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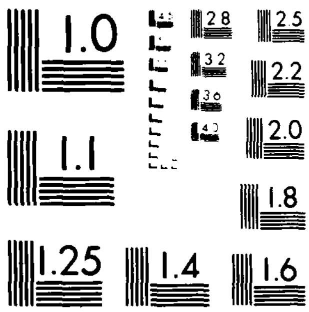


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# FOREIGN TECHNOLOGY DIVISION

## DIFFUSION OF PARTICULATE MATTER AND WIND SPEED PROFILE IN PLANETARY BOUNDARY LAYER

by

Ch'en P'an-ch'in

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DIFFUSION OF PARTICULATE MATTER AND WIND SPEED PROFILE IN PLANETARY BOUNDARY LAYER

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ABSTRACT

In this paper, the expressions of plume axis height, reflecting coefficient and transporting factor in Gaussian Diffusion-Deposition Model are derived by using theoretical and experimental results in planetary boundary layer in order to obtain a new Gaussian Diffusion-Deposition Model that could be used to describe variation of wind speed with height.

The effects of wind speed profile on relative ground-level concentrations are also discussed by using the calculated results obtained.

## I. FOREWORD

The diffusion theory based on the Gaussian model and the results of the experimental studies have received wide attention among the scientific community. In the study of diffusion of particulate matter, the Gaussian diffusion-deposition model that evolved from considerations of the gravitational settling of mass points and the effect of reflection from the ground surface has been widely applied because it still retains the fundamental properties of the Gaussian model [1]. In this model, the ground level concentration assumes the expression

$$\left.\begin{aligned} C(x,y,0,H) &= \frac{Q(1+\alpha_0(x))}{2\pi u\sigma_y\sigma_z}\exp\{-(y^2/2\sigma_y^2+(H-V_s x/u)^2/2\sigma_z^2)\} \\ \alpha_0(x) &= 1-\left[\frac{2V_d}{V_s+V_d+(uH-V_s x)\sigma_z^{-1}(d\sigma_z/dx)}\right] \end{aligned}\right\} \quad (1)$$

In the above equations, Q is the intensity of the source, H is the height of the source, C is concentration, $\sigma_y$ and $\sigma_z$ are diffusion parameters, u is wind speed, $V_s$ is gravitational settling velocity, $V_d$ is deposition velocity, x, y and z are coordinates and $\alpha_0(x)$ is the reflection coefficient of the ground.

It is worth pointing out that in the Gaussian model, the average wind speed acts as a constant, and has a transporting effect on the diffusing mass points. Here the relation between the concentration C and the wind speed u is given by $C \alpha u^{-1}$. On the other hand, in the Gaussian diffusion-deposition model, the effect of the wind speed is threefold. Not only does the wind speed have a transporting effect on the pollutants, but it also has an effect on the trajectory of mean motion of the diffusing mass points and the reflection coefficient. Moreover, since in fact the wind speed varies continually with height, the assumption of a constant wind speed necessarily produces some error in the estimation of concentrations in the downwind direction.

Wojciechowski [2] discussed the effects on the diffusing particles of the wind given according to the expression by Roberts. In this paper, the theory and experimental results of wind speed profile in planetary boundary layer studies will be used to discuss the effects of the average wind speed profile on plume axis height, reflection coefficient and the transport of diffusing mass points. The deviations of the estimation of concentrations arising from these effects will also be examined.

## II. AVERAGE TRAJECTORY OF MOTION OF DIFFUSING PARTICLES AND THE WIND SPEED PROFILE IN ATMOSPHERIC BOUNDARY LAYER /157

In equation (1), the height of the plume from the ground is described with $H-V_s x/u$. If the wind speed is a function of height, then this has an effect on the diffusing particles with settling velocity $V_s$. The trajectory of such a particle can be described by the following equations:

$$\begin{cases} \frac{dx}{dt} = u(z) \\ \frac{dz}{dt} = V_s \end{cases} \quad (2)$$

In the equations, t is time and u(z) is the wind speed at height z.

