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AN IMPROVED METHOD FOR THE IDENTIFICATION OF AN UNDECLARED TRANSBOUNDARY EMISSION SOURCE

An improved model has been proposed for identifying a transboundary undeclared emission source. In this model, the sampling strategy consists in a simultaneous control of pollutants (of different chemical nature) from an inner-boundary (known) source and a transboundary (unknown) source. The merit of the present development in source identification lies in the consideration of a continuum atmospheric stability with the dispersion parameters, depending on the meteorological conditions as well as specific nature of the terrain. The theoretical analysis is based on the applicability of the Gaussian Plume model describing the dispersion of a pollutant from a known source.

1. INTRODUCTION

The Gaussian Plume Model (GPM) is readily accepted as the pollutant dispersion model and has been cited by various textbooks [1]–[4]. TURNER [5] estimated the values of the model parameters (the dispersion parameters) for different meteorological conditions. Accepting the validity of the GPM, concentration data can be generated for a known emission source. When the source is unknown, however, most of the parameters of the GPM remain unknown, and the reverse problem (i.e., the concentration being known, the location of the source to be determined) could not be solved. In our previous works [6], [7], we developed a method for locating an unknown/undeclared point emission source. The method offers the possibility of identifying transboundary emission sources. It seemed to us that the model could be more precise and improved. To that end, in this paper, the probable error sources in the determination of the coordinates of an undeclared transboundary emission source have been identified. It seems that a serious error might appear as a result of considering inaccurate atmospheric stability classes. This is not simply a subjective error of the experimenter, rather an inevitable

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error due to division of the atmospheric stability into six discrete classes only. In reality, the atmospheric stability is a continuum. Error appears also due to the acceptance of the literature data of dispersion parameters as equally valid for all terrains. In the present work, a new sampling strategy is developed, in which the consideration of discrete atmospheric stability has been avoided and uncertainty in the value of dispersion parameter has been minimized. This is achieved by simultaneous control of pollutants from a known and an unknown source. The pollutants from the unknown and known sources are chosen to be different in chemical nature. Pollutant dispersion data from the known sources are used to estimate the dispersion parameters on the spot, and these parameters are used to find the location of the unknown source. Basic assumption in the development of the method is the same as that in the previous works [6], [7], i.e., the method is based on the assumption that the GPM fully describes the dispersion of pollutants in the atmospheric air. The basic criterion for the selection of the sampling sites also remains the same as that in the previous works, i.e., the sampling sites are chosen in such a way that the straight line joining them is perpendicular to the wind direction.

The merits of the present development in the identification method lie in the consideration of a continuum atmospheric stability with the dispersion parameters, depending both on the atmospheric conditions and specific nature of the terrain. The present development of the method requires a single simultaneous time control of pollutant from the known and unknown sources at two pairs (minimum numbers) of sampling stations; each pair lying on the straight lines parallel to each other and perpendicular to the wind direction. The theoretical analysis recommends that (1) the GPM is to be validated first, i.e., fitted to concentration data (emitted from a known source) and the dispersion parameters estimated, and (2) then these fitted values of the dispersion parameters are to be used to fit the experimental pollutant concentration data (emitted from an unknown source) to the GPM and the coordinates of the unknown emission source determined. Estimation of the dispersion parameters on the spot would provide much better results in source identification.

2. BASIC EQUATIONS FOR GPM

The concentration of a pollutant at a given point due to emission from a source may be estimated by GPM. The model describes the dispersion process under steady state conditions of emission. In this model, the origin of a mobile reference system xyz is fixed to the emission source E, and the x-axis always coincides with the wind direction. The pollutant concentration C at any sampling site S (x, y, z) is calculated by the following relations [1]–[4]:

$$C = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left[\exp \frac{-(z-H)^2}{2\sigma_z^2} + \exp \frac{-(z+H)^2}{2\sigma_z^2} \right] \tag{1}$$

with

$$\sigma_y = a\left(\frac{x}{1000}\right)^b \ , \tag{2a}$$

$$\sigma_z = c\left(\frac{x}{1000}\right)^d + f \ , \tag{2b}$$

where C is the concentration of the pollutant, g/m^3; Q is the strength of the emission source (the mass of pollutant emitted per unit time), g/s; u is the wind speed, m/s; y is the distance of the sampling site from the central line x, m; H is the effective stack height, m; σ_y and σ_z are the standard deviations in the horizontal and vertical directions, m; the indices a, c, d and f are functions of the downwind positions x as well as atmospheric stability conditions. The value of b is taken to be 0.894 (WARK and WARNER [3]).

