Emetere ME, Annals of Environmental Science / 2013, Vol 7, 71-77

MODELING OF PARTICULATE RADIONUCLIDE DISPERSION AND DEPOSITION FROM A CEMENT FACTORY

Moses E Emetere*

Department of Physics, Covenant University
Canaanland P.M.B 1023, Otta, Nigeria.

Received May 29, 2013, in final form October 11, 2013, accepted November 12, 2013.

ABSTRACT

Particulate dispersions from industrial stacks are referred to as pollutants - chemical components that portend threats to life forms. Based on research work around a known cement factory, the model described in this paper is a holistic analysis of dispersion and deposition of radionuclide and non-radionuclide particulates. A virtual mathematical experimentation laboratory was used to simulate different possibilities in this indigenous model. The 3D model showed a good level of accuracy by determining field values of air-deposited pollutants. The highest chemical transformation and air transport path was seen in the mild diffusion region. The radionuclide dispersion from the cement factory could be controlled by building very high wind breakers 50m to 500m along the horizontal location of the factory.

Keywords: radionuclide, mild diffussion, dispersion, modelling, deposition, plume shift

1. INTRODUCTION

Predictions of the volume of harmful substances in the atmosphere, especially from industrial sites are precautionary in the long run. Average estimates of the channel of waste (air) disposal from industries are mainly from low or high stacks that are placed either horizontally at certain heights or vertically within a specified height. Predicting the holistic impact of pollution from all industrial anthropogenic sources is more than an up-hill task. For detailed discussion, we narrow-down the industrial anthropogenic sources to the cement factory. However, from the basic knowledge of pollution dispersion, pollution from stacks positioned horizontally are localized in its immediate environment but stacks positioned at a specified height have dual impact on both its immediate and distant environs depending on the height of the stack and the rate of pollutants released into the atmosphere. A cement factory is a typical example of industrial anthropogenic sources that adopts the vertically-positioned stack.

Due to the present awareness on the dangers of pollution to life forms, many cement factories have employed various preventive measures, e.g. constructing a very high stack among other precautionary measures. In effect, the rate of air pollution has greatly been reduced though more can be done.

Dispersion of air pollution in and around any cement factory depends on various factors, including the height of the stack, weather conditions, topography, and air upthrust. Theoretically, the concentration of contaminants in the environment is determined basically by four processes, namely advection, diffusion, ground deposition and chemical transformation [1-4]. These processes are the working principles behind different pollution models, e.g. the dispersion model, the photochemical model, the particle model, the odor model and the remote sensing dispersion model.

From the research of Olukorede et al. [5] and Gbadebo et al. [6], some of the particulates from the stack of a cement factory contain gaseous radionuclides, which can be inferred from minute deposition of radionuclides within its environs. According to Jibiri et al. [7], the concentration of ^{238}U around a cement factory was estimated at 1.76 MeV, ^{232}Th was estimated at 2.615 MeV and gamma energies were set at 1.465 MeV. Past research has captured different models of radionuclide deposition [8,9].

In this paper, wind field dynamics was introduced to determine the direction of both the dispersion and deposition of particulates at a given time. A mild diffusion region was also incorporated into the model, which is different from the turbulent diffusion introduced by Roberts [10] to account for other chemical transformations and transport. Accidental radioactive discharge of material have been proven to produce dispersion plumes [11].

* Corresponding author: Email, moses.emetere@covenantuniversity.edu.ng

2. LITERATURE REVIEW

Our work is based on a theoretical model that has been applied to existing experimental data from the most famous cement factory in Nigeria (Portland Cement in Ewekoro). The experimental work carried in the study area includes a) investigating the health and environmental effects of the Ewekoro cement industry on the surrounding settlement of Ewekoro, in Ogun State [12]; b) examining the effect of cement dust on the photosynthetic apparatus of few cash crops e.g *Chromolaena odorata* and *Manihot esculenta* [13]; c) analyzing the chemical and physico-chemical parameters of ground water samples from wells around the Ewekoro cement factory [14]; d) estimating the concentrations of radionuclides around the environs of the cement factory by extracting soil samples [6,15]; and e) investigating particulate deposition of cement dust within and around the Ewekoro environs [16]. Other research work carried out within the cement factory can be placed under each category mentioned above.

3. MATERIAL AND METHODS

The Ewekoro cement factory is located five km north of Ewekoro town (6º55′N3º12′E/6.93ºN3.21ºE). It is within the tropical rainforest belt of Ogun State in southwest Nigeria. The topography of Ewekoro is classified as southern upland [6]. It has an area of 594 km^2 and a population of 55,156 according to the 2006 census. The developmental pressure from metropolitan Lagos has resulted in mass migration of people to neighboring communities like Ewekoro.

