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Study on Conventional Atmospheric Dispersion Models in China, America and Canada

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ABSTRACT

The conventional atmospheric dispersion models used in China (CRADM), America (HPDM) and Canada (AMS) are investigated. The main differences between the three models are described, and the various aspects of CRADM, HPDM and AMS for same input are compared and discussed. Some problems in application of atmospheric dispersion models to environmental impact assessment are analyzed and suggestions for rivision are proposed. Results show that the Briggs plume rise formula in neutral condition overestimates the real rise due to the fact that the accumulative effect of ambient turbulence on plume is not considered in his model.

Key words: Atmospheric dispersion, Conventional model, Plume rise

I. INTRODUCTION

Since the 1980s, it has been found that some atmospheric dispersion models for conventional applications are not good in coinciding with the observations and do not include the developments in this field (Smith, 1984; Hayes et al., 1986). Several research programmes for developing the state–of–art models have been presented during this period. These models, such as HPDM (Hanna et al., 1992) and AMS (Ministry of Environment, Canada, 1987), do not use the traditional Pasquill stability classification and P–G diffusion parameter system. They apply the non–Gaussian PDF model under convective condition. The achievements in the studies of planetary boundary layer (PBL) and atmospheric diffusion since 1970s are assimilated in those models, and more tracer experiments and observational data of SO_2 ground level concentration (GLC) have been used in the model examinations. At present, the second generation models for conventional applications are being or have been developed in some countries.

The earliest conventional atmospheric dispersion model in China was Described in the national standard GB3840–83. In 1991, GB / T3840–91 was published by the National Environment Protection Agency and the National Technique Supervision Agency, in which the method to calculate GLC of air pollutants was suggested. It is the only model for conventional application in China, which is similar to CRESTER, ISC models of USA. To understand the performance of CRADM, comprehensive comparisons with HPDM and AMS are put forward in this paper. Using the meteorological data (January and April 1989) obtained from five stations in Jiangsu Province, the stability is classified according to the methods specified in different models, and the sensible heat flux Q_H, mixing layer height Zi and Monin–Obukhov length L, friction velocity u_*, scaling temperature θ_*, convective velocity scale w_*, etc. are calculated. Finally, checking computations for the three models are carried out using 6800 combinations of source parameter and meteorological conditions. The results indicate that the models have evident difference with each other, and they are all have some disadvantages. Several schemes are suggested for improvements of HPDM which is especially suitable for coal–fired power plants.

The problem of plume rise, which has great influence on atmospheric diffusion, is also discussed in this paper. For the time being, almost every country uses the series of formulas given by Briggs, especially for the thermal buoyant plume. Great emphasis is put on the problem of plume rise under neutral conditions. It is concluded that Briggs formulas overestimate the rise height due to the fact that accumulative effect of ambient turbulence is not taken into account.

II. DESCRIPTION OF CRADM, HPDM AND AMS

The characteristics of CRADM are summarized as follows:

1) The Gaussian plume model is applied;

2) Atmospheric stability is classified into 6 classes(A–F) by P–T method;

3) The P–G diffusion parameters are used, and they are fitted to the form of the power law at different distances;

4) An extreme scheme which includes either complete or no penetration is used to treat the plume penetration at the top of the mixing layer;

5) The plume rise height is calculated by the modified Holland formula and Briggs formula (Briggs, 1969);

6) The mean wind speed at the top of the stack is calculated based on the power law.

The concepts of HPDM and AMS can be seen in references.

III. COMPARISONS BETWEEN CRADM, HPDM AND AMS

As mentioned above, CRADM as well as CRESTER and ISC belong to the same model system, in which Gaussian plume model, P–T stability classification and P–G diffusion parameters are applied. On the other hand, CRADM is obviously different from HPDM and AMS which belong to the second generation model system. Apparently, application of different model in environmental impact assessment (EIA) will lead to different results. In this paper, we use the same meteorological and source data as input in order to investigate their response to output, such as PBL parameters and GLC. Furthermore, the results of different models are analyzed and compared.

