-diameter distribution of the particles based on approximately 1200 size measurements is given in table 2 and in fig. 1.

Values of settling speed v_s were computed by successive approximations from the following relations (see, for example, Johnson, 1954, p. 223).

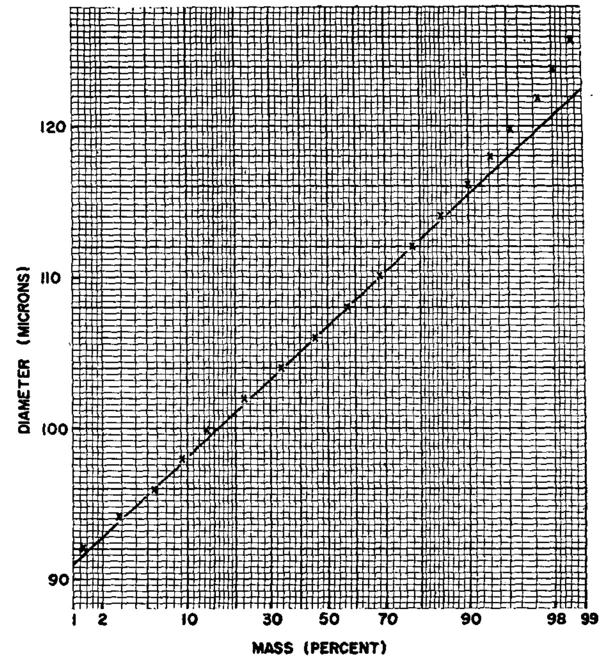

FIG. 1. Mass-diameter distribution of glass microspheres used in the field experiments.

$$\begin{aligned} v_s &= \frac{2(\rho_s - \rho_a)}{9\mu}(24/C_D Re)r^2 \\ Re &= 2\rho_a r v_s/\mu \end{aligned} \tag{12}$$

where v_s = terminal velocity of sphere of radius r in still air,
ρ_s = density of glass microspheres = 2.43 gm cm^{-3},
ρ_a = density of air = 1.15×10^{-3} gm cm^{-3},
μ = coefficient of viscosity = 174×10^{-6} poises,
C_D = drag coefficient, and
Re = Reynolds number.

The specified values of ρ_a and μ represent average values for the experiments under study. Empirical drag coefficients were obtained from Langmuir and

TABLE 3. Meteorological parameters.

Trial no.	$\bar{U}$ m sec^{-1}	$\bar{U}_h$ m sec^{-1}	$(T_{4\text{m}} - T_{0.5\text{m}})$ C	α	z_0 cm	$v_*(\beta = 1)$ m sec^{-1}	$v_*(\beta \neq 1)$ m sec^{-1}	β	ϵ	σ_z
1	5.42	7.33	+1.2	0.35	3.9	0.49	0.21	0.74	0.25	0.012
2	5.53	7.46	+1.1	0.35	4.3	0.51	0.23	0.75	0.27	0.014
3	6.19	7.54	+0.3	0.22	1.9	0.45	0.34	0.92	0.61	0.022
4	5.09	6.36	+0.6	0.25	3.6	0.42	0.31	0.90	0.58	0.063
5	6.06	7.31	+0.1	0.21	2.3	0.45	0.39	0.95	0.76	0.065
6	5.52	6.87	+0.4	0.24	3.3	0.45	0.33	0.90	0.59	0.054
7	3.96	4.40	−2.0	0.11	4.5	0.30	0.58	1.26	3.94	0.172
8	8.20	9.10	−1.1	0.11	0.5	0.46	0.60	1.07	1.70	0.089
9	4.87	5.60	−1.4	0.15	3.3	0.37	0.50	1.10	1.80	0.072

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Table 4. Observed and predicted crosswind-integrated deposits (mg $gm^{-1}m^{-1}$).