Figure 1 Map of the cement factory location (Diagram sourced from Encarta)

This effect might have changed the population count to about 400,000. Ewekoro is well-known for large deposits of limestone and shale which made it the host of the two cement factory. The location of the cement factory is indicated by the red dot on the map shown in Figure 1.

4. THEORETICAL DERIVATION

Based on the already completed experimental work in the factory study area [13,16], it is scientifically valid to agree that the wind speed ranges from $1ms^{-1}$ and $0.72ms^{-1}$ at 10m above the ground during the dry and wet seasons respectively[16]. All the assumptions of the plume model were observed in the following derivation. The additional assumptions made include:

1. Inclusion of the mild diffusion at the downwind plane as shown in Figure 3. Therefore, the measurement of the eddy diffusivity is between 2 -3 m^2/s , though it varies from place to place [17].
2. The angle of deviation (α & β) depends on the wind convection and it does not exceed these angles. Therefore, the cement dust noticed around the stack is a result of the cement dust splash from the lower turbulent diffusion as shown in Figures 2 and 3.
3. The presence of air upthrust and air viscosity was made negligible because of the influence of the ground heat flux [18,19].
4. The width of the plume depends on both the wind direction and the coefficient of eddy diffusivity.
5. The duration of radionuclide deposition was assumed to be between 10.00 am to 6.00 pm.
6. The sites where the samples were collected by Jibiri et al. [7] were along a straight line.
7. The radionuclide particulate is uniformly distributed along the sampling site.

Recent work had been carried out by the authors [20] on the general particulate depositions of pollutants around a cement factory. The radionuclide particulate deposition was therefore altered to incorporate the doses released to the atmosphere. First, the possible plume shift of the radionuclide particulate is given as

$$\left.\begin{aligned} D_x &= (V_x cos\alpha)t \\ D_x &= (V_x cos\beta)t \end{aligned}\right\} \quad [1]$$

where α and β are the angular plume shifts due to wind and gradient pressure influence on the radionuclide particulate. Shift α shows the plume apparent movement towards the north-west/south-east and β shows the

plume apparent movement towards the north-east/south west. In a typical plume case, its spread can be simultaneously along α and β, therefore

$$D_x = [V_x \cos(\alpha + \beta)]t \quad [2]$$

Remodeling the Gaussian plume model [21] is the main objective of this paper. The pictorial view of particulate dispersion in Figures 2 and 3) served as the control guide for this model.

Figure 2 Pictorial view of the movement of the pollutants from the stack at Ewekoro

Figure 3 expresses the different perspectives upon which the advection diffusion equations adopted for this model were derived. The mathematical expressions for the different positions are mathematically represented below.

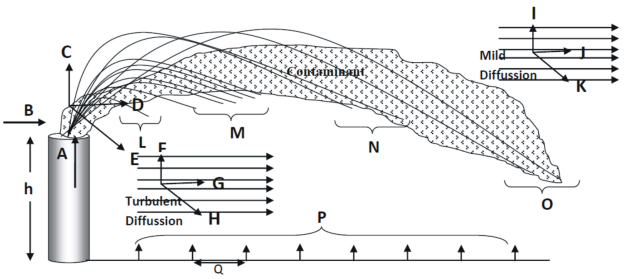

Figure 3 Contaminant dispersion pattern in the Ewekoro cement factory

Region **A**-**E** is the general particulate dispersion analysis

$$A = \frac{\partial C}{\partial t};\ B = V\frac{\partial C}{\partial r};\ C = V_z\frac{\partial C}{\partial z};\ D = V_x\frac{\partial C}{\partial x};\ E = V_y\frac{\partial C}{\partial y}\Big\} \quad [3]$$

where $V^2 = {V_x}^2 + {V_y}^2 + {V_z}^2$

Region **F**-**K** is the general particulate diffusion analysis

$$F = \frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right);\ G = \frac{\partial}{\partial x}\left(K_z\frac{\partial C}{\partial x}\right) = 0;$$
$$H = \frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right);\ I = \frac{\partial}{\partial z}\left(K_{z2}\frac{\partial C}{\partial z}\right); \quad [4]$$
$$J = \frac{\partial}{\partial x}\left(K_{z2}\frac{\partial C}{\partial x}\right) = 0;\ K = \frac{\partial}{\partial y}\left(K_{y2}\frac{\partial C}{\partial y}\right)$$

Region **L**-**O** is the general particulate deposition analysis

$$L \approx \frac{2V_{1x}^3V_y}{gV^2};\ M \approx \frac{2V_{2x}^3V_y}{gV^2};\ \approx \frac{2V_{3x}^3V_y}{gV^2};\ O \approx \frac{2V_{4x}^3V_y}{gV^2}\Big\} \quad [5]$$

where $V^2 = {V_{nx}}^2 + {V_y}^2$ and L, M, N, O represent different points of cement dust deposition along its transmission. V is the wind velocity (m/s), P is the air upthrust, C(x,y,z) is the mean concentration of diffusing pollutants of diffusing substance at a point (x,y,z) [kg/m^3], K_y, K_x are the eddy diffusivities in the direction of the y- and z- axes [m^2/s] and S is the source/sink term [kg/m^3-s].