1. *Stability Classification and PBL Parameters Calculation*

The methods for stability classification and calculation of the key PBL parameters in CRADM, HPDM and AMS are different. In order to quantitatively analyze the difference between these models, we use routine meteorological data (January and April 1989) from five observational stations in Jiangsu Province to perform model calculation. The results are listed in Table 1 and Table 2.

Table 1 shows that as far as stability classification is concerned, the results of HPDM and CRADM are generally consistent. In January, the percentage of neutral condition is above 50% and that of unstable condition is less than 5%. In April, the percentage of unstable condition increases, and that of stable and neutral conditions decreases correspondingly. This distribution pattern basically accords with the measurements. Actually, in January, solar radiation is weak at the middle–latitude region and weather in the selected days was often cloudy which lead to the high percentage of neutral and stable conditions. In April, solar radiation strengthens and the possibility of unstable condition enhances. Besides, the classification of AMS results in the smaller percentage of neutral condition and larger percentage of unstable condition. As such, we can conclude that the critical value of Q_H delimiting neutral and unstable condition is relatively small in AMS. In CRADM, stability is classified by P–T method and the proportion of unstable condition is less than that computed from the other two models. In HPDM, the thermal and dynamic factors related to atmospheric stability are considered synthetically and quantitatively, as a consequence, the final results of classification are relatively better.

Table 1. Percentage of Different Stability (%)

		CRADM	HPDM	AMS
January	unstable	< 5	5–9	50
	neutral	50–75	45–55	5–25
	stable	23–45	35–45	25–45
April	unstable	15–25	12–18	50
	neutral	35–55	40–50	5–20
	stable	25–45	35–40	30–45

Table 2 lists the calculated mixing depths from the three models. It shows that Zi values in stable condition are very close for each model. Under neutral condition, Zi calculated by formula $Zi = 0.3u_* / f$ in HPDM and AMS is very high. It is obviously unreasonable that Zi in neutral condition is greater than that in unstable condition in HPDM. Comparatively, Zi under unstable condition is a little too low in CRADM and HPDM while relatively higher in AMS. Furthermore, large leaps were found during estimation of nocturnal boundary layer depth because of the discontinuous appearance of stable and neutral conditions.

Table 2. Calculated Zi from Different Model (m)

	CRADM		HPDM		AMS	
	January	April	January	April	January	April
unstable	180–800	600–1200	300–900	550–1050	1700–1900	2300–2500
neutral	400–500	450–600	1350–1650	1600–1850	1100–1800	1400–2400
stable	70–300	90–350	40–250	40–250	100–150	100–150

The main PBL parameters ($Q_H, L, u_*, \theta_*, w_*$) computed from HPDM and AMS are also compared. The results of HPDM agree with those of AMS. Whereas these parameters are not needed in CRADM.

2. *Calculation of Ground Level Concentration*

There are two schemes applied for model calculation. One is using annual routine meteorological data of an observational station and a set of source data to calculate GLC. Part of results are listed in Table 3. The other is to make systematic checking computations, in which 6800 cases are designed to calculate GLC, while each case consists of different source and meteorological data. Therefore, the abnormality under a special case and the relative rationality can be found by analysis and comparison between different models. The calculated results show that GLC predicted by CRADM is sometimes zero, sometimes very high. The reason is that the possibility of partly penetration at the top of mixing layer is not considered and hypothesis of full penetration or full reflection is made. GLC will be underestimated or overestimated when effective source height approaching Zi. In addition, since $d\sigma_z / dx$ is too high in stability–A, the maximum GLC predicted by CRADM is obviously higher than that by the other two models. In HPDM and AMS, partly penetration is taken into account and the extreme value disappeared. Further analyses indicate that, since plume rise height under stable condition is used when defining penetration coefficient in HPDM, which means that the actual unstable or neutral conditions are treated as the stable condition, GLC may be overestimated under some meteorological conditions. In HPDM, Zi in neutral condition is very high which underestimates of penetration coefficient and overestimates GLC for higher source, or weakens the reflection near the top of mixing layer and underestimates GLC for lower source. Also, the wide range of Zi leaps in neutral and stable conditions at night can lead to great rise and fall of GLC. The formula for Zi estimation in neutral condition in AMS is same as that in HPDM, and the two models are different in standards for classification of unstable and neutral conditions, therefore, the unstable conditions in AMS are more than those in HPDM. In addition, GLC from AMS is obviously higher than that from the other two models, but it is lower for higher source.