Given a definite functional form for u(z) and suitable boundary conditions, one can obtain the equation for the trajectory of the motion of the particle.

From the similarity hypothesis applied to the ground level boundary layer, the following definite expression has been derived for the wind speed profile [3,1]:

Under neutral conditions,

$$u(z)=(u_*/k)\ln(z/z_0) \tag{3}$$

Under stable conditions,

$$u(z)=(u_*/k)\left(\ln\frac{z}{z_0}+\beta\frac{z}{L}\right) \tag{4}$$

Under unstable conditions,

$$u(z)=(u_*/k)\left\{\ln\frac{z}{z_0}-2\ln\frac{1+(1-16z/L)^{1/4}}{2}-\ln\frac{1+(1-16z/L)^{1/2}}{2}+\right.$$
$$\left.+2\tan^{-1}(1-16z/L)^{1/4}-\frac{\pi}{2}\right\} \tag{5}$$

In the above equations, $u_*$ is frictional velocity, $z_0$ is roughness length, L is Monin-Obukhov length, k is von Karman's constant, and $\beta$ is a constant to be determined.

In fact, as the thickness of the constant stress layer is usually around several tens of meters, the above results have limited applications. In diffusion studies, the power law expression is often used instead, i.e.,

$$u(z)=u_1(z/z_1)^P \tag{6}$$

In the above equation, $u_1$ and $z_1$ are reference velocity and height, and the index P is a parameter that varies with degree of stability and degree of roughness of the ground.

If the initial conditions are

$$t=0,\ z=H,\ x=0,\ \frac{dz}{dt}\bigg|_{t=0}=V_s,\ \frac{dx}{dt}\bigg|_{t=0}=u(H)$$

the wind speed profile is taken separately as that given in equations (3)-(6), equation (2) is solved and let $\bar{z}$ (plume axis height) = z, then one can obtain the equations for the trajectory of the diffusing particle as follows:

$$x=\frac{u_*}{V_s k}\left(\bar{z}-\bar{z}\ln\frac{\bar{z}}{z_0}-H+H\ln\frac{H}{z_0}\right) \tag{7}$$

$$x=\frac{u_*}{V_s k}\left(H\ln\frac{H}{z_0}-H+\frac{\beta H^2}{2L}-\bar{z}\ln\frac{\bar{z}}{z_0}+\bar{z}-\frac{\beta\bar{z}^2}{2L}\right) \tag{8}$$

$$
\begin{cases}
x = \dfrac{u_*}{48 V_s k}(\psi - \zeta) \\
\psi = 24H(2\ln H - 2 - 2\ln z_0 + 6\ln 2 - \pi) + 3L(1-16H/L)(2\ln(1-16H/L)^{1/4} \\
\quad - \ln(1-16H/L)^{1/2} - 1 - 2\tan^{-1}(1-16H/L)^{1/4}) + 6L\tan^{-1}(1-16H/L)^{1/4} \\
\quad + 2L(1-16H/L)^{3/4} - 6L(1-16H/L)^{1/4} \\
\zeta = 24\bar{z}(2\ln\bar{z} - 2 - 2\ln z_0 + 6\ln 2 - \pi) + 3L(1-16\bar{z}/L)(2\ln(1-16\bar{z}/L)^{1/4} \\
\quad - \ln(1-16\bar{z}/L)^{1/2} - 1 - 2\tan^{-1}(1-16\bar{z}/L)^{1/4}) + 6L\tan^{-1}(1-16\bar{z}/L)^{1/4} \\
\quad + 2L(1-16\bar{z}/L)^{3/4} - 6L(1-15\bar{z}/L)^{1/4}
\end{cases}
\tag{9}
$$

$$
\begin{cases}
\bar{z} = H\left[1 - \dfrac{x}{H}\omega(P+1)\right]^{\frac{1}{P+1}} \\
\omega = \dfrac{V_s}{u(H)}
\end{cases}
\tag{10}
$$

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Equations (7)-(9) give the relation between plume axis height and distance under neutral, stable and unstable conditions in an implicit form, while equation (10) gives in an explicit form the relation between the plume axis and the downwind distance for the case where the wind speed has an exponential distribution.