Trial no.	Reference	Distance from source (m) 27.4	45.7	73.2	86.9	100.6	114.3	128.0	146.3	201.2	274.2	402.3	804.6
	D_0			0.006	0.35	5.28		20.4		0.78		0.008	
1	$D_K(\beta = 1)$	0.11	1.72	4.48	4.94	4.94	4.69	4.32	3.78	2.38	1.32	0.55	0.089
	$D_K(\beta = 0.74)$	0.000	0.000	0.31	2.29	6.50	10.6	12.2	10.7	2.54	0.20	0.003	0.000
	D_F	0.000	0.000	0.008	0.30	2.02	6.26	23.9	21.5	0.08	0.001	0.000	0.000
	D_0			0.005	0.10	3.50		20.6		0.58		0.009	
2	$D_K(\beta = 1)$	0.11	1.65	4.33	4.78	4.81	4.58	4.24	3.73	2.39	1.34	0.57	0.10
	$D_K(\beta = 0.75)$	0.000	0.000	0.38	2.34	6.11	9.67	11.2	10.2	3.02	0.33	0.008	0.000
	D_F	0.000	0.000	0.005	0.24	1.74	4.72	21.9	21.6	0.23	0.003	0.000	0.000
	D_0		0.001	0.052	0.41	3.05	5.39	10.3	10.4	6.14	0.46		
3	$D_K(\beta = 1)$	0.009	0.59	3.14	4.08	4.56	4.68	4.55	4.18	2.81	1.57	0.63	0.086
	$D_K(\beta = 0.92)$	0.000	0.026	1.55	3.27	4.87	5.91	6.32	6.12	3.80	1.57	0.36	0.012
	D_F	0.000	0.000	0.000	0.03	0.43	1.84	5.96	18.3	1.83	0.037	0.001	0.000
	D_0			4.93		8.95		6.85		1.71		0.092	
4	$D_K(\beta = 1)$	0.062	1.63	5.09	5.72	5.73	5.40	4.91	4.19	2.44	1.22	0.44	0.052
	$D_K(\beta = 0.90)$	0.000	0.16	4.01	6.49	7.86	8.07	7.51	6.22	2.76	0.85	0.14	0.003
	D_F	0.000	0.007	3.13	8.90	10.8	11.2	7.36	4.62	1.13	0.034	0.001	0.000
	D_0	0.003	0.011	0.96		5.76		5.92		2.83		0.20	0.074
5	$D_K(\beta = 1)$	0.010	0.65	3.32	4.26	4.72	4.79	4.63	4.22	2.79	1.54	0.61	0.081
	$D_K(\beta = 0.95)$	0.000	0.17	2.56	4.07	5.11	5.59	5.62	5.23	3.31	1.57	0.47	0.032
	D_F	0.000	0.000	0.002	0.073	0.63	2.43	7.83	19.0	1.80	0.040	0.001	0.000
	D_0	0.002	0.006	1.32		7.09		6.86		1.87		0.24	0.30
6	$D_K(\beta = 1)$	0.037	1.19	4.28	5.03	5.22	5.07	4.72	4.15	2.58	1.36	0.52	0.069
	$D_K(\beta = 0.90)$	0.000	0.087	2.83	5.04	6.60	7.23	7.12	6.29	3.23	1.15	0.22	0.006
	D_F	0.000	0.000	0.014	0.32	1.79	6.82	18.1	22.0	0.28	0.004	0.000	0.000
	D_0	2.48	4.21	8.71		7.17		4.90		0.99		0.21	0.025
7	$D_K(\beta = 1)$	0.088	3.11	8.59	8.69	7.82	6.62	5.43	4.07	1.69	0.59	0.13	0.006
	$D_K(\beta = 1.26)$	4.35	4.51	3.44	2.97	2.58	2.26	2.00	1.71	1.15	0.76	0.44	0.16
	D_F	4.60	0.91	8.06	11.6	9.30	9.80	6.35	3.33	0.13	0.002	0.000	0.000
	D_0		0.019	0.61	1.57	3.08		5.58		4.32	2.16	0.55	0.016
8	$D_K(\beta = 1)$	0.000	0.042	0.92	1.71	2.46	3.04	3.42	3.63	3.19	2.10	0.95	0.14
	$D_K(\beta = 1.07)$	0.041	0.66	2.06	2.48	2.70	2.77	2.75	2.63	2.08	1.45	0.82	0.23
	D_F	0.000	0.000	0.000	0.001	0.015	0.11	0.42	1.94	11.8	7.20	1.55	0.000
	D_0		0.16	4.68	10.0	9.57		7.08		1.72	0.49	0.24	
9	$D_K(\beta = 1)$	0.028	1.41	5.60	6.47	6.53	6.12	5.49	4.57	2.44	1.09	0.33	0.027
	$D_K(\beta = 1.10)$	0.94	3.56	4.81	4.63	4.26	3.85	3.45	2.95	1.88	1.12	0.54	0.12
	D_F	0.000	0.000	0.19	1.67	7.78	20.9	23.8	10.2	0.42	0.000	0.000	0.000

Blodgett (1946). It was assumed that the values of settling speed v_s in the turbulent atmosphere were equivalent to the terminal velocities in still air according to eq (12). The observed mass-diameter distribution in table 2 was divided into 11 blocks, and settling speeds were calculated for the mean particle size in each block. Total deposits were obtained by summation of eq (3) over all contributions.

5. Results

Measured and derived meteorological parameters necessary for the calculation of ground deposit D_K and a limited amount of subsidiary data are listed in table 3. The parameter σ_z was obtained from continuous records of the fluctuation of a light vane in the vertical at the height of emission. For small angles, if θ represents angular deflections from the mean position of the vane in the vertical, w represents vertical air velocity, and U is horizontal wind speed

$$\theta \simeq \tan\theta = w/U$$

$$\sigma_z = (\overline{\theta^2})^{\frac{1}{2}} \simeq [\overline{(w/U)^2}]^{\frac{1}{2}}.$$

A minimum of 900 one-second mean values of θ sampled equally from beginning, middle and end of records during the emission period were used to compute σ_z in table 3.

