A Multiple Point Sources Model for Dispersion of Air Pollutants

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Abstract

The aim of this paper is construction a mathematical model in computer program. The model includes modeling of air pollution from multiple point (stacks) sources as a method for estimating short –term dispersion of pollutants using the Gaussian steady – state equation. This analytical model can be used for estimating air quality ground level concentrations (GLCs) of relatively stable pollutants for averaging time one hour in urban areas. Two systems of PGT (Pasquill-Gifford-Turner) equations and ASME (American Society for Mechanical Engineers) equations are used in the model for estimating the dispersion coefficients. Also, Briggs equations are applied for estimating the plume rise.

In spite of the basic simplicity of the plume concept, the superposition of the concentrations of many plumes from multiple point sources in an urban situation, and for a wide variety of meteorological and plume dispersion conditions, leads to complexities, which are taken into consideration in detail at the stage of model development. It therefore seems desirable to state the formal structure as unambiguously as possible.

The model was examined for checking its validity to predict the GLCs of gaseous pollutants emitted from a multiple point source of industrial activities. The predicted concentrations were in good agreement with the measured concentrations especially when ASME equations are used for estimating dispersion coefficients.

الخلاصة

يهدف البحث الى بناء نموذج رياضي على الحاسوب. يتضمن هذا النموذج نمذجة تلوث الهواء من مصادر نقطية (مداخن) متعددة ، كطريقة لتخمين انتشار الملوثات ضمن مدى قصير باستخدام معادلة كاوس للحالة المستقرة. ان هذا النموذج التحليلي من الممكن استخدامه لتخمين او حساب التراكيز الارضية لنوعية الهواء للملوثات التي تكون مستقرة نسبياً ولمعدل زمني ساعة واحدة في المناطق الحضرية. وتم استخدام نظامين لحساب معاملات الانتشار في النموذج هما نظام PGT (باسكيل–جيفورد – ترنر) ، (Pasquill-Gifford–Turner) ونظام ASME (الجمعية الامريكية للمهندسين الميكانيكيين) ، (American Society for Mechanical Engineers)، كذلك استخدمت معادلات Briggs لحساب ارتفاع الدخان الخارج من المصادر النقطية.

بالرغم من بساطة مفهوم الدخان الخارج من المدخنة او المصدر النقطي ، فأن تركيب (جمع) التراكيز للدخان الخارج من مداخن او مصادر نقطية عديدة في المناطق الحضرية وللتنوع الواسع في الانواء الجوية وظروف انتشار الدخان ، يقود الى تعقيدات تم اخذها بنظر الاعتبار وبشكل مفصل في مرحلة تطوير النموذج. لذلك السبب يظهر وبشكل مرغوب فيه ان يكون النموذج مثالي غير مبهم قدر الامكان.

لقد تم فحص النموذج للتأكد من مدى صلاحيته لتخمين التراكيز الارضية للملوثات الغازية المنبعثة من مصادر نقطية متعددة لنشاطات صناعية. ان التراكيز التي تم ايجادها باستخدام النموذج كانت في توافق جيد مع تلك التراكيز المقاسة وخاصة عند استخدام معادلات الـ ASME لحساب معاملات الانتشار.

Introduction

There has been increasing interest in recent years in the policy and practice of air pollution control. Topics such as emission standards, air quality guidelines, environmental impact statement and publication of information are the subjects of debate, investigation and legislation in many countries. In parallel with this public, scientific and political interest, a number of studies have been made involving the use of dispersion models (Comer et al. 1983).

The quantification of atmospheric effects has been placed in a framework called dispersion modeling or air quality simulation modeling. Inputs to a model require meteorological data and emissions. Initial conditions of two or three dimensional pollutant concentration distributions are needed by some models. Model output consists of estimated pollutant concentrations. These may be for various time periods and may be point estimates or a spatial average (Turner 1979).