On the basis of Pasquill and Smith's work [4], for flat lands of the open countryside, the relation between the Monin-Obukhov length and Pasquill's stability classification is as shown in Table 1. The values for P for different degrees of ground roughness and stability are taken to be those given in Table 2. Thus, based on various roughness lengths, one can calculate for fixed values of $V_s/u$ or $V_s/u_*$ the height of the plume axis $\bar{z}$ under various stability conditions.

Consulting Table 2, we chose two sets of values for P to represent, respectively, the various stability conditions of cities and countryside. We also took $\omega = 0.5$, 0.1, 0.01 and $H = 100$m to perform calculations on equation (10). The results are shown in Figure 1. It can be clearly seen from this figure that when $P = 0$, indicating that the wind speed is constant, equation (10) transforms into the form given in equation (1), and the trajectory of motion of the particle becomes a straight line intersecting the x-axis at

Table 1 Relations between Pasquill classification and Monin-Obukhov length $L$

| Pasquill stability classification | $L(m)$ | Pasquill stability classification | $L(m)$ |
|---|---|---|---|
| A | −2—−3 | D | ∞ |
| B | −4—−6 | E | 35—75 |
| C | −12—−15 | F | 8—35 |

Table 2 Values of $P$ under different conditions of stability and roughness

| 1 粗糙度状况 | B | C | D | E | F | 6 参考文献 |
|---|---|---|---|---|---|---|
| 2 平坦乡村 | | 0.11 | 0.14 | 0.20 | 0.33 | (5) |
| 3 城市(日本) | 0.15 | 0.20 | 0.25 | 0.30 | | (6) |
| 4 北京西郊 | 0.15 | 0.20 | 0.23 | 0.36 | | 7 注 |
| 5 沈阳 | 0.17 | 0.20 | 0.25 | 0.30 | | (6) |

8 注：引自北京西郊环境质量评价工作.

1--roughness condition; 2--flat countryside; 3--cities (Japan); 4--western suburb of Peiching; 5--Shenyang; 6--references; 7--remark; 8--Remark: This is taken from an evaluation of environmental quality of the western suburb of Peiching

a slant. $P \neq 0$ indicates that the wind speed varies with height, causing the plume axis to bend downwards. With increasing stability (increasing value of P), the curvature of the curve increases and the deviation of the trajectory from a straight line becomes more pronounced.

Applying the same method to perform calculations on equations (7)-(9) for given values of $V_s/u_*$, $z_0$, L, β and other related parameters, one can obtain results similar to that given in equation (10).

Figure 2 gives the results obtained from equations (7) and (10), under neutral conditions and for roughness lengths $z_0$ = 1 cm and 50 cm. It shows that the results obtained from these two equations are very similar when the roughness length is small.