In the trial series, stability conditions ranged from intense inversions at night in winter over frozen ground (trials 1 and 2) to convective conditions under clear skies at midday in summer (trials 7 and 8).

Observed crosswind-integrated deposits D_0 and the predicted deposits D_K based on Rounds' solution ($\beta = 1$) and on Godson's approximate solution ($\beta \neq 1$) are given in table 4. The predicted deposits D_F of a simple fallout model, which includes only the dispersive effects of variable particle size and variable horizontal mean wind speed, are included for reference purposes in table 4. These have been examined in detail in a previous paper (Hage, Diehl and Dudley, 1960b). Before discussing the results, it is well to consider some of the obvious sources of error.

The observed crosswind-integrated deposits in table 4 are subject to errors due to the systematic decrease of mean particle diameter with distance from the source. Corrections for this error would

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TABLE 5. Comparison of predicted deposits $D_K(\beta = 1)$ for large variations in $\bar{U}$ and z_0 (mg gm^{-1}m^{-1}).

Trial no.	$\bar{U}$ m sec^{-1}	z_0 cm	Distance from source (m) 73.2	86.9	100.6	114.3	128.0	201.2	402.3	804.6
1	5.42	3.9	4.48	4.94	4.94	4.69	4.32	2.38	0.55	0.09
	4.82	3.9	4.98	5.60	5.62	5.29	4.84	2.35	0.46	0.06
8	8.20	0.5	0.92	1.71	2.46	3.04	3.42	3.19	0.95	0.14
	8.20	4.0	1.36	2.06	2.62	2.98	3.16	2.71	0.94	0.19
	7.33	4.0	2.25	3.00	3.47	3.68	3.69	2.60	0.80	0.15

not alter the recovery substantially but would result in higher deposits near the source and lower deposits on the most distant sampling arcs. A limited number of mean size measurements on individual sampling arcs suggests that such errors may range from negligible values in the vicinity of the position of maximum deposit to between 30 and 40 per cent near the 5 and 95 per cent cumulative mass limits of the deposit curve.

Despite careful wind-tunnel calibrations, it is likely that the wind-speed measurements contain errors due to turbulence in the atmosphere. Errors in wind speed enter into the calculation of many of the parameters which were needed for the K-theory calculations. Examples of the effects of relatively large changes in the values of mean wind speed $\bar{U}$ and the roughness parameter z_0 on the predicted deposits D_K $(\beta = 1)$ are shown in table 5.

It is difficult to estimate the errors involved in the calculation of the stability parameter β. The range of values of β and the transition from $\beta < 1$ to $\beta > 1$ at approximately zero vertical temperature gradient are in agreement with Deacon's (1949) results. However, Godson's modified solution is rather sensitive to the magnitude of β, and the possibility of appreciable errors due to this source should be kept in mind in assessing the results.

Other sources of error include the variations of horizontal wind speed with time, the use of point rather than area mean wind speeds, and the use of sampling arcs rather than a rectangular network of samples.

6. Conclusions

A study of the data in table 4 reveals that, under inversion conditions (trials 1 to 6), Rounds' solution predicts excessive dispersion of the particles in the direction of the wind. Under lapse conditions (trials 7 and 8), however, the predictions are not unreasonable.

Godson's approximate solution improves the prediction in all stable cases, but the degree of improvement is insufficient to account for the observed sharply peaked deposit in intense inversions (trials 1 and 2). Under neutral to slight inversion conditions (trials 4, 5, and 6), the predictions of Godson's solution are near or within the limits of error of the assessments and calculations. Under lapse conditions, however, the modified solution predicts excessive dispersion (trials 7 and 8).

Superficially, trials 3 and 9 appear to be inconsistent with the other experiments in the series. Crosswind-integrated deposits in trial 3 suggest that the experiment was conducted under significantly more stable conditions than trials 4, 5 and 6. This is not reflected in the values of β or in the vertical temperature gradient between 4 m and $\frac{1}{2}$ m. Trials 4 and 9 which were carried out in similar mean wind speeds show similar deposits despite large differences in β and in vertical temperature-gradient values. On the other hand, the observed deposits in both examples are consistent with the vertical eddy energy as measured by the parameter σ_z in table 3. It would seem that either measurements of vertical temperature-gradient and wind-speed profile alone cannot be relied upon in every case to define adequately the vertical gustiness or that additional measurements of these quantities to heights above the emission level are required. This question cannot be settled from the data which is available in the present series of experiments.

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