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MATHEMATICAL MODEL FOR THE STUDY EFFECTS OF METEOROLOGICAL CONDITIONS ON DISPERSION OF POLLUTANTS IN AIR

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ABSTRACT:- The purpose of the present work was to investigate air quality that contained pollutant gases (SO_2 , NO_2 , CO) released from the thermal power plant as case study. Gaussian Plume Model and the computer program (visual basic 6) is used to calculate concentrations dispersion of gas pollutants at different meteorological conditions (wind speed, ambient temperature); maximum concentration values, downwind distance and required effective stack height estimation.

A typical theoretical investigation of a case study concerning existing air pollution problems at an industrial area (4Km) downwind distance by using the computer program. The results showed that the concentration of SO_2 (890 $\mu g/m^3$) released from stack may is higher than the EPA standard. Also the optimum point of the ground level concentration of pollutants decreases with increasing effective stack height.
Keywords: Dispersion model, Pollutant gases, Power plant.

INTRODUCTION

Contaminate gases, liquid and particulate matter discharges into the air are transported over along distance by large-scale air-flows and dispersed by small-scale air-flows or turbulence, which mix contaminates with clean air. This dispersion by the wind is a very complex process due to the presence of different sized eddies in atmospheric flow (1).

The major portion of the recognized air pollutants are gases such as carbon monoxide (CO), the oxides of nitrogen (NO_x), the oxides of sulfur (SO_2), unburned hydrocarbons and particulate matter (dusts, smokes, mists, aerosol). These pollutants are emitted by different sources, such as: transportation, electric power generation, refuses burning, industrial and domestic fuel burning) (2). Increasing air pollution levels due to rapid urbanization and growth in industrial emissions are now causes of major concern in many large cities of the world (3-6). When strategies to protect public health are under consideration, establishing ambient air quality standards and regulations have been introduced in order to set limits on the emissions of pollutant(7). To achieve these limits, consideration was given to mathematical and computer modeling of air pollution. Therefore, air quality models are indispensable tools for assessing the impact of air pollutants on human health and the urban environment (8).

The necessity for such models has increased tremendously especially with the rising interest in the early warning systems in order to have the opportunity to take emergent and preventive action to reduce pollutants when conditions that encourage high concentrations are predicted. On the other hand, long-term forecasting and controlling of air pollution are also needed in order to prevent the situation from becoming worse in the long run. Such forecasting is especially important to sensitive groups i.e. children, asthmatics, pregnant women and elderly people [9, 10].

Kim et al.[11] focused and discussed emission factor and sources profiles of air pollutants particulate matter, $PM_{2.5}$ and (CO, NO_x, CO_2) emitted from in-use diesel vehicles. Kim et al. [12], Gupta & Kumar [13] and Marieq [14] , showed diesel vehicles contribute significantly to the fine particulate and its chemical composition which they have important health, atmospheric and climate implications. Krewit et al.[15] investigated that the particulate (less than 2.5μm diameter) has one of the highest health risks attributable to electricity generation and it can be treated as a conserved species in outdoor air on the time scale of transport within 100Km.

Thermal power generation is the largest source of SO_2 and other gas pollutants in the city besides other industrial processes [16]. It is commonly understood that SO_2 reduces atmospheric visibility, damages various materials and agricultural crops and is detrimental to human health [16]. When SO_2 is oxidized and hydrolyzed it gives rise to acid rain. The quantitative estimation of the long-term average of SO_2, NO_2, CO and fly ash has been dealt with by many researchers [17-20].

Chih-Chung and Hui-Hsuan [21] investigated how atmospheric air pollutants (PM_{10}, SO_2, NO, CO) and meteorological conditions (wind speed) affect atmospheric turbidity.

The relation between the concentration of industrial pollutants SO_2 in the air in the vicinity of Bratislava and the degree of injury to local was studied by Navara and Kaleta [22] and from their results they concluded that vegetation visibility and is injured most seriously near the industrial complex of Bratislava, where the SO_2 concentration in the air reach annual average in the range 20-100μg/m^3 and SO_2 of 10-70μg/m^3 occurring in the region at the distance of 5-15Km from the pollution sources cause chronic damage to the vegetation.

In closed environments the concentration of CO can easily rise to total levels. On average, 170 people in the United State die every year from CO produced by non-automotive consumer products [23].

The energy produced from Iraqi stations (steam, gas, diesel, and hydraulic) comes from combustion of heavy oil, light oil and natural gas. The combustion process of fuel is accompanied by emission to the atmosphere of huge amounts of exhaust pollutant gases, with increasing rate annually corresponding to that of conventional electric energy produced. The energy produced from thermal power station is 54.9% of the average total energy produced monthly as shown in Fig.1[24] .

The aim of the present work is to use a mathematical model (Gaussian Plume Model) to evaluate ground-level concentration of emission gases pollutant from the thermal power plant in Baghdad. The effects of variations for meteorological parameters (ambient temperature, wind speed) and affecting stack height in the model that are expected to affect the gases pollutant dispersion in air were investigated.

AIR POLLUTANTS DISPERSION MODELING

Atmospheric dispersion is the mathematical modeling simulation of how air pollutants disperse in the ambient atmosphere. It is performed with computer programs that solve the mathematical equations and algorithms which simulate the pollutant dispersion. The models also serve to assist in the design of effective control strategies to reduce emission of harmful air pollutants [8, 25, and 26].

The trend in recent years has been to use more statistical models instead of traditional deterministic models [10]. The statistical models are based on semi-empirical relations among available data and measurement [8] to establish an empirical relationship between air pollutant concentrations and meteorological parameters. Petro et al., [25] studied dispersion SO_2 pollution in the city of Talcahuano-chile by applying three mathematical approaches:

descriptive statistical analysis, Fourier analysis and wave let analysis. Their results showed high SO_2 dispersion values, an annual average standard deviation of 63.5μg/m^3, fluctuating of the data due to seasonal and daily cyclical components. Also they demonstrate correlations between SO_2 concentration and several meteorological variables. Argyropoulos et al., [27] studied modeling the ground-level concentration of pollutants dispersion (SO_2, CO, smoke) of smoke plume rise from large hydrocarbon tank fire in neutrally stratified atmosphere. It is concluded, the ground-level concentration of smoke, SO_2, CO do not exceed the safety limit and there are no death zones due to pollutant concentrations.