Table 3. Ground Level Concentration of Three Models ($\mu g / m^2$)

		CRADM	HPDM	AMS
A	Jan.15 12:00	0	43.2	60.2
	Feb.15 12:00	0	69.0	72.1
	Mar.15 12:00	111.8	94.0	86.8
	Apr.15 12:00	0	54.3	82.3
	May.15 12:00	0	94.8	87.3
	Jun.15 12:00	163.8	142.6	88.8
	Jul.15 12:00	165.1	130.1	81.4
	Aug.15 12:00	358.0	64.1	95.6
	Sep.15 12:00	218.9	176.7	148.2
	Oct.15 12:00	212.5	63.8	73.5
	Nov.15 12:00	345.8	159.9	128.6
	Dec.15 12:00	0	45.8	62.4
B	Jan.15	45.0	15.8	17.3
	Feb.15	0	3.2	7.7
	Mar.15	13.3	13.0	9.1
	Apr.15	0	8.8	9.8
	May.15	19.6	25.4	25.7
	Jun.15	20.0	10.0	6.9
	Jul.15	50.3	33.8	30.9
	Aug.15	43.9	16.2	19.3
	Sep.15	10.8	19.9	19.6
	Oct.15	20.2	9.5	7.2
	Nov.15	34.4	15.1	14.5
	Dec.15	0	1.9	5.2
C	1993	5.9	8.5	7.9

A: maximum 30 min average concentration; B: maximum daily average concentration; C: annual average concentration.

3. *Model Improvements*

On the basis of analyses and comparisons mentioned above, we propose several schemes for model improvements, especially for HPDM which is more applicable to plume from power plant. Five different schemes are listed in Table 4. For each scheme, checking computations are conducted. By comparisons and analyses, scheme 3 is finally selected. On the whole, its results are close to those of the previous HPDM, but some extremely high concentrations have disappeared when partly penetration happens. There isn't any wide range of rise and fall on concentration at night. Some results are a little higher as compared with the old version. In fact, when considering plume penetration, the improved scheme overcomes the too conservative and mandatory provision in which the plume rise in stable condition is used. Under neutral condition, mixing depth is calculated by using $Zi = 0.2u_* / f$, and it is lower than that calculated by the previous HPDM. When Zi in stable and neutral conditions is discontinuous at night, a formula similar to that in stable condition is used which overcomes the large leaps of Zi.

Table 4. Different Schemes for Improvements

Scheme	Content
1	$p = 1.5 - (Z_i - h_s) / \Delta h_i$, $\Delta h_i = (\Delta h + \Delta h_s)/2$, Δh is the calculated plume rise $\Delta h_s = 2.6 \left[\frac{F}{U\left(\frac{d\theta}{dz}\frac{g}{T_a}\right)} \right]^{1/3}$
2	In neutral condition: $Z_i = 0.2u_* / f$, When Zi is discontinuous at night: $Z_i = \frac{0.67L}{3.8}\left(-1 + \sqrt{1 + 2.28\frac{u_*}{fL}}\right)^{1/3}$; In unstable condition: $Z_i(t_2) = [Z_i(t_1)^2 + 0.1575Q_H(t_2 - t_1)]^{0.5}$
3	Schemes 1 and 2 are considered simultaneously
4	In neutral condition, Zi calculation is same as scheme 2 In unstable condition: $\frac{\partial Z_i}{\partial t} = \frac{1.8(W_*^3 + 1.1u_*^3 - 3.3u_*^2 fZ_i)}{g\frac{Z_i^2}{T_a}\frac{\partial \theta^+}{\partial z} + 9w_*^2 + 7.2u_*^2}$
5	Schemes 1 and 4 are considered simultaneously