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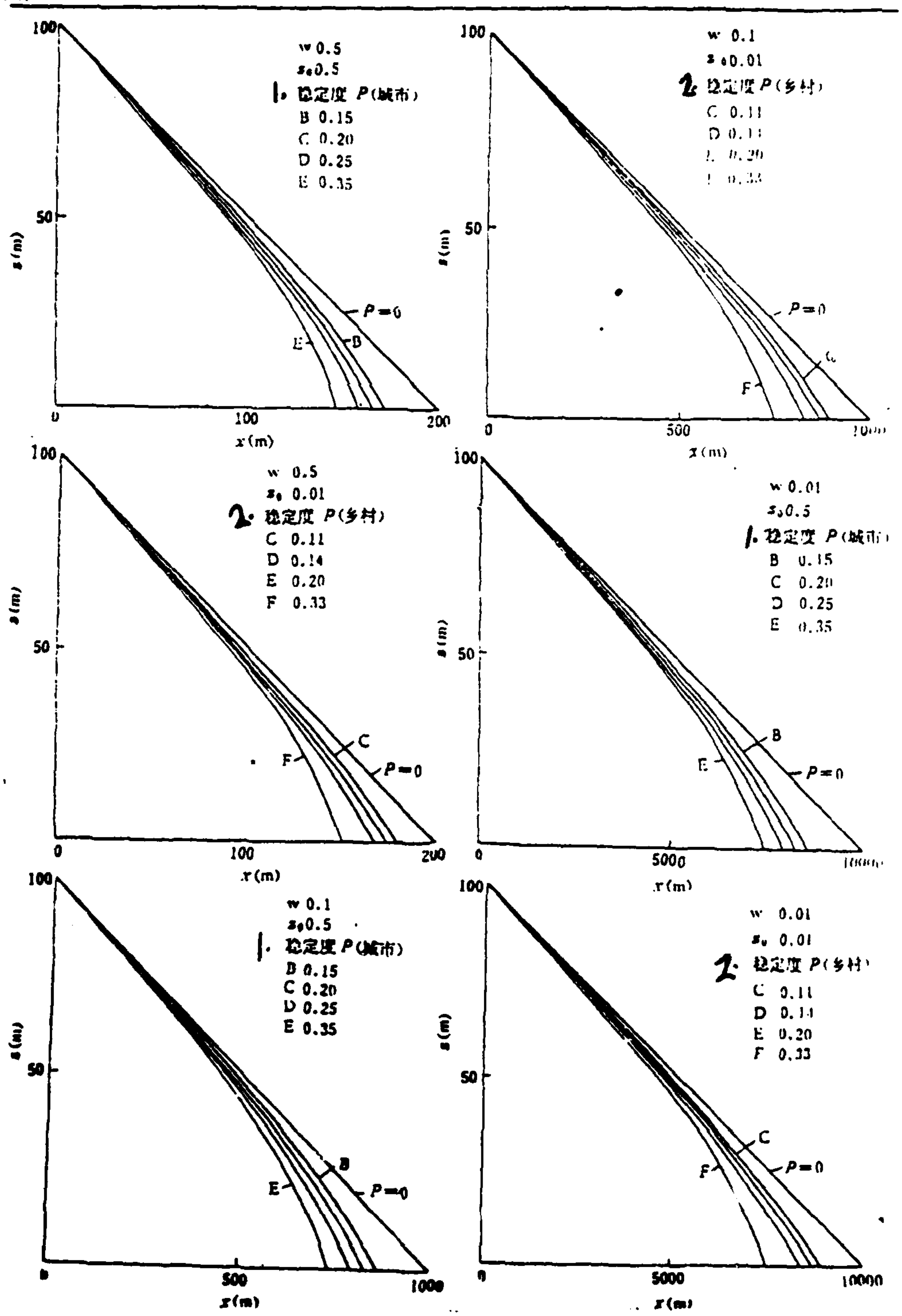


1--stability P (cities; 2--stability P (countryside)
Fig. 1. Trajectories of mean motion of particles.