A model widely used for estimating atmospheric concentrations of a chemical, downwind from a source, is the steady state Gaussian Plume Model. There are numerous research works that involve an estimating pollutant concentration downwind from multiple sources utilizing the steady state Gaussian Plume Model at different areas [1, 5, 16, 26, 27-30].

The basic equation for this model is as the following[31,32]:

$$\frac{dc}{dt} = K_{xx}\left(\frac{\partial^2 c}{\partial x^2}\right) + K_{yy}\left(\frac{\partial^2 c}{\partial\ y}\right) + K_{zz}\left(\frac{\partial^2 c}{\partial^2 z}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

which is known as Fikian diffusion equation.

To solve Eqn.(1) some assumptions and boundary condition[31-33] are used to get the following equation:

$$c = \frac{Q}{2\pi\sigma_Y\sigma_Z u}\exp\left(-\frac{y^2}{2\sigma_y{}^2}\right)\left\{\exp\left[-\frac{(Z-H)^2}{2\sigma^2{}_z}\right] + \exp\left[-\frac{(Z+H)^2}{2\sigma_z{}^2}\right]\right\} \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

which is called Gaussian Plume Model.

Two most important variable affecting the degree of pollutant emission dispersion obtained are the height of the emission source point and the degree of atmospheric turbulence. But at any downwind distance x, environmental pollution effect people, animals and plants are concentrated at height Z=8m above the ground [34].

The dispersion coefficients σ_y, σ_z were calculated as prescribed by Turner [35], depending on atmospheric stability class. Effective plume rise (H) at different distance from the source is calculated by Briggs [36] as shown in the following Equation:

$$H = H_S + \Delta H \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where H_s represents actual physical height of the pollutant plume's emission source point and ΔH plume rise due to the plumes buoyancy calculated as follows [32,33]:

$$\Delta H = \frac{1.6(F_b)^{1/3}(3.5x^*)^{2/3}}{u} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where $x^*=34\ F_b^{0.4}$ $\quad F_b \geq 55$
$x^*=14\ F_b^{0.625}$ $\quad F_b < 55$

$$F_b = gv_s\frac{d^2}{4}\left(\frac{T_S - T_a}{T_a}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The downwind and crosswind distance of the receptors from the thermal power plant are calculated as [16]:

$$x = S\cos T + R\sin T \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$
$$Y = S\sin T - R\cos T \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

The wind speed (u) in Eqn.(2) is calculated at stack exit as [36]

$$u(z) = u_{10}\left(\frac{Z}{10}\right)^{p} \qquad \text{.....................(8)}$$

Perkins [37] reported that Smith recommended p=0.25 for neutral condition and p=0.5 for stable condition, u_{10} (wind speed at 10m stack height).

Several specials forms derived from the basic Gaussian plume Eqn. (2) for evaluated sources are frequently used to treat specific situations. One form which is more important in dispersion of pollutants is [31]: Maximum ground level concentration for an elevated source which can be calculated approximately from Equation (9) by substituted for Z=0, y=0 and $H^2=2\sigma_z^2$ in Eqn.(2) as following:

$$C_{\max} = \frac{0.117Q}{u\sigma_y\sigma_z} \qquad \text{...........................(9)}$$

CASE –STUDY and INPUT PARAMETERS

The thermal power plant as the case study which will be examined in the present work, which considers a South Baghdad Power generation stations. The capacity of the power plant is 40MW and its daily fuel (heavy fuel oil) consumption is about $1800m^3$/day.

The rate gases pollutants (SO_2, NO_2, CO) emission estimated by combustion chemical reaction equation, the weight percent of sulphur content in fuel oil=3.5% [24]. The power station has six stack of heights 50m, diameter of 2m and temperature of 417K at stack exit. The receptor is industrial area of 4km to the North-East of South Baghdad power station. It is assumed that an equal amount of SO_2 and other gases is emitted from each stack.

The meteorological data and conditions over industrial area were proposed for all expected weather conditions that may take place at the study region as shown in Table (1) [38].

The total exist gases velocity is estimated depend on the continuity equation and total fuel consumption for one stack. Orsat analyzer was used to measure the average volumetric percentage for exit gases from the stack [24].

Therefore the emission rates of these pollutants are:

$SO_2=228.4\times10^6$ μg/sec

$CO=231.4\times10^6$ μg/sec

$NO_2=28.7\times10^6$ μg/sec

The model used the Gaussian Plume Eqn. (2) to calculate different parameters and ground level concentration of SO_2, NO_2, CO, which are emitted from stack.

The computer program using visual basic 6[30], which are adopted to calculate the ground-level concentration resulted from multiple point sources for Baghdad South power station and other parameters such as effective stack height and concentration of gases pollutants.

Therefore above data and equations are used in program computer to evaluate the air quality by this model and comparison with standard limits by EPA.

RESULTS and DISCUSSION

Effect of Meteorological Parameters

The meteorological parameters (temperature and wind speed) effect on the dispersion of pollutant gases can be described and calculated by the diffusion equation or Gaussian plume model Eqn. (2).

Figures 2-4 show the effects of the meteorological parameters on dispersion concentration of pollutants gases. It can be seen for SO_2, NO_2 and CO emission from stack decreases with increasing time, temperature and wind velocity because greatest plume spread causes higher pollutant dilution. Also it can be seen from these figures, the concentration of SO_2 is higher than the other pollutants of gases. This is may be due to the percentage of sulphur content in fuel oil. The higher concentration of SO_2 in effluent gases is more effect on air quality because it reacts with other chemicals in the atmosphere to form sulfate particles, an important contributor to the fine particle mix that circulates with the air we breathe or to form acid rain (39).