Multiple source plume (particularly Gaussian –plume) models are commonly used for mathematical modeling of concentrations of inert pollutants over urban areas. Although there are many special purpose computational algorithms currently in use, the basic element that is common to most is the simple plume from a single point source release. The spatial distribution of pollution in such a plume is the underlying model component from a physical –meteorological point of view, and the multiple source air quality simulation model is then developed by simple superposition of the individual plumes from all the emissions. The latter are then in practice idealized as being either large elevated single point sources or continuous horizontal area –source distributions of emissions, perhaps at several different heights above ground level. Hourly meteorological data required are wind speed, wind direction angle, stability class, and ambient temperature. Information of emission required of point sources consists of emission rate, stack height, exit gas velocity, and exit gas temperature. Also, the distances from point source to receptor in geographic coordinates are input by the user (Calder 1977, Sulaymon and Al-Rubaye'e 2001).

The Programmed Model

Input Requires:

The input data required for estimating the ground level concentration (GLC) are stored in four files, these are:

1- The hourly meteorological data which are wind speed (u), wind direction angle (ψ), ambient temperature (Ta), and stability class.
2- The physical stack parameters of each point source which are exit gas velocity (Vs_i), stack diameter (D_i), stack temperature (Ts_i), and stack height (hs_i).
3- The emission rate of pollutant of each point source (Q_i).
4- The distances in geographic coordinates (xg_i and yg_i) between each point source and the receptor.

Basic Principles for Calculating GLC:

The following assumptions are made:

- Dispersion from points results in Gaussian distribution in both the horizontal and vertical directions through the dispersing plume; therefore steady state Gaussian plume equation can be used.
- The estimating of concentration may be made for each hourly period using the mean meteorological conditions appropriate for each hour.
- Total concentration at the receptor is the total of the concentrations estimated from all point sources.

Using of the Programmed Model for Computations of GLC:

The computer program can be loaded and running on a Pentium computer (RAM – 16MB). To run the program, each file calls by its name (name of file which the data are stored). Each run will calculate the hourly GLC for one pollutant at one site at different meteorological conditions. The program steps are:

Wind speed at stack height:

In meteorological stations, the wind speed is measured at 10 m height, therefore the wind speed at stack height is calculated for each stack (ith point source) using Equation 1 (Smith and Frankenberg 1975, Perkins 1974) and the values of n =

0.25 for unstable and n = 0.5 for stable atmospheric conditions. For neutral conditions, the wind speed is the average of the two wind speeds at unstable and stable conditions.

$$\frac{u}{u_i} = \left(\frac{z}{z_i}\right)^n \qquad (1)$$

Dispersion coefficients:

The PGT (Pasquill-Gifford- Turner) Equations , Eqs. 2 and 3 (Green 1980, Rao 1994), are applied to calculate the dispersion coefficients σ_y and σ_z for each point source plume .

$$\sigma_{y_i}(x_i) = \frac{k_4\, x_i}{\left[1 + (x_i / k_1)^{k_5}\right]} \qquad (2)$$

$$\sigma_{z_i}(x_i) = \frac{k_2\, x_i}{\left[1 + (x_i / k_1)^{k_3}\right]} \qquad (3)$$

Also, the ASME (American Society for Mechanical Engineers) Equations, Eqs. 4 and 5, are used in the programmed model to calculate σ_y and σ_z (Sufan 1990).

$$\sigma_{y_i}(x_i) = A x_i^{\,p} \qquad (4)$$

$$\sigma_{z_i}(x_i) = B x_i^{\,p} \qquad (5)$$

According to Dobbins (1979), the downwind and crosswind distances x_i and y_i for the *i*th point source are determined using Equations 6 and 7.

$$x_i = x_{gi} \sin\psi + y_{gi} \cos\psi \qquad (6)$$

$$y_i = -x_{gi} \cos\psi + y_{gi} \sin\psi \qquad (7)$$

In these equations x_i and y_i are function of distances in geographic coordinates (xg_i , yg_i), and wind direction angle ψ (Figure 1). The distances xg_i and yg_i represents the distances between the *i*th point source and the receptor.