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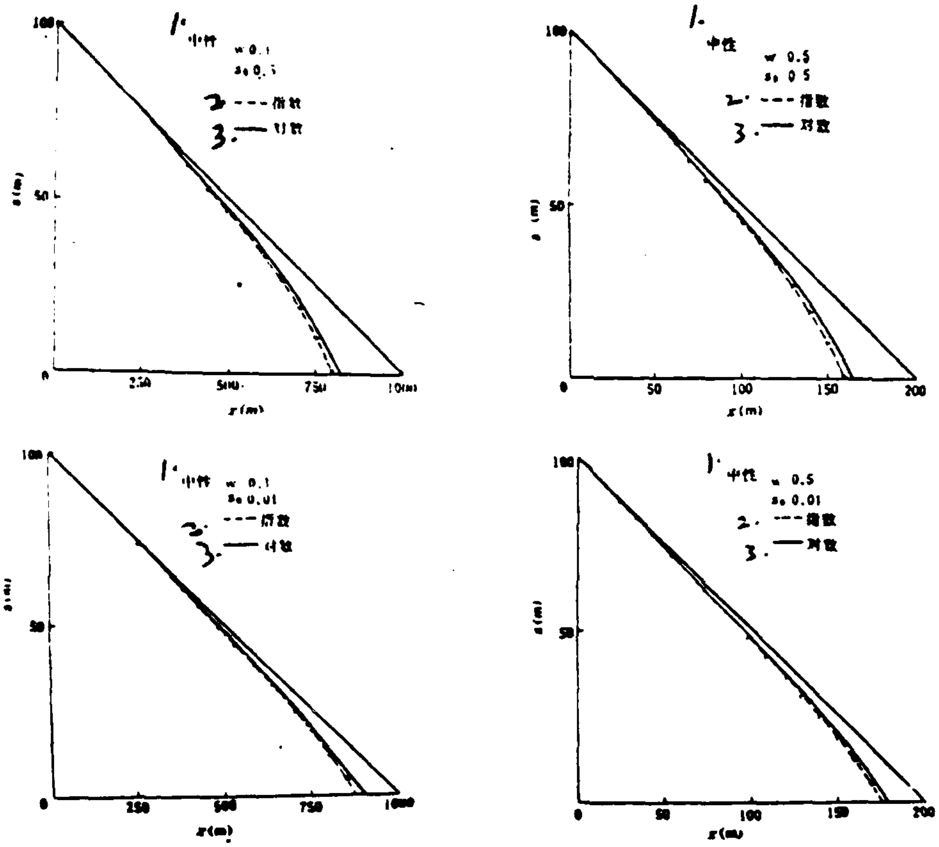


Fig. 2. Comparison between trajectories of mean motion of particles in neutral conditions when wind speed profile is shown respectively by power law or logarithmic law.

1--neutral conditions; 2--power law; 3--logarithmic law

## III. GROUND REFLECTION COEFFICIENT, TRANSPORTING FACTOR AND WIND SPEED PROFILE

The ground reflection coefficient in equation (1), $\alpha_0(x)$, has been derived under the assumption that the wind speed $u=u_H$ [7]. If the variation of wind speed with height takes the form given in equation (6), then the plume axis will be as shown by the broken lines in Figure 3. If the streamline for constant wind speed is represented by ST, then, because the wind speed increases with height, the streamline moves backward to ST'. The ground reflection coefficient $\alpha_1(x)$ can be derived as follows.

The streamline ST' should be described by the equat  n below:

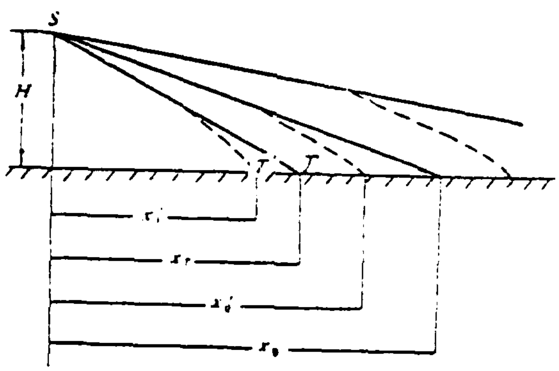

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Fig. 3. Sketch of effects of wind speed with height on plane axis.

$$\begin{cases} z^* = H\left\{1-\omega(P+1)\dfrac{x}{H}\right\}^{\frac{1}{P+1}} - k\sigma_z(x) \\ k = \dfrac{H(1-\omega(P+1)x_T/H)^{\frac{1}{P+1}}}{\sigma_z(x_T)} \end{cases} \quad (11)$$

In the above equations, $z^*$ denotes the distance from ground level of the particle in the plume on the streamline ST'. Differentiating equation (11), we obtain

$$\frac{dz^*}{dt} = -\left\{V_s + \frac{u_H H}{\sigma_z(x_T)}\,(1-\omega(P+1)x_T/H)\,\frac{d\sigma_z(x)}{dx}\right\} \quad (12)$$

Equation (12) shows that the vertical velocity of the particle is made up of the gravitational settling velocity and the turbulent flow diffusion velocity. The negative sign denotes downward transport.