Figures 5-6 show the maximum concentration of SO_2, NO_2 and CO which are calculated from Eqn. (9) and are increased with increasing of time and ambient temperature, as shown in Figs. 5 and 6, but Fig.7 show a fluctuated relationship of the maximum concentration with wind speed, depending on the stability of condition of weather and height plume of gases. Maximum concentration of effluent gases is getting from smallest plume spread and when the atmosphere is most stable. Therefore the management of power plant must be design a program to reduce the release of SO_2 and other pollutants from fuel-fired power plants.

Effect of Effective Stack Height.

The results of effective stack height (H) can be obtained from Eqn. (4) and input data for modeling dispersion concentration of gases pollutant by using Gaussian model Eqn. (2).

Figures (8a), (8b) and (8c) show the ground level concentrations of SO_2, NO_2 and CO and increased with increasing effective stack height until to reach the optimum point and then the concentration of gases decrease with increasing an effective stack.

But the results in Figs. (9a,b,c) indicated the maximum ground level concentration of effluent gases SO_2, NO_2 and CO decrease with increasing effective stack height, depending on wind velocity and stability conditions.

Air Quality

In the present work, the SO_2 concentrations are worked out for down wind distance up to 4Km for stability class D in the ground. Figure (10) show computed SO_2 concentrations at different downwind distance from the power station for wind speed 3.2 and 7.5 m/sec at receptor height 8m (i.e. Z=8m in Eqn.3) at any down wind distance, environmental pollution affect people, animals and plants is concentrated at height 8m above the ground (34).

It can be seen from Fig.10; the concentration of SO_2 increased down stream of the stack to a certain location where the maximum value is reached, and after that the gas intensity is reached. As seen from Fig. 10, the higher concentration of SO_2 (890 and 370µg/m^3) can occur at distance of 1.5Km from the plant when the wind speed is 3.2 and 7.5m/sec, respectively. In these two cases, the concentration of SO_2 have crossed the EPA and WHO standards (365µg/m^3 24-hr average). For start exposure (7.8hr), a critical concentration is about 800-1300µg/m^3 (40). With such high levels of SO_2 (724-992µg/m^3) these could be an adverse effect on human health, sensitive plants and visibility. Thus, under trapping and fumigation conditions, the power station will have a strong impact at distance 1.5Km to the thermal power plant.

Effect of Interaction Parameters on Dispersion of Gases Pollutants

The combined effect of the two independent variables temperature or downwind distance and wind speed on concentration dispersion of pollutants effluent gases were studied by three dimensional diagrams and contour graphs, representation as shown in Figs.(11-15). Such graphs are relatively simple and should be useful to power plants for workers, because they explore to the maximum concentration of gases pollutants from SO_2, NO_2, CO (Figs.11-14).

Figure (15) gives the kind of contour shape for effect of different down-distance with height receptor 8m on the concentration.

The contour lines are sketched and appropriately labeled to represent the maximum concentration of SO_2 reach that in atmosphere and is useful to display quickly the dangerous especially when this value of concentration of SO_2 is more than the allowable standard limit 365$\mu g/m^3$ in air quality standards EPA. This standard is designed to protect human health.

CONCLUSIONS

1- High concentration of SO_2 (890μ/m^3) at downwind distance 1.5Km and 3.2m/sec wind speed may exceed the EPA standard. The high concentration which can spread in the area from the power plant may cause discomfort to the people.
2- The concentration of SO_2, NO_2, CO emission from stack decreases with increasing time, temperature and wind speed.
3- Effective stack height is a control on dispersion of ground level concentration and maximum concentration of pollutant gases. Therefore further control measures for the emissions of SO_2, NO_2 and CO from power plant and increase in stack height is suggested to reduce the negative environmental effects.

NOMENCLATURES

C	Concentration of gases pollutants	$\mu g/m^3$
C_{max}	Maximum ground level concentration	$\mu g/m^3$
d	Stack exit diameter	m
EPA	Environmental protection agency	------
F_b	Buoyancy flux parameter	m^4/sec^3
g	Acceleration gravity	m/sec^2
H	Effective plume rise	m
H_s	Actual stack height	m
K_{xx}	Eddy diffusion coefficient	m^2/ sec
PM	Particulate matter in size range micron	µ
Q	Emission rate of gases pollutants	g/sec
R	East coordinates of the receptor	m
S	North coordinates of the receptor	m
t	Time	sec
T	Wind direction	degree
T_a	Ambient temperature	K
T_s	Stack gas temperature at the stack exit	K
u	Wind speed	m/sec
u_{10}	Wind speed at 10m stack height	m/sec
v_s	Stack gas exit velocity	m/sec
WHO	World health organization	
x	downwind distance from stack	m
Y	Crosswind distance of stack	m
Z	Height above ground	m
	Greek symbols	
σ_y	Crosswind dispersion coefficient	m
σ_z	Vertical dispersion coefficient	m

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Table (1) all expected meteorological conditions each stability category. [38]

Time (day)	Ambient Temp. (K)	Wind direction angle (degree)	Wind speed at 10m.(m/sec)	Stability category
1	278	275	2.1	Very unstable
2	290	265	3.5	Very unstable
3	294	310	5.0	unstable
4	298	305	6.0	unstable
5	305	325	6.5	unstable
6	310	320	4.2	neutral
7	320	285	2.9	Stable

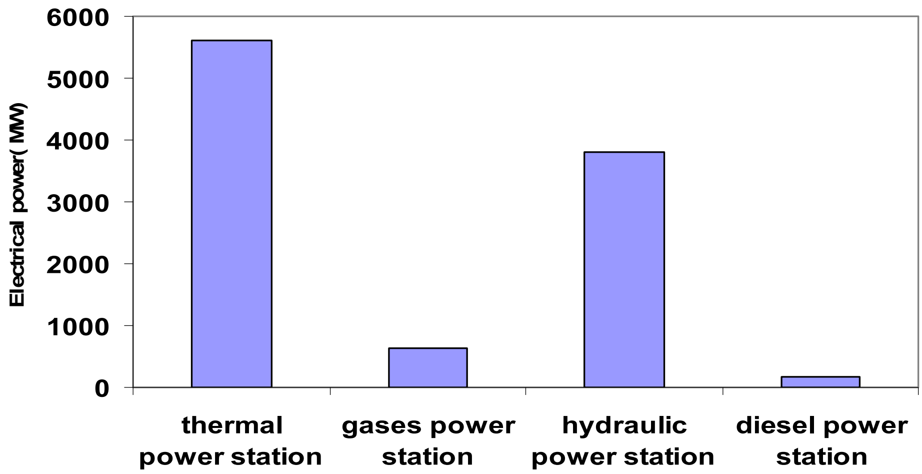

Fig.(1): The relation between electrical power generation with power station type in Iraq.