IV. THE PLUME RISE FORMULAS CONSIDERING THE ACCUMULATED EFFECT OF AMBIENT TURBULENCE

It is well known that the rise height of a strong thermal plume is very important to dispersion calculation. Since the 1970s, great advancement in theories of plume rise has been achieved (Briggs, 1975; 1984). Several Briggs formulas were used in atmospheric dispersion models, the most popular one is the formula under neutral condition. It was induced from his "break-up" model, in which it assumes that the plume rise accords with the "2/3" power law and the plume structure itself will break up and then the plume rise comes to the end when the dissipation rate of internal turbulent energy within the plume is equal to that of ambient turbulent energy. Thus, Briggs obtained the following equations:

$$\Delta H = 1.2\left(\frac{F}{Uu_*^2}\right)^{\frac{3}{5}}(H_s + \Delta H)^{2/5} \ , \qquad (1)$$

$$\Delta H = 1.3\left(\frac{F}{Uu_*^2}\right)\left(1 + \frac{H_s}{\Delta H}\right)^{\frac{2}{3}} \ , \qquad (2)$$

$$\Delta H = 1.54\left(\frac{F}{Uu_*^2}\right)^{\frac{2}{3}} H_s^{1/3} \ , \qquad (3)$$

where ΔH is the final rise height, Hs the geometric height of plume source. Eq. (3) is widely used at present. According to Li (1987), influence of ambient turbulence on plume rise becomes significant as the plume rise velocity $\overline{W}$ becomes smaller though it is not important at the begining. This accumulative effect cannot be neglected, as a result, there exists evident deviation between the real trajectory of plume rise and that of "2 / 3" power law. When the effect of ambient turbulence is taken into account, the plume trajectory equation is:

$$Z = \left(\frac{3+2i}{2\beta^2}\right)^{\frac{1}{3+2i}} F^{\frac{1}{3+2i}} U^{\frac{3}{3+2i}} X^{\frac{2}{3+2i}} \ , \qquad (4)$$

where i is ambient turbulence intensity. Eq. (4) regresses to the power law of " 2 / 3" when $i = 0$.

From Eq. (4), the formulas under neutral condition were given earlier by Li (1987):

$$\Delta H = \left\{(\eta\kappa)^2\left[\frac{2}{(3+2i)\beta^2}\right]^3\right\}^{\frac{1}{5+6i}}\left(\frac{F}{Uu_*^2}\right)^{\frac{3}{5+6i}}(H_s + \Delta H)^{\frac{2}{5+6i}} \ ,$$

$$= A_1(i)\left(\frac{F}{Uu_*^2}\right)^{\frac{3}{5+6i}}(H_s + \Delta H)^{\frac{2}{5+6i}} \ , \qquad (5)$$

$$\Delta H = A_2(i)\left(\frac{F}{Uu_*^2}\right)^{\frac{1}{1+2i}}\left(1 + \frac{H_s}{\Delta H}\right)^{\frac{2}{3(1+2i)}} \ , \qquad (6)$$

$$A_2(i) = \left\{(\eta\kappa)^2\left[\frac{2}{(3+2i)\beta^2}\right]^3\right\}^{\frac{1}{3+6i}} \ .$$

$$\Delta H = A_3(i)B(i)\left(\frac{F}{Uu_*^2}\right)^{\frac{2}{3(1+2i)}} H_s^{1/3} \ , \qquad (7)$$

$$A_3(i) = \left\{(\eta\kappa)^2\left[\frac{2}{(3+2i)\beta^2}\right]^3\right\}^{\frac{2}{9(1+2i)}} \ ,$$

$$B(i) = \frac{\left(\frac{3}{2}\right)^{\frac{4}{9(1+2i)}}}{\left(\frac{1}{2}\right)^{\frac{1-6i}{9(1+2i)}}} \ ,$$

where $A_1(i)$, $A_2(i)$, $A_3(i)$ and $B(i)$ are the combined coefficient. They are functions of turbulence intensity. If taking $\eta = 1.5$, $\kappa = 0.4$, $\beta = 0.6$ (Briggs, 1975), the coefficients have values as listed in Table 5.

