THE RISE MODEL OF BUOYANT PLUME LIMITED BY MECHANICAL TURBULENCE

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ABSTRACT

This paper has investigated the rise of bent-over buoyant plume in neutral condition. By means of the combined-effect model proposed at earlier time, authors have deduced a formula of final rise limited by mechanical turbulence and therefore have concluded that the corresponding formula neglecting the accumulated effect of ambient turbulence is only its particular case. By analyzing the function relation of the various affecting factors with the plume rise in the existing equations, it is proved that the formula derived from the combined-effect model is the most reasonable and shows more conformity to the observations.

I. INTRODUCTION

The plume rise is an essential subject in the research of air pollution. The rise height of thermally buoyant plume is usually much greater than the stack height. Therefore, if the rise height can not be correctly calculated, the design of stack height and calculation of the ground concentration of pollutants will be meaningless. Now there exist scores of plume rise formulas, but the calculated results with the same plume source and meteorological condition may differ more than ten times from each other. Many of these formulas are purely empirical. Due to difference of experimental conditions, deficiencies in data and incompleteness of observational means, particularly during early research period, the results obtained from these experiments can hardly be comparable.

Since the 1970s great advance in theories of plume rise has been achieved (e.g., Briggs, 1975; 1984). At the same time, further research on plume rise, particularly on the final rise models for a strong thermal plume source, has benefited from increased understanding of turbulence, wind and temperature fields in the boundary layer and accumulated data obtained by advanced tools of sounding such as lidar. The research put emphasis on the rise of bent-over buoyant plume under neutral conditions, which is a subject of great current interest. In recent years, some new concepts are introduced and new facts are found both in theory and analysis of observational data. They mainly include the following aspects:

(1) The values calculated from most of the rise formulas are lower than those detected. In earlier period, the rise height of plume was usually determined by means of photographs,

When the plume is weak, the actual final rise cannot be measured. Thus the empirical formulas based upon it would tend to predict a lower rise. On the contrary. those observed by lidar can reach as high as 3—4 km or more (Weil, 1979).

The unreal higher ground concentration obtained from some dispersion calculations is related to the fact that the rise formula adopted is too conservative.

(2) The rise height increases with elevation of plume source (Briggs, 1984). If no account is taken of the effect of the ambient turbulence, the thermal plume under neutral conditions will rise indefinitely according to the power law of 2/3. Only under the effect of the ambient turbulence, would the rise just come to a termination. In the boundary layer, the mechanical turbulence is weakened upward. Therefore, when the buoyant flux is equal, the higher the plume source, the higher the final rise and the farther it extends.

(3) The rise height decreases with increasing wind velocity, but has a stronger dependence than U^{-1}. $\Delta H \propto U^{-1}$ is the most common form of existing rise formulas. Nevertheless, the wind speed, in addition to having the direct effect of dilution, will strengthen the mechanical turbulence and accelerate the mixing-up effect. Therefore, when considering the effect of ambient turbulence, a final rise model should have a stronger relation than U^{-1}any way (Briggs, 1984; Csanady, 1973).

(4) The accumulated effect of ambient turbulence should not be ignored. The theoretical models usually assume that the ambient turbulence has no influence on rise at its main stage. Chen (1981), for the first time, put forward a model considering the accumulated effect of ambient turbulence, and Li (1982) further confirmed this idea with his combined-effect model. Such a model is more reasonable in theory and conforms better to the observational data both at home and abroad. In addition, it solves the problem that the final rise is overestimated by some formulas.

The rise of bent-over buoyant plume in neutral conditions is discussed hereafter and a set of formulas of final rise limited by mechanical turbulence are derived based on the combined-effect model. It is found that the corresponding formula of Briggs is only their particular case. The relation between rise height and various affecting factors in existing formulas is also analyzed in this paper. The formula derived from the combined-effect model proves to be the most reasonable and its results is more consistent with observations.

II. THE FINAL RISE FORMULA DERIVED FROM THE COMBINED-EFFECT MODEL

Among the existing final rise models, the Briggs' "break-up" model has given a more successful approach of limitation. It assumes that when dissipation rate $\bar{\varepsilon}$ of internal turbulent energy within the plume is equal to that of ambient turbulent energy ε, the plume structure itself will break up and transform into a passive p ume and then the plume rise will come to a termination. This limiting condition can be expressed as

$$\varepsilon=\eta\frac{W^3}{Z}, \tag{1}$$

where the right side of the equation represents the dissipation rate of internal turbulent energy within plume, W average vertical speed of plume, Z the calculated height at exit, and η the dimensionless coefficient.