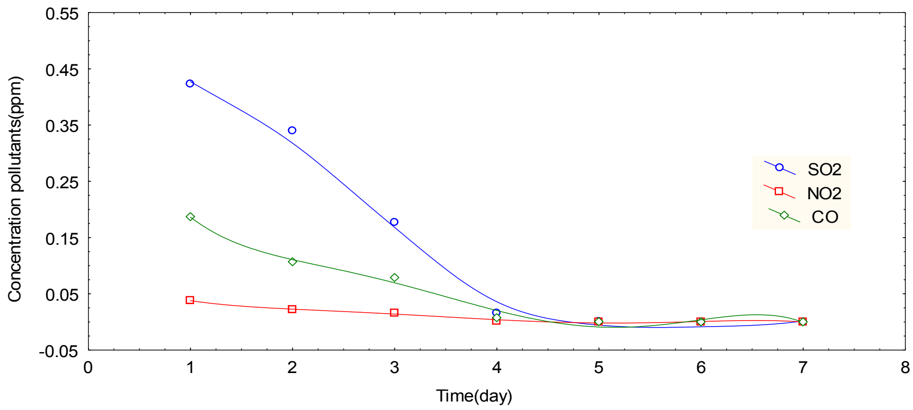

Fig.(2): The relation of concentration of pollutants gases with time.

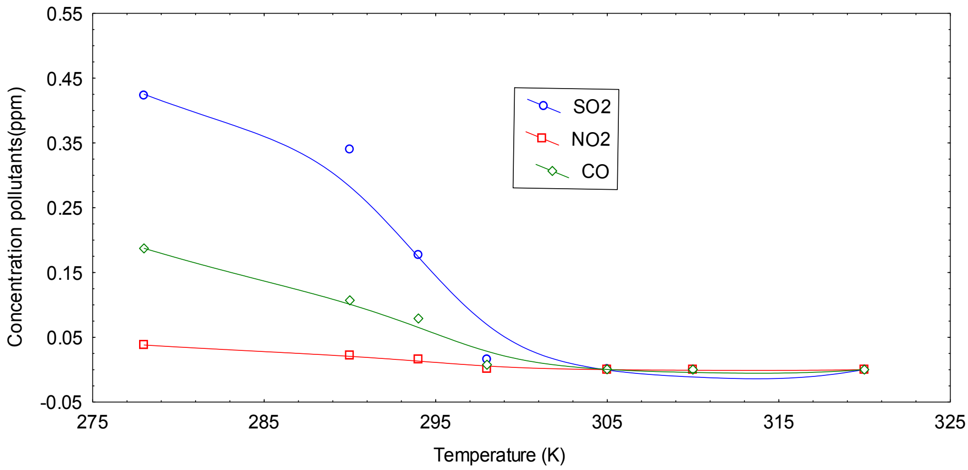

Fig.(3): The relation of concentration of pollutants of gases with temperature.

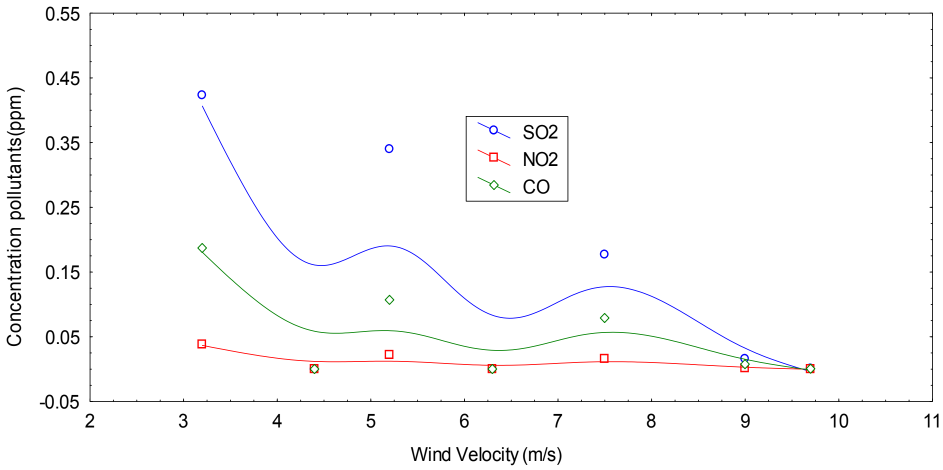

Fig.(4): The relation of concentration of pollutants gases with wind velocity.

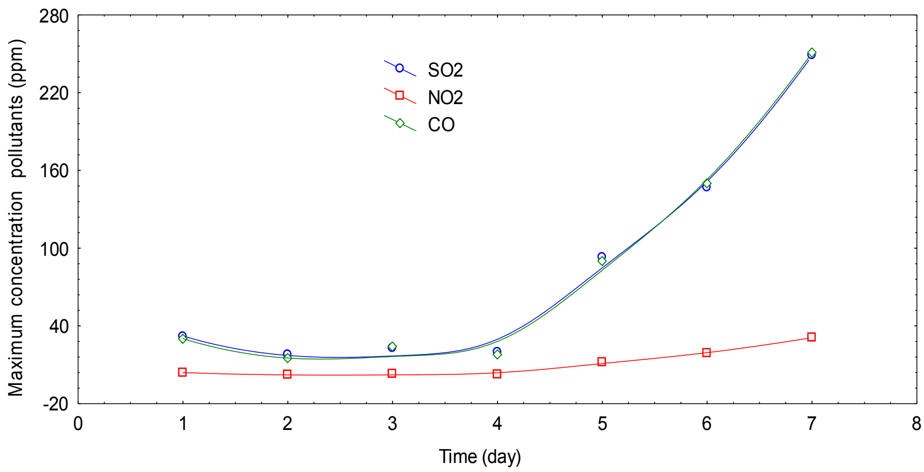

Fig.(5): The relation of maximum concentration pollutants of gases with time.