The value for the effective stack height H (m) is the sum of the physical stack height h (m) and the plume rise ΔH (m):

$$H = h + \Delta H. \tag{3a}$$

ΔH is calculated from the following formula [8]:

$$\Delta H = \frac{v_s d_s}{u}\left\{1.5 + \left[2.68\times 10^{-5} P\left(\frac{T_s - T_a}{T_s}\right) d_s\right]\right\}, \tag{3b}$$

where v_s is the stack velocity, m/s; d_s is the stack diameter, m; P is the atmospheric pressure, Pa; T_s is the stack temperature, K; and T_a is the air temperature, K.

When the emission source is known, all the parameters required in equations (1)–(3) are known, and the pollutant concentration C may be computed, otherwise most of the parameters in these equations remain unknown and by measuring the pollutant concentration at a sampling station the location of a source could not be determined from the above relations.

3. BASIC EQUATIONS PROPOSED IN THE PREVIOUS WORKS

In our previous works [6], [7], we developed a model in which considering the validity of GPM the location of a source could be determined. We introduced a fixed reference frame $\eta\xi$. The co-ordinates of the emission source E and the sampling site S_i with respect to the fixed reference frame $\eta\xi$ were denoted by (α, β) and (η_i, ξ_i), respectively. If θ were the inclination of the wind direction to a negative direction of the ξ-axis, the following relations held true (for details see ISLAM [6]; ISLAM and ROY [7]):

$$\alpha = \eta_i - y_i \cos\theta + x_i \sin\theta, \tag{4a}$$

$$\beta = \xi_i + y_i \sin\theta + x_i \cos\theta. \tag{4b}$$

It is obvious from equations (4a) and (4b) that if x_i and y_i are known somehow, the location of the emission source (α, β) can be determined.

If the sampling were performed at two sites simultaneously, the ratio of the concentrations would be the function of only downwind positions and atmospheric stability conditions, and would not depend on Q. Moreover, if a pair of sampling sites S_i (x_i, y_i, z_i) and S_i' (x_i', y_i', z_i') satisfied the conditions

$$x_i = x_i' = x \quad \text{and} \quad z_i = z_i' = z\,, \tag{5}$$

then – following equations (1), (2a) and (2b) – the ratio of the respective concentrations C_i'/C_i was given by

$$\frac{C_i'}{C_i} = \exp\left[- \frac{(y_i'^2 - y_i^2)}{2\sigma_y^2} \right]. \tag{6}$$

If the line joining the sampling stations with the same height ($z_i = z_i'$) were situated perpendicularly to the wind direction, the pair of sampling sites would satisfy the condition $x_i = x_i'$.

Let $r = y_i - y_i'$ denotes the distance between the sampling sites S_i and S_i'. Then by simple algebraic manipulation we have from equation (6)

$$y_i = \frac{r^2 + 2\,\sigma_{yi}^2 \ln\left(\dfrac{C_i'}{C_i}\right)}{2r}\,. \tag{7}$$

Combining equations (7) and (2a), we arrive at

$$y_i = \frac{r^2 + 2\,(a\,x^b)^2 \ln\left(\dfrac{C_i'}{C_i}\right)}{2r}\,. \tag{8}$$