In fact, when W, which maintains the plume structure, becomes rather small, and at the same time, the plume grows to such an size that the ambient eddies containing more energy will participate sufficiently in the mixing-up effect, the plume structure itself can then really break up in short time and terminate plume rise. This physical model can reasonably explain why the plume, after its rather long buoyant stage, usually comes to keep level in a short distance. The drawbacks of the general final rise models lie on the fact that the effect of the ambient turbulence prior to its break-up are totally ignored. Hence, the formulas derived from these models will have higher calculated values. In order to overcome the above-mentioned deficiencies, the accumulated effect of the ambient turbulence should be account for during the whole rising stage. For this purpose, starting from the combined-effect model, the plume trajectory equation is developed (Li, 1982):

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

where Z is the plume rise height (m), F the buoyancy flux parameter (m^4/s^{-3}), U the average wind speed at plume height (m/s), X the downwind distance from the plume source (m), i the ambient turbulence intensity and β the coefficient (m^{-i}). When ignoring the effect of ambient turbulence (i.e., $i=0$), β is dimensionless. Obviously, the power law of "2/3" is a particular case of Eq. (2) when $i=0$.

ε in Eq. (1) is given as (Briggs, 1975)

$$\varepsilon=\frac{u_*^3}{\kappa H_e}, \tag{3}$$

where u_* is the friction velocity(m/s), κ the Karman constant, and H_e the effective source height (m). The above expression is strictly tenable only to the surface layer. Combining with the work of other researchers, Briggs has found that it is actually applicable to the higher layer (even up to 1200 m). He, therefore, has considered that Eq. (3) can be applied approximately to the typical plume height.

According to Eqs. (1)—(3), the solution of final rise height limited by the mechanical turbulence is obtained:

$$\Delta H=\left\{(\eta\kappa)^2\left[\frac{2}{(3+2i)\beta^2}\right]^3\right\}^{\frac{1}{5+6i}}\left(\frac{F}{Uu_*^2}\right)^{\frac{3}{5+6i}}(H_s+\Delta H)^{\frac{2}{5+6i}} \tag{4}$$

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

or

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

$$A_2(i)=\left\{(\eta\kappa)^2\left[\frac{2}{(3+2i)\beta^2}\right]^3\right\}^{\frac{1}{3+6i}}. \tag{5}$$

Eqs. (4) and (5) containing the unknown ΔH in both sides are much inconvenient to apply, so they are simplified to the following approximations:

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

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

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

where ΔH is the final rise height, H_s the geometric height of plume source, and $A_1(i)$, $A_2(i)$, $A_3(i)$ and $B(i)$, are the combined coefficients, and 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 1.

Table 1. 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

Neglecting the effect of ambient turbulence, Briggs obtained the corresponding equations on the basis of power law of "2/3" (Briggs, 1975; 1984):

$$\Delta H=1.2\left(\frac{F}{Uu_*^2}\right)^{\frac{3}{5}}(H_s+\Delta H)^{\frac{2}{5}}, \tag{7}$$

$$\Delta H=1.3\left(\frac{F}{Uu_*^2}\right)\left(1+\frac{H_s}{\Delta H}\right)^{\frac{2}{3}}, \tag{8}$$

$$\Delta H\simeq 1.54\left(\frac{F}{Uu_*^2}\right)^{\frac{2}{3}}H_s^{\frac{1}{3}}. \tag{9}$$

The above equations suggested by Briggs in recent years are applicable mainly to stronger thermal plume source under neutral and windy conditions. Obviously, they are particular cases of Eqs. (4)—(6) with $i=0$, respectively.

Both Eqs. (6) and (9) are approximate expressions. When wind speed is not too small or when $\Delta H<2H_s$, the deviation from each other is not large. They are safer than the original equations and are convenient to apply and more appropriate to be a practical formula.

III. THE REACTION MECHANISM OF THE PRINCIPAL FACTORS AND THEIR QUANTITATIVE RELATION TO THE RISE HEIGHT

If the minor factors are ignored, the factors determining the final rise of bent-over buoyant plume under neutral conditions should include F, U, H_s and i. Most formulas, however, contain only two independent variables F and U. Just a few scientists consider the additional effect of H_s and only Chen (1981) and Li (1982) further consider the effect of ambient turbulence. Moreover, though most of the formulas have been expressed in the power form of the independent variables, the power values are quite different from each other. This is the basic reason why the existing formulas can hardly be comparable with each other. In view of this problem, analyzing comprehensively the reaction mechanism of each factor, the observed fact and calculated results of formulas with various types, we decide the independent variables that must be accounted for and their reasonable quantitative relation to the rise height.