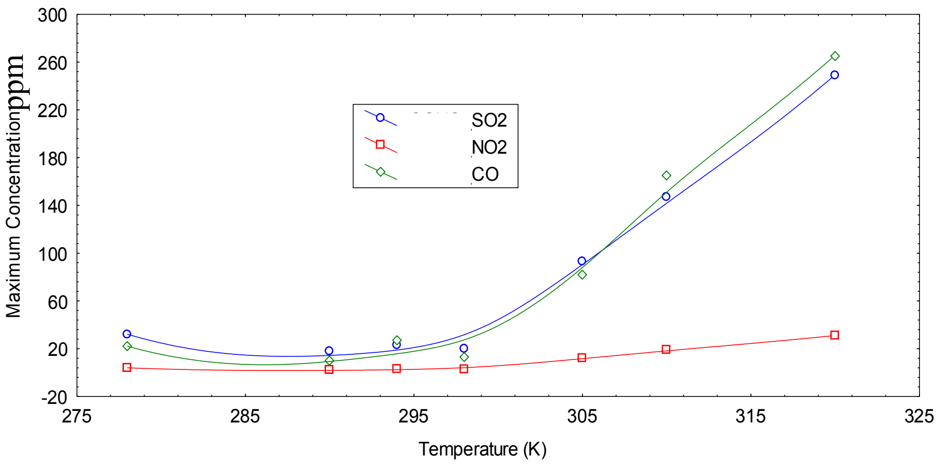

Fig.(6): The relation of maximum concentration of gases pollutants with temperature.

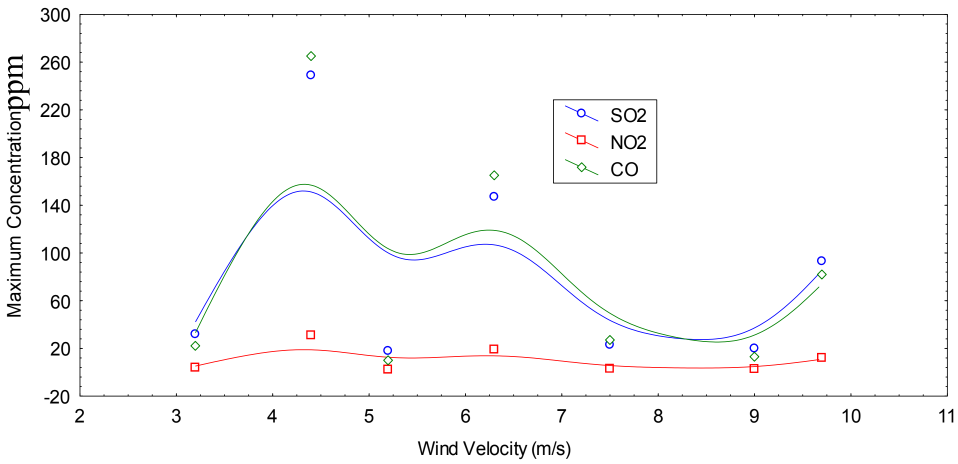

Fig.(7): The relation of Maximum concentration of pollutants gases with wind velocity.

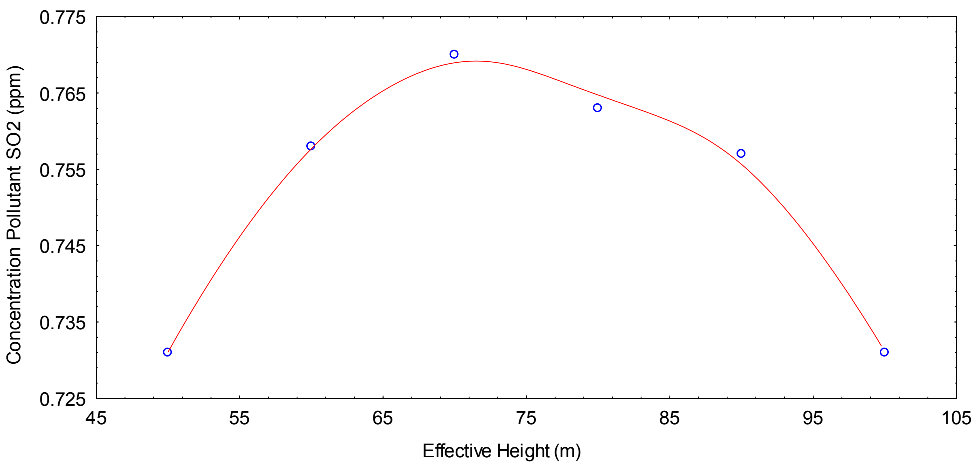

Fig.(8-a): The relation of concentration SO_2 gas with effective stack height.

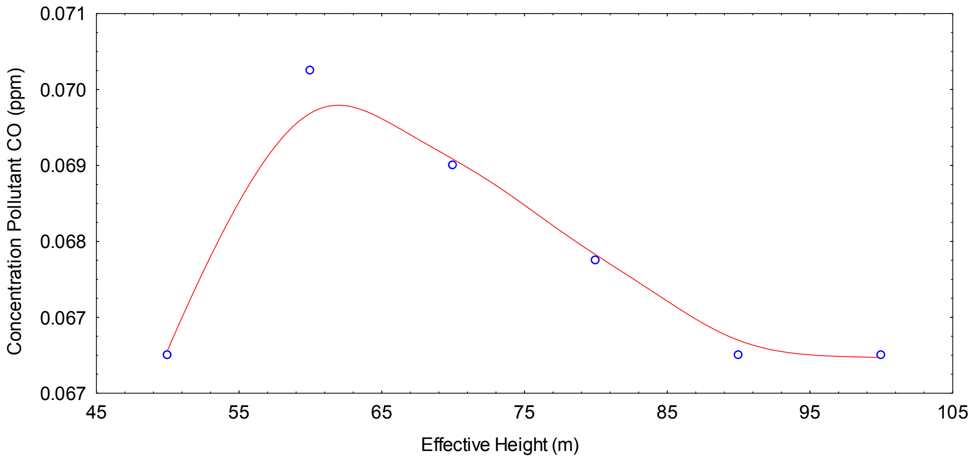

Fig.(8-b): The relation of concentration NO_2 gas with effective stack height.