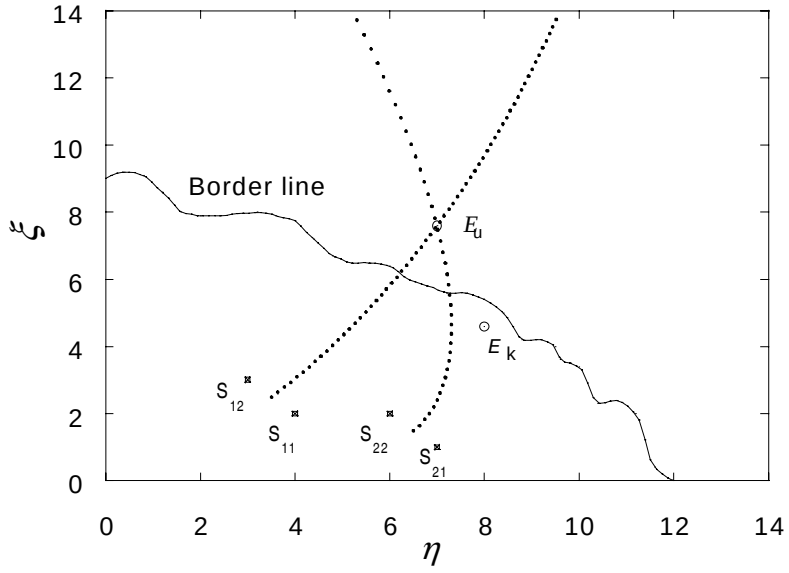
Although the emission source (α, β) was unknown, for a given couple of sampling sites satisfying condition (5), the values of r and C_i'/C_i were known. In our previous model [6], [7], it was assumed that the value of a was the same as those reported by MARTIN [9] and TURNER [5]. The value of b was also accepted to be always constant at 0.894 as done by DAVIS and CORNWELL [1]. Under these circumstances, we found a functional relationship between x and y. For any value assigned to x_i, we had a defi-

nite value of y_i. Thus for a given wind direction θ, we had a sequence $<x_i, y_i>$ for which the ratio of the pollutant concentration would be C_i'/C_i. Inserting the values of any set of the sequence $<x_i, y_i>$ in equations (4a, b), we obtained the sequence $<\alpha_i, \beta_i>$ from which an equipotential emission source curve could be drawn. For a given wind direction and atmospheric stability class, the unknown emission source lying at any point of this curve could cause the same concentration ratio as C_i'/C_i for the sampling sites S_i and S_i'. For different wind directions, a similar procedure could be applied in order to obtain different equipotential curves representing emission source. The point of the intersection of these curves gave the location of the emission source $E(\alpha, \beta)$.

Error sources of the previous method. The previous method would seem very precise as long as we deal with ideal data. But if we want to solve real problems by means of the present model, we have to face all the limitations of GPM. The main sources of errors are as follows: variation in the emission rate Q, deviation of the meteorological conditions from the steady state, identification of stability class, and errors in measurement of experimental parameters, e.g., concentration and wind direction. Error due to variation in the emission rate Q is to some extent minimized as the concentration ratio (C_i'/C_i) is used as the input parameter. Errors in the measurement of experimental parameters such as concentration and wind direction could also be minimized by using precise methods and equipments. However, errors in the identification of atmospheric stability class, which will result in the acceptance of erroneous dispersion parameters, would certainly cause serious error in the source-identification method. Such an error is inevitable due to the application of discrete atmospheric stability classes. Error appears also due to the acceptance of the literature data of dispersion parameters as equally valid for all terrains.

4. IMPROVED VERSION OF THE PREVIOUS MODEL

As discussed in the previous section that considerably erroneous result may evolve due to erratic consideration of the atmospheric stability classes, such an error is inevitable. To overcome this error, GPM should be validated first of all by appropriate field data (emission from known sources), and the dispersion parameters a and b for the prevailing meteorological conditions and terrain should be determined, and this should be done simultaneously with the collection of experimental data allowing the unknown source to be identified. Such a method would eliminate the necessity of identifying the atmospheric stability classes and would minimize the error introduced due to the terrain effect. The values of a and b thus obtained will be in conformity with the continuous nature of the atmospheric stability classes and take account of specific terrain effect.



Organization of data collection for the present method. E_u is the unknown transboundary emission source, E_k is the known source, and (S_{11}, S_{12}) and (S_{21}, S_{22}) are two pairs of sampling stations, each pair of which individually satisfies the condition expressed by equation (5)