1. *Buoyancy Flux Parameter* F

The plume rise formulas are usually expressed in the form of $\Delta H \propto F^m$, but their adoped values for m are quite different, being 1/4, 1/3, 1/2, 3/5, 2/3 and 1 etc., respectively (Briggs, 1969; Moses, 1972). Among these values, 1/2 is most often adopted in empirical regressive formulas.

In Holland formula (U.S. Weather Bureau, 1953), $m=1$. As is well known, the calculated results are a few times smaller than the actual cases when F is small, and moderate when F is rather great, which means that the value m should be obviously smaller than 1. On the other hand,the power law of "2/3" apparently means $Z \propto F^{\frac{1}{3}}$, but the termination distance X_T also increases with F. Considering the superimposed effects of both explicit and implicit factors, this law actually indicates that the value m should be apparently greater than 1/3, i.e., $1/3<m<1$.

The range of value m can be further reduced by taking advantage of the plume rise data of 16 fossil fuel-fired power plants (Briggs, 1969). Based upon the data, we obtain

$$\Delta HU \propto F^{0.58}.$$

Including the extensively varying range of value F, the above data provide better representation. However, the relation $\Delta H \propto U^{-1}$ in the above equation is incorrect (most observations were carried out under moderate wind speeds, so the relation would not bring about a very great effect). Moreover, the effects of factors such as H_S etc. are not incorporated into the equation. Therefore, the actual value m should be in the range of $0.58 \pm \Delta$. Considering $1/3 < m < 1$, it is appropriate to let $m=1/2$—$2/3$, being the intermediate among the existing equations.

Table 2. The Value m in the Combined-Effect Model

i	0	0.05	0.10	0.15	0.20
m	0.667	0.606	0.556	0.513	0.476

Both Eqs. (6) and (9) are theoretical. The value m in Eq. (9) is 2/3, while Eq. (6) indicates that value m is related to the ambient turbulence intensity, as shown in Table 2.

The data in Table 2 conforms the above analysis and shows that when the ambient turbulence intensity grows stronger, the dependence of rise height on the thermal flux of plume source, F, becomes weaker. This conclusion accords with the analysis of reaction mechanism, and further supports the reasonableness of the combined-effect model.

2. *Plume Source Height* H_S

The most of the rise height equations do not include the height factor H_S is a serious weakness. Particularly in case of a relatively high and strong thermal plume source, neglecting of H_S will lead to rather great deviation.

The ambient turbulence plays a critical role in the termination of rise. The weaker the turbulence, the higher the final rise. Under the neutral condition the turbulence decreases upward and hence rise height also depends on the elevation of plume source itself. Therefore, the rise equation should include the height factor H_S.

In China, the principle of the "Emission Standard" and the design of stack height is to control the ground concentration of pollutants. The calculated stack height depends on not only ΔH, but also the discharged pollutant amount (for example, the sulphur S^y contained in coal) and permitted maximum ground concentration C_m. A large number of tests have shown that the formulas without H_S will have serious drawbacks in practice. When the effluent amount is small (for example, S^y below 1%) or the permitted C_m is comparatively large (0.35—0.4 mg/m^3), the stack to be built, according to the equations, would be very low, even with a negative height. Otherwise, the stack would be very high, too conservative to be feasible under the current technological-economic conditions in China. On the contrary, the formulas involving H_S will be applied suitably in a much wider scope and able to avoid the occurrence of the above-mentioned extreme situations.

As to the dependence of rise height on H_S, Briggs (1969) suggested:

$$\Delta H \propto H_s^n, \ n=\frac{2}{3}.$$

This is a result obtained by pure empirical selection of a final rise distance based on the power law of "2/3". If the other conditions keep unchanged, doubling H_S will have ΔH increased by about 60%. It seems to be too strong a dependence.

The theoretical value n, in both Briggs' "break-up" model and the combined-effect model, is 1/3. Thus drawbacks caused by neglecting the effect of H_S will be overcome on the one hand, and the relation between ΔH and H_S not so strong as suggested by Briggs (1969) on the other.