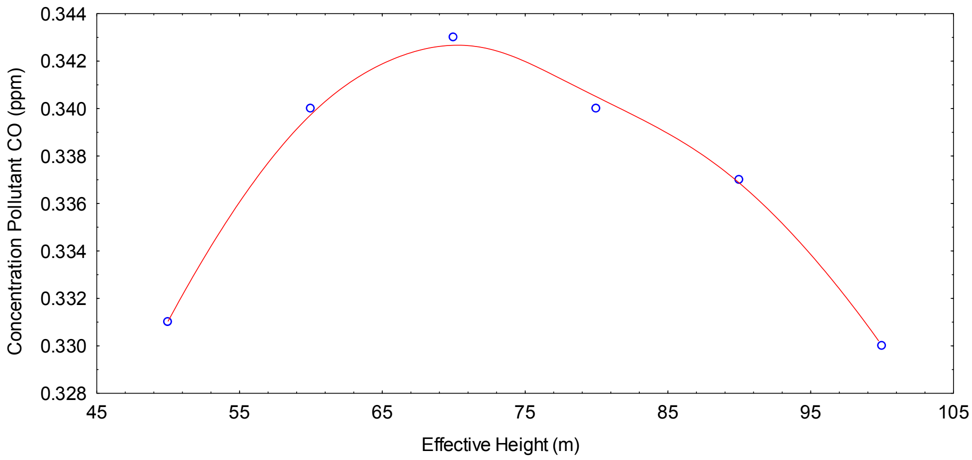

Fig.(8-c): The relation of concentration CO Gas with effective Stack height.

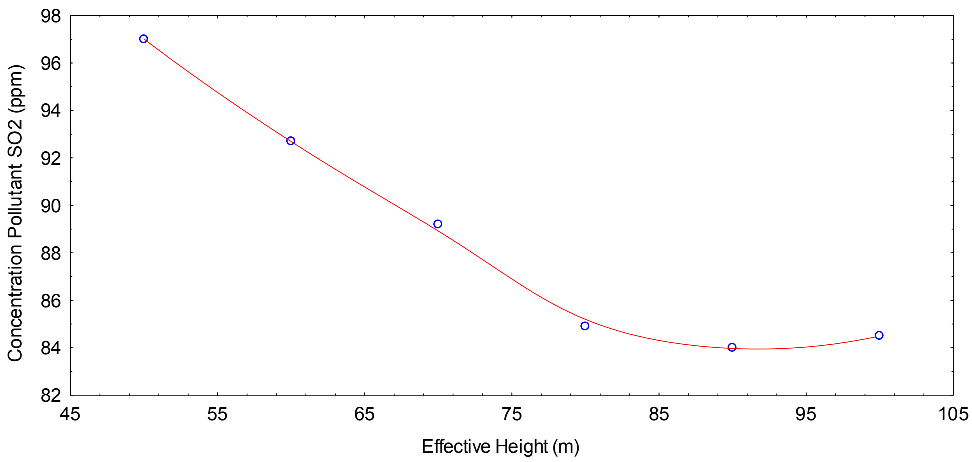

Fig.(9-a): The relation of maximum concentration SO_2 gas with effective stack height.

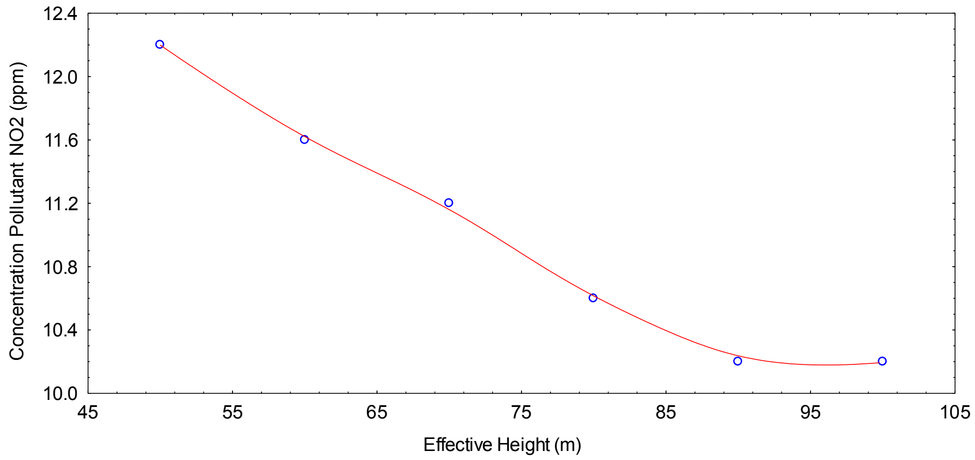

Fig.(9-b): The relation of maximum concentration NO_2 gas with effective stack height