Table 5. The Values of Combined Coefficients for Different Turbulence Intensity

i	0	0.05	0.10	0.15	0.20
$A_1(i)$	1.18	1.15	1.12	1.10	1.08
$A_2(i)$	1.32	1.25	1.19	1.15	1.11
$A_3(i)$	1.20	1.16	1.13	1.10	1.07
$B(i)$	1.29	1.24	1.19	1.15	1.12

Li (1987) named it as "combined-effect" model since it considers the combined effects of the internal and ambient turbulence. Thus, Eqs. (1)-(3), suggested by Briggs, and being widely used in atmospheric dispersion models, are particular cases of Eqs. (5)-(7) with $i = 0$, respectively. Eq. (3) and Eq. (7) can be checked by using the plume rise data of 16 coal-fired power plants (Briggs, 1969). Comparisons of the calculations with the observations are shown in Fig. 1 and Table 6. In the absence of original data, those shown in the figure are just the sets of values under the mode of wind speeds in each experiment. The entire available data are of 20 groups, where 3 groups of the abnormal are omitted, so the data selected are of 17 groups.

Table 6. Comparison between Calculated Plume Rise with Observation

Data Used	Equation	$\bar{K}$	σ_k	r
Entire	L	0.952	0.449	0.72
	B	2.00	1.23	0.66
Chosen	L	0.872	0.272	0.90
	B	1.74	0.683	0.88

L: Combined-effect model; B: Break-up model; $\bar{K}$: averaged ration of calculated plume rise to observations; σ_k: standard deviation of ratio; r: correlation coefficient.

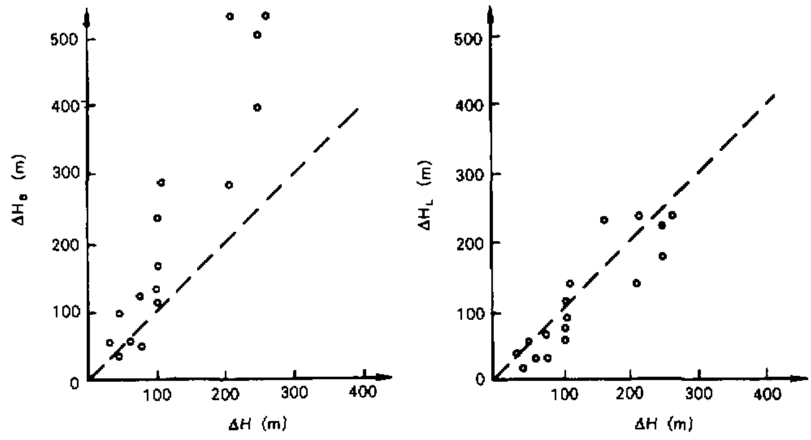

Fig. 1. Comparisons between calculated results of Eqs. (3) and (7) with observations.

Both Fig. 1 and Table 6 indicate that the "combined–effect" model is the superior one. The data calculated by Eq. (7) being 10% lower is entirely due to the fact that parameters chosen are slightly conservative, while in the same case, those from Eq. (3) are 70% higher. Based on the same principle, the plume rise formula under convective condition was induced by Li (1987). The value calculated from it is also lower than that of Briggs. Of course, a conventional atmospheric dispersion model is usually made up of many components, so a positive deviation from one component may be offset by a negative one from another.

V. DISCUSSION

The available data from atmospheric dispersion experiments are far from meeting the needs of model development and validation. As a supplementary approach, the stability classification and atmospheric boundary layer parameters of different models have been calculated by use of the same meteorological data set. The ground level concentrations are computed in the context of 6800 kinds of source and meteorological conditions. Through comparisons and analysis, we can find the merits and demerits of different models and get some valuable informations for model development and revision. The present conventional atmospheric dispersion models should be improved and harmonized in the following aspects:

1) Atmospheric stabilities restrict the PBL parameterization schemes, plume rise formulas and dispersion calculations. It is principal to harmonize the methods and critical values of stability classification.

2) The approaches of estimating mixing layer height and plume penetration affect the calculated GLC, so it is very important to harmonize the methods of determining the two factors.

3) For a strong buoyant plume, calculation of rise height has an important influence on GLC. The Briggs formula overestimates the plume rise for ignoring the accumulative effects of ambient turbulence.

4) There are many factors that affect GLC of an elevated source. As some physical mechanisms are not well understood, the atmospheric dispersion models for conventional applications should not be too complex. Otherwise, the mutual effects of some factors in the models will cause irrational results under certain model parameter combinations.

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