3. *Average Wind Speed U*

Almost all the formulas are expressed in the form of $\Delta H \propto U^{-p}$ where value p can be 3/4, 1, 1.4, 2, 3, etc. (Briggs, 1969; Moses, 1972), but mostly $p=1$.

The relation $\Delta H \propto U^{-1}$ can be classically derived from the power law of "2/3", which takes into account only the diluting effect of wind speed, but neglects its influence on the termination distance and height of the final rise. According to that law, only ΔH in the same distance is inversely proportional to U, which has been validated by observed data at home and abroad (Briggs, 1969; Group of editors, 1985). All theoretical models considering the effect of U on the final rise can develop a relation much stronger than U^{-1}.

Value p the equations of Csanady (1973) and Bosanquet (1957) is equal or approximate to 3. Such a strong relation has never been validated and should not be explained entirely by the fact that final rise has never been observed. If take $u_* \propto U$, the Briggs' "break-up" equation gives $p=2$, which is closer to the observed events than in $p=3$. The value p in the combined-effect model is listed in Table 3.

Table 3. The Value p in the Combined-Effect Model

i	0	0.05	0.10	0.15	0.20
p	2	1.82	1.67	1.54	1.43

It can be found that due to the effect of ambient turbulence, the dependence of final rise on wind speed grows weaker. Compared with the power law of "2/3", the plume trail described by the combined-effect model is deflected downward, i.e., the height at the same distance is lower. This makes the effect of wind speed on final rise weakened relatively.

Though the above-mentioned value p is quite different from each other, the fundamental conclusion is the same: The dependence of final rise on wind speed should obviously be stronger than that shown by a diluting model ($\Delta H \propto U^{-1}$).

Some observed results are shown in Fig.1. In this figure, values of p in two data sets obtained at Xuzhou Power Plant are 1.46 and 1.30, respectively, while that obtained by lidar (Weil, 1970) is 1.98. At present, because of few precisely determined final rise data sets, no accurate experimental value of p can be achieved.

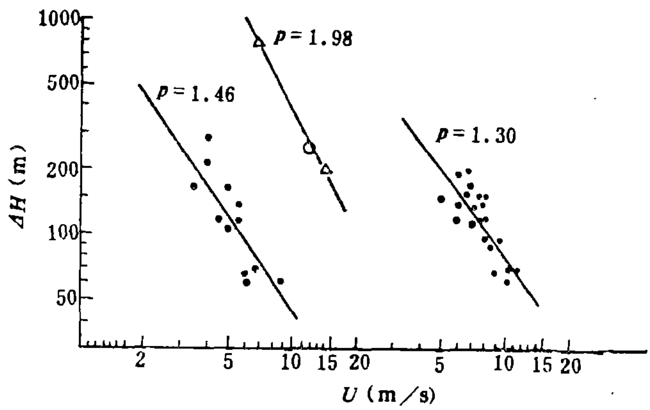

Fig. 1. Some observed results of value p.

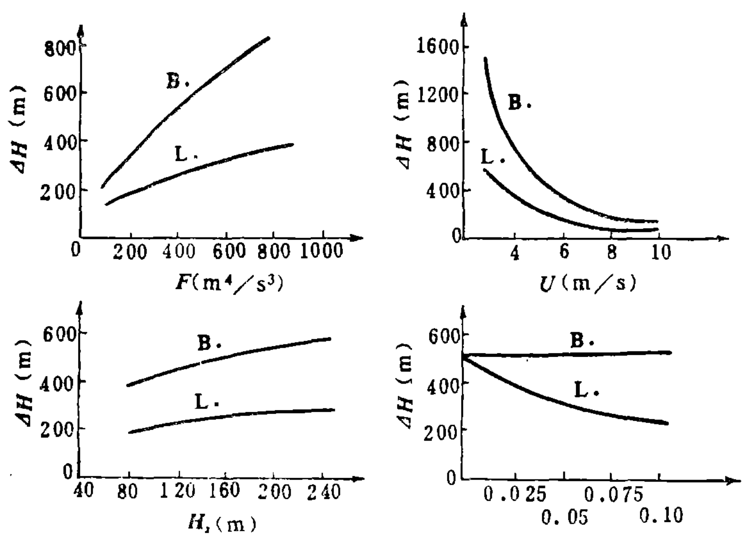

Fig. 2. Comparison between the calculated examples of Eqs. (6) and (9).
L represents the combined-effect model, and B the Briggs' model.