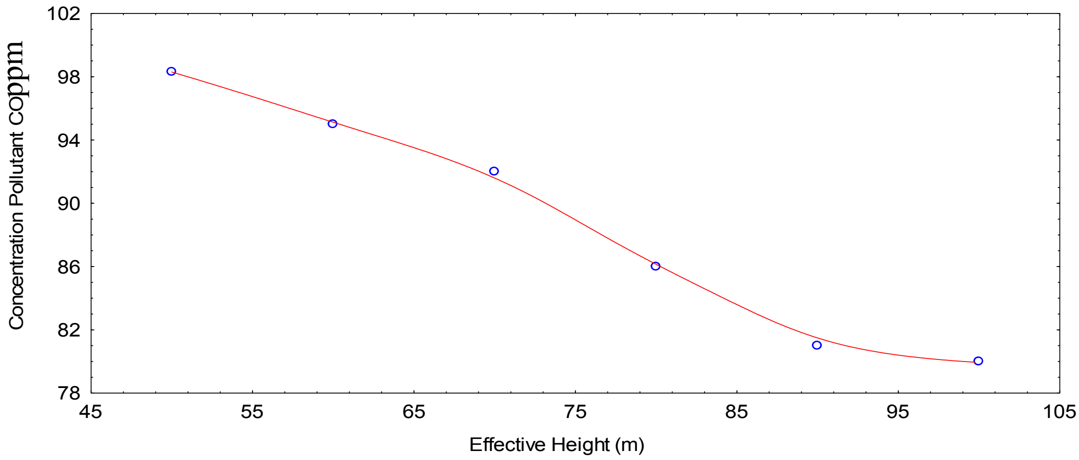

Fig.(9-c): The relation of maximum concentration CO gas with effective stack height

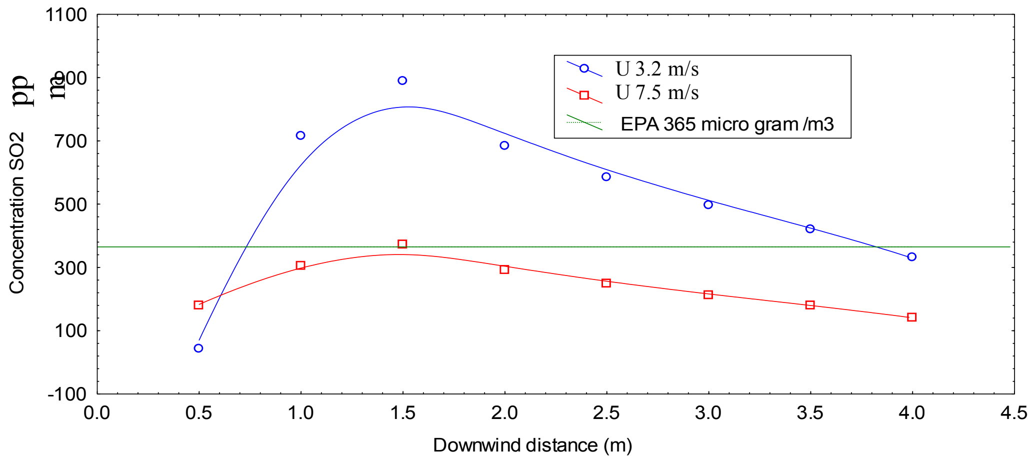

Fig.(10): Computed concentration of SO_2 for downwind distance with wind speeds.

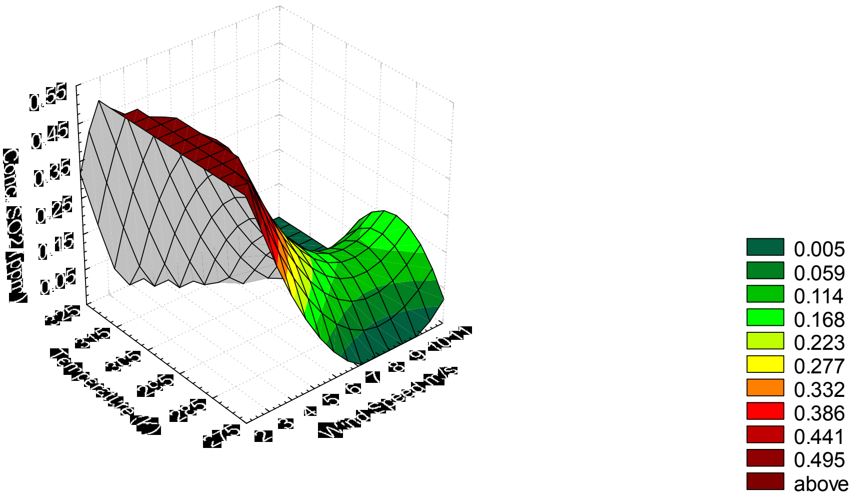

Fig.(11): Effect of temperature and wind speed of weather on concentration. of SO_2

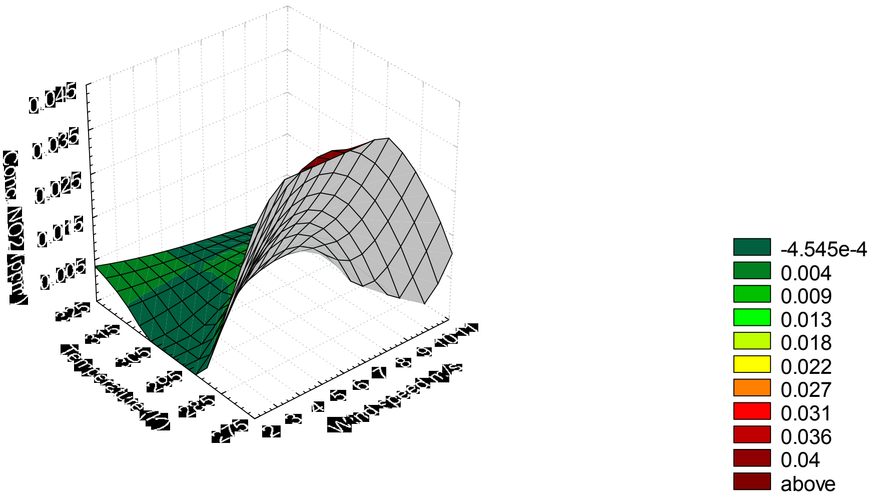

Fig.(12): Effect of wind speed and temperature of weather on concentration of NO_2 distance weighted Least squares.