Define the rate of deposition D as the product of the deposition velocity and the ground level concentration

$$D = V_d C(x, y, 0) \tag{13}$$

If deposition occurs at ground level and $\alpha_1(x)$ is used to denote the consumption of the source, then, according to the law of conservation of mass, the ground level settling should be equal to the difference between the fluxes from the real and image sources. Hence,

$$V_d(1+\alpha_1)C_s(x, y, 0) = (V_s + V_t)C_s(x, y, 0) - \alpha_1(V_s + V_t)C_s(x, y, 0) \tag{14}$$

In the above equation, $C_s$ denotes that part of the ground level concentration due to the real source; $V_t$ denotes the turbulent flow diffusion velocity. From equation (12), on the ground level $V_t = -\left\{\frac{u_H H}{\sigma_z(x_T)}(1-\omega(P+1)\, x_T/H)\frac{d\sigma_z(x)}{dx}\right\}$, Inserting equations (12) into (14), one obtains the expression for $\alpha_1(x)$:

$$\alpha_1(x) = 1 - \left\{\frac{2V_d}{V_d + V_s + \frac{u_H H}{\sigma_z(x)}(1-\omega(P+1)x/H)\frac{d\sigma_z(x)}{dx}}\right\} \tag{15}$$

In the Gaussian diffusion-deposition model, the wind speed used in describing the transport effect of the wind is usually taken to be that at the height of the exhaust, $u_H$, in the same manner as when using the Gaussian model. Since the height of the plume axis continually decreases, taking the wind speed at the height of the plume axis is a more nearly true representation of the actual situation. If the distribution of the wind speed is given by equation (6), then the wind speed at the height of the plume axis should be

$$u(\bar{z}) = u_H\left(\frac{\bar{z}}{H}\right)^P = u_H\left[1 - \frac{x}{H}\omega(P+1)\right]^{\frac{P}{P+1}} \tag{16}$$

## IV. EFFECTS ON GROUND LEVEL CONCENTRATION

To help illustrate the problem, we use equation (1) as our basis and take $u = u_H$. The relative ground level concentration can be expressed as

$$\frac{u_H C(x,0,0)}{Q} = \frac{(1+\alpha_s(x))}{2\pi\sigma_y\sigma_z}\exp\left(-(H - V_s x/u_H)^2/2\sigma_z^2\right) \tag{17}$$

The effects of the wind speed profile on the ground level concentration as produced via plume axis height, reflection coefficient and the transport term can be obtained by calculating $C_1$, $C_2$ and $C_3$ by substituting equations (10), (15) and (16) into the corresponding terms in equation (17). Let $I_1$, $I_2$ and $I_3$ denote the relative change in concentration due to the above three factors, and we have

$$I_1 = C/C_1 = \exp\left[\frac{\bar{z}^2 - (H - \omega x)^2}{2\sigma_z^2}\right] \tag{18}$$