From the above analysis, the height factor introduced by Briggs' "break-up" model has made progress in theory. However, only when the accumulated effect of ambient turbulence is considered, would the values of m and p be more reasonable, and closer to the analysis of their reaction mechanism and observed results. Fig. 2 is a comparison between the calculated examples of Eqs. (6) and (9). The calculating prameters adopted are $F=400$ m^4/s^3, $H_S=180$ m, $U=5$ m/s, $i=0.10$ and $U/u_*=12$.

Obviously, because the accumulated effect of the ambient turbulence is accounted for. the calculated value of Eq. (6) is lower than that of Eq. (9), the curve slope is gentle and no extremely high values appear (that U is small and the buoyant bent-over condition is not satisfied is out of discussion). Eq. (9) is a particular case of Eq. (6) when $i=0$.

IV. COMPARING WITH THE OBSERVED RESULTS

In applying Eqs. (6) and (9), the method to determine u_* and i should be given. Under the conditions of neutral stratification and homogeneous underlying surface, there is no apparent difference between the wind profile defined by the logarithmic law and that observed at tower layer. Briggs has confirmed that this, just the same as Eq. (3), can be applied approximately to higher level and gives the ratio of U to u_* at various heights under the conditions of various roughness Z_0 and typical underlying surfaces.

When u_* is given, it is not difficult to determine the turbulence intensity in principle. At the major stage of buoyant rising, the atmospheric turbulence of low frequency, mainly the horizontal component with a size remarkably larger than the characteristic one of plume, has a rather little effect on the entrainment process. Thus for a neutral stratification and homogeneous underlying surface, the following conventional approximate expression can be adopted:

$$i=c\frac{u_*}{U}. \tag{10}$$

The constant c has been measured and given by Monin and Yaglom (1971) and other researchers.

The plume rise data at 16 coal-fired power stations (Briggs, 1969) can be used to check Eqs. (6) and (9) in the degree of comformity to the actual case. The stack heights of these plants range between 61 and 180m, the plume rise during the experimental peorid, mostly between 150 and 300 m, and the surface roughness between 0.3 and 1.0m. Based upon these conditions and the above-mentioned method to determine u_* and i, we provide slightly conservative estimates by letting $U/u_*=14$, $i=0.1$ and substituting them into Eqs. (6) and (9).

Comparisons of the calculations with the observations are shown in Fig.3 and Table 4. 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 non-normal are ommitted, so the data selected are of 17 groups. Table 4 shows the calculated results of plume rise equations suggested by the national standard GB 3840-83 to suit urban and rural areas.

Both Fig. 3 and Table 4 indicate that the combined-effect model is the superior. The data calculated by Eq. (6) being 10% lower is entirely due to the fact that parameters chosen are slightly conservative, while in the same case, those obtained from Eq. (9) are 70% higher. We should point out that the calculated values by the National Emission Standard equations

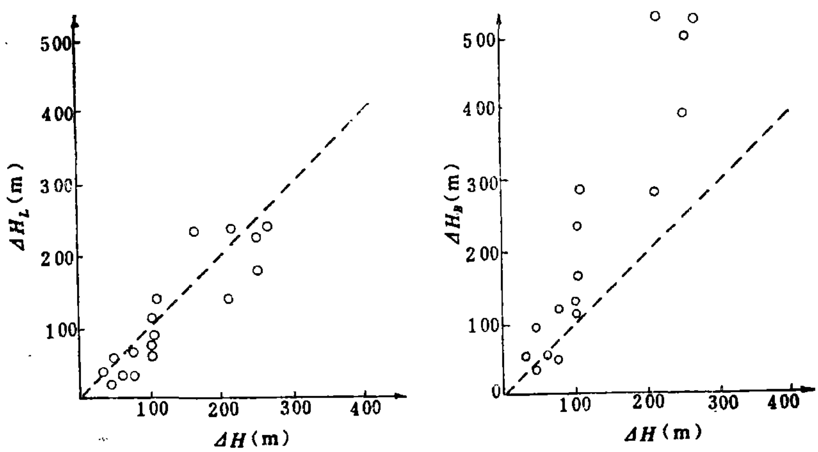

Fig. 3. Comparisons between calculated results of Eqs. (6) and (9) with observations.