The assumption is that the rate of emission of contaminant from the stack and the wind impact act in the same direction. Therefore, the governing equations are

$$\frac{\partial C}{\partial t} + V_x\frac{\partial C}{\partial x} - V_z\frac{\partial C}{\partial z} - V_y\frac{\partial C}{\partial y} = \frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right) +$$
$$\frac{\partial}{\partial z}\left(K_{z2}\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial y}\left(K_{y2}\frac{\partial C}{\partial y}\right) - P + S \quad [6]$$
$$-V_z\frac{\partial C}{\partial z} = -\frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right) \quad [7]$$

$$V_x \frac{\partial C}{\partial x} = \frac{\partial}{\partial y}\left(K_{y2}\frac{\partial C}{\partial y}\right) - \frac{\partial}{\partial z}\left(K_{z2}\frac{\partial C}{\partial z}\right) \quad [8]$$

Equation [8] was solved using separation of variables i.e. C = X(x)Y(y) in which the initial boundary conditions are x = 1, X = 1; y = 1, Y = 1; z = 1, Z =1. The first solutions of C by equations 7 and 8 are

$$C(y,z) = \frac{Q}{2} e^{\sqrt{\left(y^2+\frac{1}{yk_y}\right)}+z} \left(e^{\left(\frac{V_z+\sqrt{V_z^2-4k_z}}{2k_z}\right)z} - e^{\left(\frac{V_z-\sqrt{V_z^2-4k_z}}{2k_z}\right)z} \right) \quad [9]$$

$$C(x,y,z) = Q\sqrt{\frac{y^3z^3}{K_yK_zV_x^2}}\exp(xV_x) + In\left(\sqrt{\frac{K_y}{y}}\right) + In\left(\sqrt{\frac{K_z}{z}}\right) \quad [10]$$

Equation [9] was also solved using separation of variables with varying initial boundary conditions. The following expressions emerged

$$T = X^{V_x}; Y^{V_y} = Z^{V_z}; X = e^{\left(\frac{x}{k_z+k_{z2}}\right)^{\frac{1}{2}}}; Y = e^{\left(\frac{y}{k_y+k_{y2}}\right)^{\frac{1}{2}}}$$

This eventually gave the solutions

$$C(x,y,z) = \frac{V_xV_y}{V_z} e^{\left(\frac{4x}{k_z+k_{z2}}\right)^{\frac{1}{2}}} e^{\left(\frac{4y}{k_y+k_{y2}}\right)^{\frac{1}{2}}} \quad [11]$$

$$C(x,y,z) = \frac{V\cos(\beta-\alpha)V_y}{V_z} e^{\left(\frac{4x}{k_z+k_{z2}}\right)^{\frac{1}{2}}} e^{\left(\frac{4y}{k_y+k_{y2}}\right)^{\frac{1}{2}}} \quad [12]$$

$$C(x,y,z) = \frac{V\cos(\beta)V_y}{V_z} e^{\left(\frac{4x}{k_z+k_{z2}}\right)^{\frac{1}{2}}} e^{\left(\frac{4y}{k_y+k_{y2}}\right)^{\frac{1}{2}}} \quad [13]$$

Hanna et al. [22] defined the following formalism: W is the worst case cloud width [m] (usually we assume W = 0.1x, where x is distance from the source). The value of W was substituted in the modeling for either x and y in the solutions. From equations [2] and [5], the equation relating the two-dimensional height-range movement of the particulate radionuclide from the stack of the cement factory is given as

$$H = \frac{gt}{2}\left[\left(\frac{V_yV_x}{V^2}\right)sin^5(\alpha+\beta)\right] \quad [14]$$

Different deposition points ranging from 0 to 25,000m were documented by Jubril et al. [7]. The eddy diffusivities were assumed to be K_z = 200m^2/s, K_{z2} =100m^2/s, K_y =120m^2/s and K_{y2} = 150m^2/s.

5. RESULTS AND DISCUSSION

The validity of equation 11-13 is confirmed in Table 1. The mean particulate concentration at deposition sites were in concurrence with the experimental air pollutants deposition data reported by Olaleye et al. [16]. The large percentage error apparent in the theoretical reading may be as a result of the inclusion of domestic air pollutants e.g. dust around the sampling points [23].