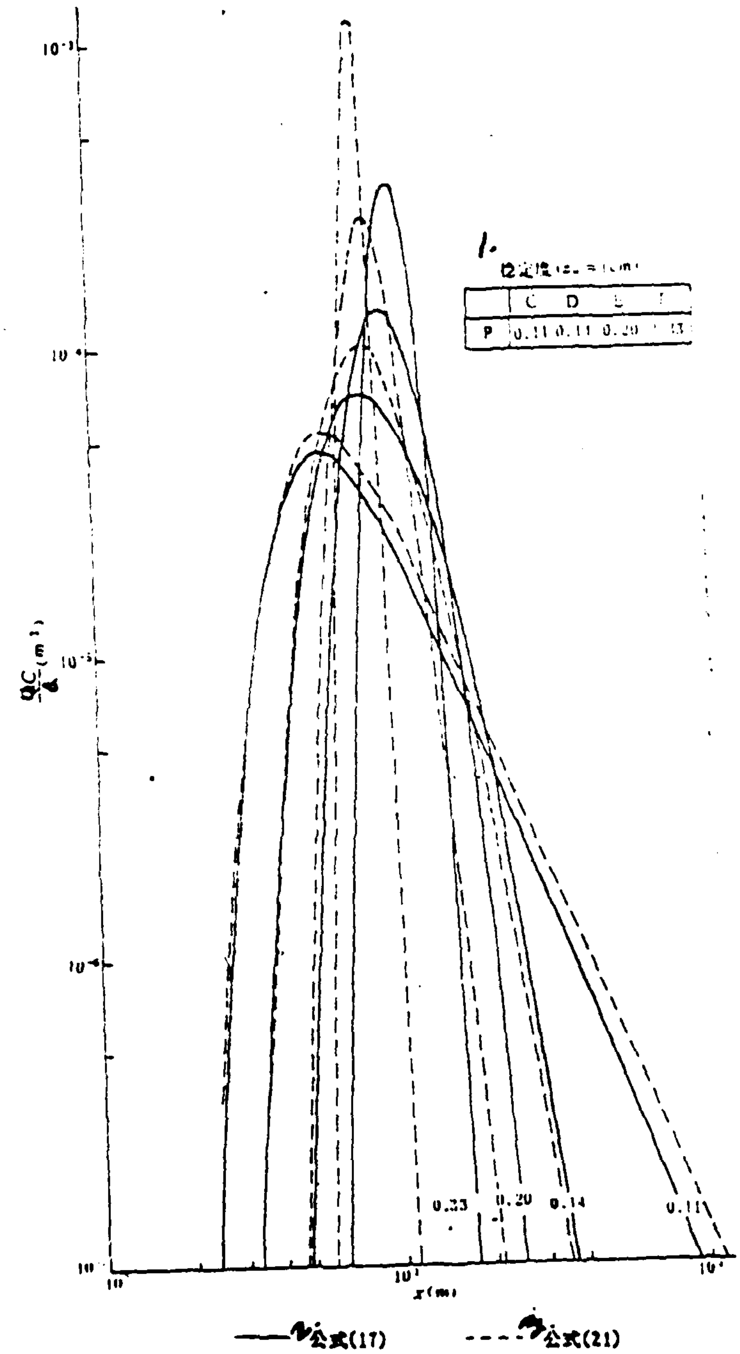
$$I_2 = C/C_2 = \left[1 - \frac{2V_d}{V_d + V_s + (u_H H - V_s x)\sigma_z^{-1}\left(\frac{d\sigma_z(x)}{dx}\right)}\right] \Bigg/ \left[1 - \frac{2V_d}{V_d + V_s + H(1 - \omega(P+1)x/H)\left(\frac{u_H}{\sigma_z(x)}\right)\left(\frac{d\sigma_z(x)}{dx}\right)}\right] \tag{19}$$

$$I_3 = C/C_3 = \left[1 - \frac{x}{H}\omega(P+1)\right]^{\frac{P}{P+1}} \tag{20}$$

After the variation of wind speed with height is taken into consideration, the axial relative ground level concentration takes the expression

$$\frac{u_H C(x,0,0)}{Q} = \frac{1+\alpha_1(x)}{2\pi u\left(\frac{\bar{z}}{H}\right)\sigma_y\sigma_z}\exp\left(-\bar{z}^2/2\sigma_z^2\right) \tag{21}$$

For $\omega = 0.1$, $V_d = V_s = 0.1$ m/sec, $H = 100$m, and $\sigma_y$ and $\sigma_z$ taken from the interpolation formula of Briggs [6], perform calculations on equations (17)-(21) for a given value of P. As the value of $u(\bar{z})$ in equation (21) self-adjusts with plume axis height, we set the lower limit of the height to be $u(\bar{z}) = u_{10}$.




1--stability; 2--equation (17); 3--equation (21)

Fig. 4. Variations of concentration along relative plume axis with distances.