Table 4. Comparison between Calculated Plume Rise with Observations

Data Used	Equation	$\bar{K}$	σ_k	r
Entire	L	0.952	0.449	0.72
	B	2.00	1.23	0.66
	NESu	1.18	0.401	0.81
	NESr	1.29	0.439	0.81
Chosen	L	0.872	0.272	0.90
	B	1.74	0.683	0.88
	NESu	1.16	0.355	0.92
	NESr	1.27	0.389	0.92

L: Combined-effect model; B: Break-up model;
NESu and NESr: National Emission Standard equations for urban and rural areas;
$\bar{K}$: averaged ratio of calculated plume rise to observations;
σ_K: standard deviation of ratio; r: correlation coefficient.

being only 15—30% higher and σ_K and r being also good enough, are related to the fact that in the information chosen by Table 4, the stack heights are relatively low, mostly lower than 130 m. The stacks, however, in the coal-fired power plants of medium size or more newly built in China are generally higher than 180 m. The dependence of plume rise on the stack height in National Emission Standard equations is very strong. If the stack height takes 180 m, the calculated values in Table 4 would increase further by 25% on the original higher basis. Therefore, the plume rise calculations for tall stacks may not be very safe.

In China, only at Xuzhou Power Plant a large number of measurements of plume rise have been systematically carried out. A photograph of an average plume trajectory is taken once a minute, samping with a 20 min. Using 33 groups of data under neutral conditions, we have checked Eqs. (6) and (9) in which u_* and i chosen are the same as Table 4. The checking-up results are listed in Table 5.

Table 5. Comparison between Calculated Plume Rise with Observations at Xuzhou

Equations	$\bar{K}$	σ_k	r
L	1.05	0.227	0.77
B	2.23	0.563	0.71
NESu	1.61	0.409	0.76
NESr	1.76	0.448	0.76

Xuzhou Power Plant has a stack 180 m high. There is a hill around 100 m high to the north about 1 km away from the plant, and the terrain rises gradually farther away. During the experimental period, the hill is in upstream of the prevailing wind; and the turbulence is stronger than that over the plain. According to the combined-effect model, the rise height should be lower than that over the plain. The value $\bar{K}$ in Table 5 is obviously higher than that in Table 4. This accords with theoretical inference. Because Xuzhou Power Plant is located on the verge of hilly region and has a tall stack, the value $\bar{K}$ in the National Emission Standard equations tents to be apparently larger. That equation is stipulated to be applied in plains.

V. CONCLUSIONS

(1) The affecting factors included in most existing plume rise formulas are incomplete and their functional relations are incorrect.

(2) Under the conditions of neutral stratification and homogeneous underlying surface, the major factors to determine the bent-over buoyant plume rise are the buoyant flux of plume source, average wind speed, plume source height and the ambient turbulence parameter.

(3) Briggs has introduced an important factor, the plume source height, into the rise formulas. This is an important progress in theory. However, because the accumulated effect of ambient turbulence is not considered, the model provides higher estimates.

(4) The final rise formula derived from the combined-effect model has the factors included completely. Moreover, the weighted importance attached by various factors and their quantitative relations with the rise height, get all it to be more reasonable. On considering the accumulated effect of ambient turbulence, and overcoming deficiencies of overpredicting the plume rise by some final rise theoretical formulas, it accords with the actual facts more closely. Based upon the various types of surface and boundary layer conditions, we can also determine the calculating parameters to obtain a practical equation suitable to various typical conditions. Such equation can not be obtained by means of conventional plume rise formulas.

(5) Viewing the strong thermal plume sources in medium and small cities and large city suburban areas or rural villages located in plain and getting calculating parameters slightly conservative, we obtain a practical equation derived from the combined-effect model:

$$\Delta H = (25\sim 32)\left(\frac{F}{U^3}\right)^{0.556} H_S^{0.333}, \qquad (11)$$

where the coefficients in parenthesis should be determined by the method suggested in Section IV according to the values of H_S and Z_0 etc.

The buoyant plume rise is very important to the correct calculation of ground concentration and is rather complicated, however. To consider the accumulated effect of ambient turbulence is the important progress in theory. Further analysis of the reaction mechanism demands the atmospheric turbulence and the plume trajectory information observed synchronistically at the plume height. This theory, however, is just put forward by Chinese investigators in the 1980s. The lack of synchronistic observations of atmospheric turbulence in the past experiments greatly limits further research. We hope the subject will have new development on the basis of well-designed experiments in the future.

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