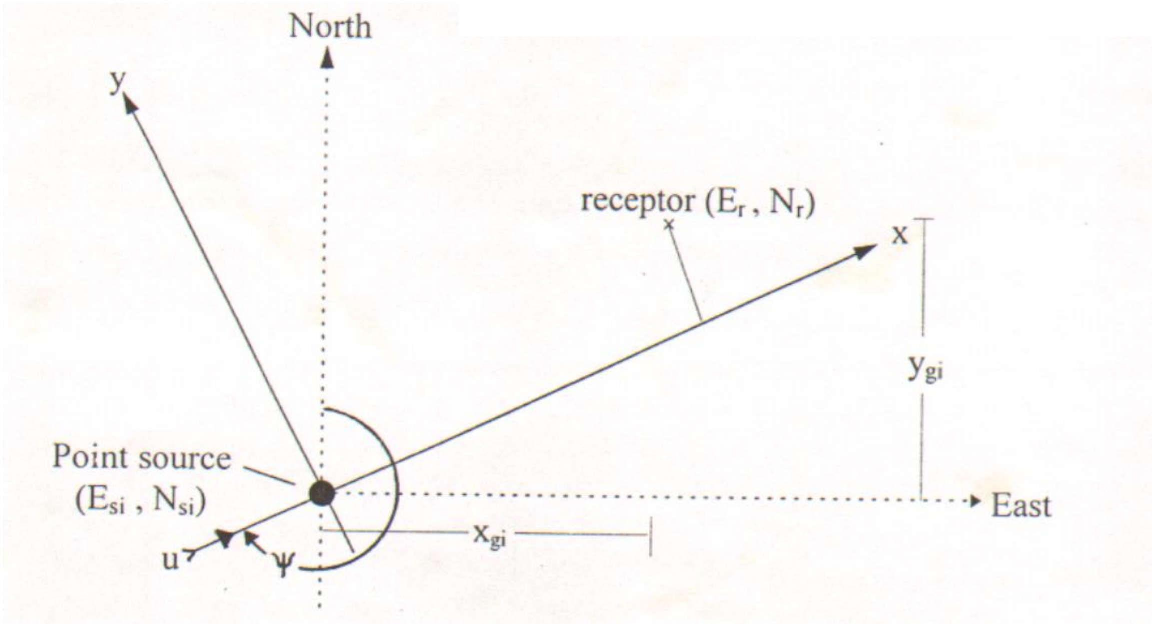

Figure (1): The dispersion from a point source in geographic coordinates. The locations at the *i*th source (Es_i , Ns_i) and the receptor are arbitrary.

The effective height:

The effective height (H_i) is the sum of physical stack (point source) height (hs_i) and plume rise (Δh_i). The physical stack height is given in the file of input physical stack parameters as mentioned above. The plume rise is calculated by using Briggs (1975) formula, Equations 8 and 9 (Zannetti 1989, Strom 1976).

$a)\ for\, x_i \le x^*$

$$\Delta h_i(x_i) = k\, F_{bi}^{\ 1/3}\, u_i^{-1}\, x_i^{\ 2/3} \tag{8}$$

$b)\ for\, x_i \succ x^*$

$$\Delta h_i(x_i) = 1.6\, F_{bi}^{\ 1/3}\, u_i^{-1}\, x_i^{*2/3} \left[\frac{2}{5} + \frac{16}{25}\frac{x_i}{x^*} + \frac{11}{5}\left(\frac{x_i}{x^*}\right)^2\right]\left[1 + \frac{4}{5}\frac{x_i}{x^*}\right]^{-2} \tag{9}$$

$$x^* = 2.16 F_{b_i}^{\ 2/5}\, hs_i^{\ 3/5} \qquad for\ hs_i \prec 305\, m \tag{10}$$

$$x^* = 67 F_{b_i}^{\ 2/5} \qquad for\ hs_i \ge 305\, m \tag{11}$$

Among the various schemes, the Briggs (1975) formula is the most widely applied. Also the reasons for selection this formula are:

- The formula recommended by Briggs for determination the plume rise from several adjacent stacks (multiple point sources).
- Sensitivity of formula to effluent and ambient temperature difference.
- The downwind distance is taken into consideration.
- Applicability of formula to all meteorological conditions.

Computations of GLC:

Dobbins (1979) reported that the concentration at a location of interest, designated as a receptor, down wind of a number of sources whose coordinates are given in a geographic coordinate system can be found from the solutions of Gaussian equation.