Table 3 gives the variation of $I_1$, $I_2$ and $I_3$ with distance. It can be seen from the table that $I_1$ first increases then decreases with distance. In the range of 1-4 km, $I_1 > 1$, and $I_2$ and $I_3$ increase with increasing distance. However, $I_2$ is greater than 1 while $I_3$ is less than 1. The rate of variation of $I_1$, $I_2$ and $I_3$ with distance increases with increasing stability. This shows that the assumption of $u = u_H$ = constant, through its effect on the plume axis, has caused the estimation of the concentration in the range of 1-4 km to be on the high side. The same assumption, through its effect on the ground reflection coefficient and the transport factor has, respectively, led to an overestimation and underestimation of the axial ground level relative concentration, the effect of the wind speed profile on concentration being greater for higher stabilities.

The results computed from equations (17) and (21) are shown in Figure 4. It can be seen that for a roughness length of 1 cm, and type C atmospheric stability, the results obtained from equations (17) and (21) are relatively close. Out beyond 3-4 km, the results obtained from equation (17) are lower than those obtained from equation (21). Under neutral conditions (type D), the difference becomes more pronounced. Under stable conditions (types E and F), the ground level relative axial concentration calculated from equation (21) has an increased rate of change with distance. This shows that the overall effect of the variation of wind speed with height on ground level concentration is an increased maximum value of concentration and the appearance of the phenomenon of a "regression" of distance. This result is in keeping with the observations made by Csanady in 1964 [9]. The fact that the difference between the results obtained from equations (17) and (21) increases with increased stability indicates that the effect of wind speed on ground level relative concentration is more pronounced under stable conditions, and should be paid attention to.

Table 3 Variations of $I_1$, $I_2$, $I_3$ with distances under different stability condition

| $I_1$ \ $x$(km) / stability (P) | 0.1 | 0.5 | 1.0 | 1.5 | 2.0 | 4.0 | 6.0 | 8.0 | 10.0 | 15.0 | 20.0 | 25.0 | 30.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B(0.15) | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| C(0.20) | 0.98 | 0.98 | 1.01 | 1.02 | 1.02 | 1.00 | 0.99 | 0.98 | 0.97 | 0.95 | 0.95 | 0.94 | 0.94 |
| D(0.25) | 0.94 | 0.95 | 1.04 | 1.10 | 1.10 | 1.01 | 0.91 | 0.81 | 0.73 | 0.56 | 0.41 | 0.31 | 0.23 |
| E(0.35) | 0.74 | 0.72 | 1.61 | 2.43 | 2.64 | 0.99 | 0.23 | 0.04 | 0.01 | | | | |

| $I_2$ \ $x$(km) / stability (P) | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.75 | 0.8 | 0.85 | 0.9 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C(0.11) | 1.00 | 1.01 | 1.02 | 1.05 | 1.08 | 1.15 | 1.29 | | 1.7 | | 97.8 |
| D(0.14) | 1.00 | 1.01 | 1.03 | 1.06 | 1.12 | 1.21 | 1.42 | | 2.17 | 4.63 | |
| E(0.20) | 1.00 | 1.02 | 1.05 | 1.09 | 1.17 | 1.33 | 1.74 | | 4.65 | | |
| F(0.33) | 1.01 | 1.03 | 1.08 | 1.17 | 1.34 | 1.77 | 3.86 | 8.65 | | | |

| $I_3$ \ $x$(km) / stability (P) | 0.1 | 0.5 | 0.7 | 0.755 | 0.78 | 0.808 |
|---|---|---|---|---|---|---|
| B(0.15) | 0.98 | 0.89 | | | | 0.7 |
| C(0.20) | 0.98 | 0.86 | | | 0.63 | |
| D(0.25) | 0.97 | 0.82 | | 0.56 | | |
| E(0.35) | 0.96 | 0.75 | 0.46 | | | |

## V. CONCLUSION

From the above analysis, it can be seen that the newly derived Gaussian diffusion-deposition model that takes into account the variation of wind speed with height is a better description of the diffusion of particles in the atmosphere. The wind speed profile can affect the ground level concentration through curving of the plume axis, the reflection coefficient and the transporting factor, and the effect becomes more pronounced under the stable layer.

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