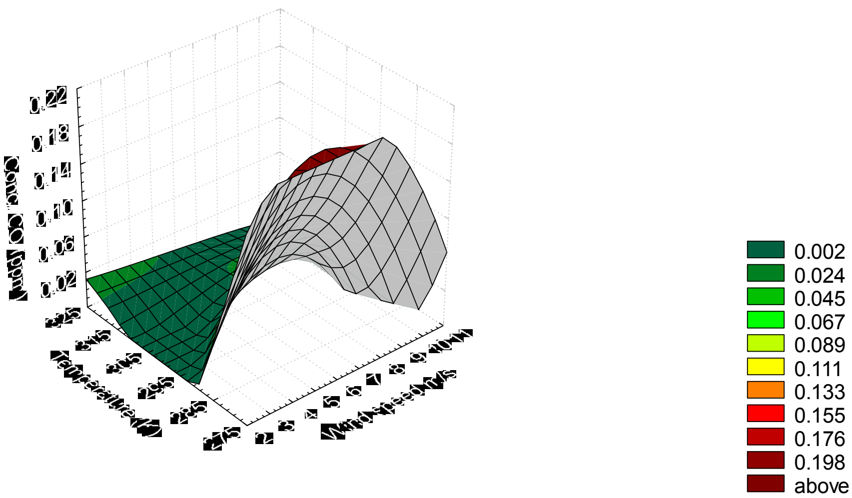

Fig.(13): Effect wind of speed and temperature of weather on concentration of CO

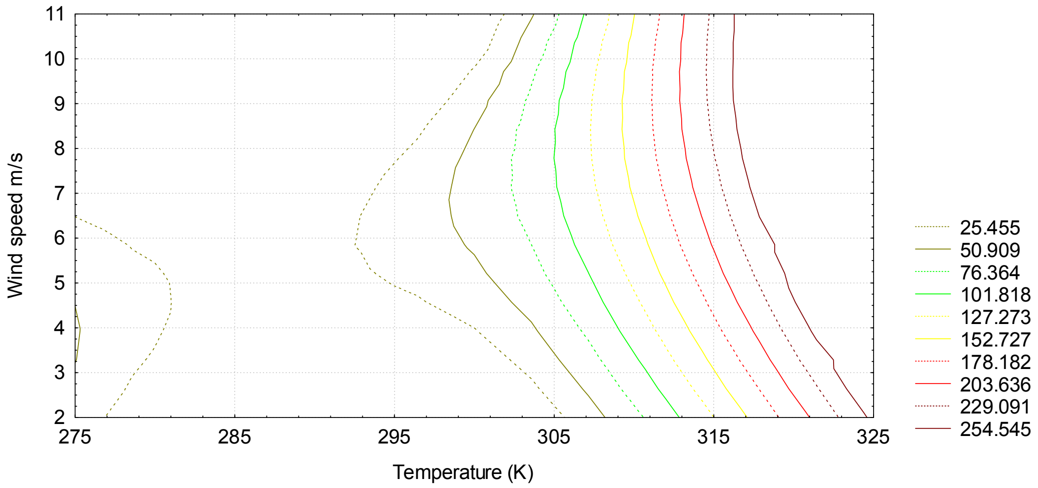

Fig.(14): maximum concentration SO_2 Contour graph as a function of temperature and wind speed.

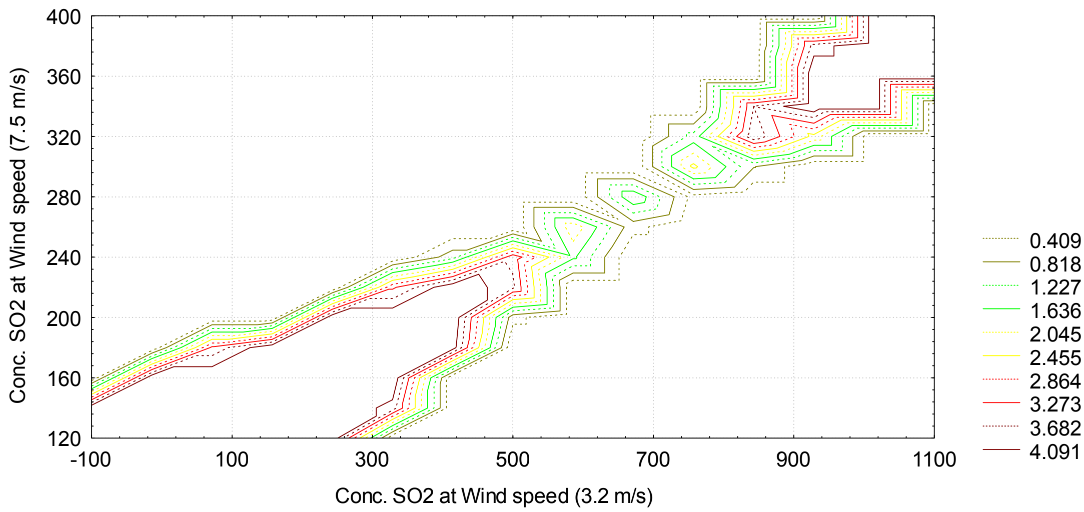

Fig.(15): Concentration SO_2 contour graphs as a function of downwind distance and velocity.

موديل رياضي لدراسة تاثير الظروف الجوية على انتشار الملوثات في الهواء

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الخلاصة

يهدف البحث الى تعيين نوعية الهواء المحتوي على الغازات الملوثة (SO_2, NO_2, CO) المنبعثة من وحـــدة الطاقة الكهربائية الحرارية. وتم استخدام موديل كاوسين لحساب تراكيز الملوثات الغازية واستخدم برنـــامج الحاســـبة (Visual basic 6) المنتشرة في ظروف جوية مختلفة (سرعة الريح، درجة حرارة المحيط) وقيم التراكيز القـــصوى والمسافة باتجاة الريح وتعيين ارتفاع المدخنة المؤثر.

وتم تحليل نظري لدراسة حالة تمثل مشاكل تلوث الهواء على منطقة صناعية لمـــسافة ٤كـــم باتجـــاة الـــريح باستخدام برنامج الحاسبة. وقد اظهرت النتائج بان تركيز غاز SO_2 (٨٩٠ مايكروغرام/مترمكعب) المنبعث من المدخنة اعلى من من القيم القياسية ل EPA وكذلك القيم المثلى لتركيز الملوثات عند مستوى سطح الارض يقل بزيادة ارتفـــاع المدخنة المؤثر.