The GLC of gaseous pollutant in μg/m^3 can be estimated by using Equation 12.

$$C(E_r, N_r, 0) = \frac{1}{\pi u_i} \sum_{i=1}^{N} \frac{Q_i}{\sigma_{yi}\sigma_{zi}} \exp\left[-\frac{y_i^{\,2}}{2\sigma_{yi}^{\,2}} - \frac{H_i^{\,2}}{2\sigma_{zi}^{\,2}} \right] \tag{12}$$

The summation indicated in equation 12 should be extended over those sources which lie the upwind sector from which a significant contribution is received at the receptor. The hourly GLC at the receptor from each source is calculated, and the total hourly concentration is the sum of the concentrations from all sources.

Concentration estimates for various sampling times:

If the PGT profiles are used for estimating σ_{yi} and σ_{zi} , the calculated concentration from each source will represent 10 min average concentration (Calvert 1984, Rao 1994) and Equation 13 should be used to correct concentration predicted by the dispersion model to 1-hour average concentration.

$$C_2 = C_1 \left[\frac{t_1}{t_2} \right]^q \tag{13}$$

If the ASME profiles are used, the predicted concentration will represent 1- hour average concentration without using Equation 13.

Summary:

The analytical programmed Gaussian plume model applicable to urban areas for pollutants emitted from multiple point sources. Calculations are made for 1–hour time period. The multiple source air pollution models which have been most widely used are based upon an empirical representation of steady state plume downwind from single source. Such models treat all emission in region of interest as a group of a single point sources, and represent concentrations on the basis of the standard Gaussian plume formulation. The superposition capability of concentrations adds flexibility and is an important advantage of the Gaussian technique, an addition its inherent simplicity, ease of use and short computational times.

The two systems of PGT and ASME are used in the programmed model for estimating the dispersion coefficients, also the Briggs equations are applied for plume rise.

The programmed model was tested to predict the gaseous pollutants emitted from multiple point sources for an industrial activities. The predicted concentrations were in good agreement with the measured concentrations especially when the ASME profiles used for estimating σ_y and σ_z.

The present work is innovative technique of the multiple source programmed mathematical modeling, and represent the first and only attempt to predict the ground level concentrations of pollutants from a multiple point sources in Iraq.

Nomenclature:

u wind speed at altitude z (usually z = 10 m), m/sec.

u_i wind speed at altitude z_i (z_i is the height of *i*th point source), m/sec.

σ_{yi} horizontal (crosswind) dispersion coefficient of the *i*th point source (m).

σ_{zi} vertical dispersion coefficient of the *i*th point source (m).

x_i downwind distance from the *i*th point source to the receptor (m).

y_i crosswind distance from the *i*th point source to the receptor (m).

k_1, k_2, k_3, k_4, k_5 constants are given according to stability class.

A, B, P constants are given according to stability class.

x_{gi} , y_{gi} distances in geographic coordinates from the *i*th point source to the receptor.

Ψ wind direction angle, the angle measured clockwise from north to a ray pointing to the direction of origin of the wind (degree).

Δh_i plume rise of the *i*th point source (m).

k constant between 1.6 and 1.8 .

hs_i stack height (the ith point source height), m.

F_{bi} buoyancy flux of the ith point source = $g\ Vs_i\ r_{si}^2\ (Ts_i - Ta)/Ts_i$,m^4/sec^3.

g acceleration due to gravity , m/sec^2.

Vs_i stack gas velocity (velocity of the exit gas from the ith point source), m/sec.

r_{si} exit radius of stack (exit radius of the ith point source) , m.

Ts_i stack gas temperature (temperature of the exit gas from the ith point source), ^{o}k.

Ta ambient temperature, ^{o}k.

$C\ (E_r, N_r, 0)$ concentration of pollutant at a ground level receptor located at (E_r, N_r) owing

to the N point sources. Where E_r and N_r are east and north coordinates while

the subscript r for the receptor.

Q_i emission rate of pollutant by the ith point source located at (Es_i, Ns_i).

H_i effective height of release of the ith point source, $H_i = hs_i + \Delta h_i$.

C_2 required concentration for the time t_2 (t_2 = 1 hour).

C_1 concentration calculated by dispersion the model for shortest time t_1 (10 min).

q constant has a value between 0.17 and 0.20 .

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