The organization of data collection for the present method may be illustrated by the figure. The unknown source E_u (in fact, its location is unknown) is outside the borderline. There is a known emission source E_k inside the borderline. The two sources are emitting different pollutants. There are two pairs of sampling stations denoted by S_{11}, S_{12} and S_{21}, S_{22}, respectively, where the concentration of the pollutants from both the sources is monitored. Each pair of the sampling stations individually satisfies the condition expressed by equation (5), i.e., the line joining the sampling stations S_{11} and S_{12}, and also S_{21} and S_{22} are individually perpendicular to the wind direction. Also these two pairs do not lie on a single line. Let the distances between the sampling stations in these pairs be r_1 and r_2, respectively. The values of the corresponding horizontal and vertical distances of the sampling stations S_{11} and S_{21} from the known source E_k at a given wind direction are x_{11}, y_{11}, x_{21} and y_{21} (which are also known). Now if the concentrations of the pollutant emitted from the known source measured at different sampling stations are C_{11}, C_{12}, C_{21} and C_{22}, then rewriting equation (8) for the present case we obtain:

$$y_{11} = \frac{r_1^2 + 2\,(a\,x_{11}^b)^2\,\ln\left(\dfrac{C_{12}}{C_{11}}\right)}{2r_1}\,, \tag{9a}$$

$$y_{21} = \frac{r_2^2 + 2\,(a\,x_{21}^b)^2\,\ln\left(\dfrac{C_{22}}{C_{21}}\right)}{2r_2}\ . \tag{9b}$$

Now solving equations (9a, b) for a and b, we have

$$a = \exp\frac{\left[\ln x_{21}.\ln\dfrac{2r_1y_{11} - r_1^2}{2\ln\left(\dfrac{C_{12}}{C_{11}}\right)} - \ln x_{11}.\ln\dfrac{2r_2y_{21} - r_2^2}{2\ln\left(\dfrac{C_{22}}{C_{21}}\right)}\right]}{\ln\left(\dfrac{x_{21}}{x_{11}}\right)^2}, \tag{10a}$$

$$b = \frac{1}{2}\ln\frac{\left[\dfrac{2r_1y_{11} - r_1^2}{2r_2y_{21} - r_2^2}.\dfrac{\ln\left(\dfrac{C_{22}}{C_{21}}\right)}{\ln\left(\dfrac{C_{12}}{C_{11}}\right)}\right]}{\ln\left(\dfrac{x_{11}}{x_{21}}\right)}. \tag{10b}$$

The values of the dispersion parameters a and b so estimated correspond to the prevailing atmospheric stability classes and also, to some extent, account for the specific nature of the terrain. Since the concentrations of the pollutant emitted from the transboundary emission source are measured simultaneously at the same sampling stations, these values of a and b could be used to locate the unknown source as described in section 3 of the present paper (for details about the method, the readers are referred to ISLAM and ROY, [7]). Note that errors in the measurements of concentration and wind direction as well as variation in emission rate have been integrated and appeared as the error in the estimated values of a and b. Thus, if n pairs of sampling stations are considered and the data are treated by the improved method, as many as $n\,(n-1)/2$ sets of (a, b) will be obtained showing the variations in the estimated values of a and b; each set being valid for the corresponding couple of pairs. The equipotential emission source curves would not intersect at a point; rather would intersect at different points in a zone. The searched point source would lie in that zone.

The major drawback of the new model is that it is not validated by field data. In fact, the validity of the model is similar to that of the GPM, which proves correct in the field. The sampling strategy and the analyzing method developed in the present model make it, however, more suitable for the concentration data than the GPM itself.

5. CONCLUSIONS

1. An improved model has been constructed for identifying a transboundary undeclared emission source.

2. A new simple method is developed to determine the pollutant dispersion parameters on the spot. The parameters determined by this method account for the prevailing meteorological conditions and terrain effects.

3. This method eliminates the confusion arising from the recognition of atmospheric stability classes.

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UDOSKONALONA METODA IDENTYFIKACJI BLIŻEJ NIEROZPOZNANEGO TRANSGRANICZNEGO ŹRÓDŁA EMISJI

Przedstawiono udoskonaloną wersję modelu służącego do identyfikacji bliżej nierozpoznanego transgranicznego źródła emisji. Istotną zaletą tej wersji modelu jest rozpoznanie źródła emisji w zmiennych warunkach równowagi atmosfery z parametrami dyspersji zależnymi zarówno od warunków meteorologicznych, jak i od ukształtowania terenu. Podstawą teoretycznej analizy jest model Gaussowski opisujący dyspersję zanieczyszczeń ze znanego źródła emisji.