Table 1 Total Deposited air particles (source: ref [16])

	Experimental Air deposition	Theoretical Air deposition	% error
Alaguntan	23.5	23.3 (β = 30)	1.20
Itori	27.9	25.3 (β = 60)	9.20
Staff Qtrs	10.4	10.3 (β = 40)	0.97
Olapeleke	15.8	12.8 (β = 5)	19.5
Wasinmi	5.3	5.9 (β = 0)	10.2

Based on the validity of the model (as seen in Table 1), radionuclide particulate deposition analysis was investigated as shown in Figure 4. The range of the radionuclide particulate deposition was proportional to the variation of the angular plume shift, which was analyzed within α = 0^o to 60^o and β = 0^o to 45^o. It was also observed that the prolonged operation period (Figure 4b) of the cement factory creates a pathway introduced as a mild diffusion region (Figure 3) flow in which lighter particulates drift to a higher altitude (free troposphere) to deposit at farther distances. For the radionuclide particulates to be able to travel as far as 25000m as reported by Jibiri et al. [7], it must have attained a maximum height of 3.6Gm (see Figure 5). The possibility of particulates within the mild diffusion region traversing the tropopause was validated.

The V_x and V_y components of the wind speed shown in Figure 5 confirmed the final directional movement of the air pollutants which agrees with the principles of deposition [3,4,24,25]. The deposition is therefore two-dimensional (that is, the plume of the radionuclide particulate moves both forward (y-axis) and sideways (x-axis) along the horizontal plane. Due to the radioactive decay of the radioactive-elements years before the experiments were carried out (7), it is difficult to predict the radionuclide deposition beyond 50m from the cement factory. Furthermore, in the mild diffusion region the magnitude of the height shows that

the particulates experience their highest chemical transformation because air particles at this point are lighter by mass and energetic enough to interact with atmospheric currents [26,27].

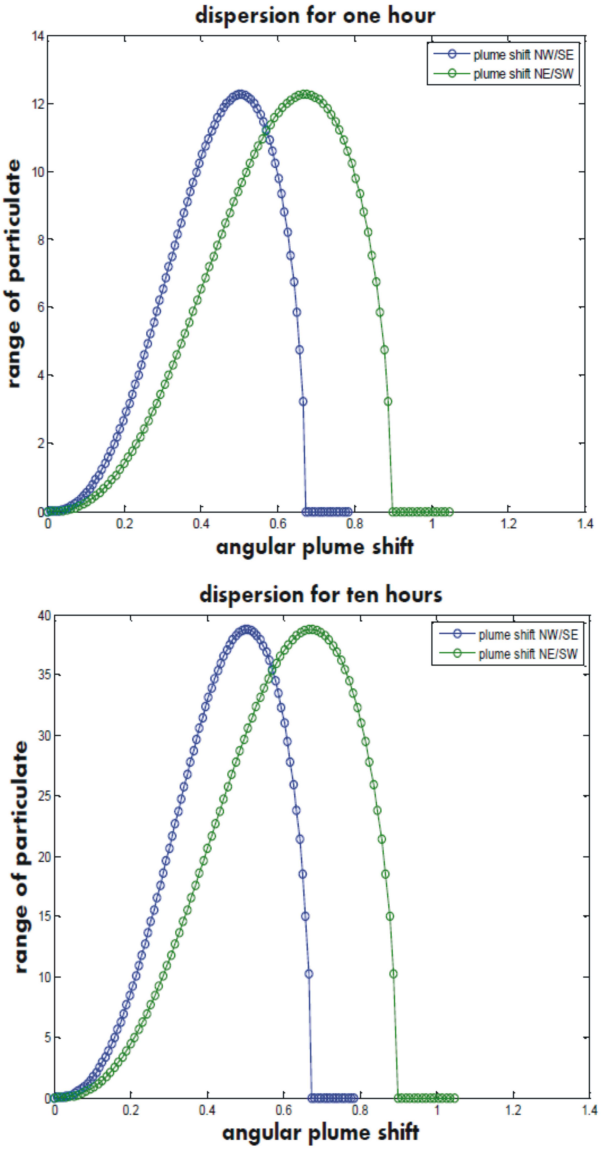

Figure 4 Range of radionuclide particulate within one and ten hours, respectively

6. CONCLUSIONS

The accuracy of the model (Table 1) is validated upon comparison with experimental data. The angular plume shift over this region shows that the latter is directly dependent on the wind pattern. The mild diffusion region was proven to be the region of highest chemical transformation and an air pathway for the flow of radionuclide particulate beyond the tropopause [28]. The solution proffered towards controlling radionuclide dispersion from a cement factory is to build very high wind breakers 50m to 200m beyond the factory. To control general particulate dispersion from the cement factory, the wind field dynamic is calculated using the mathematical inverse of equations 6 and 13.

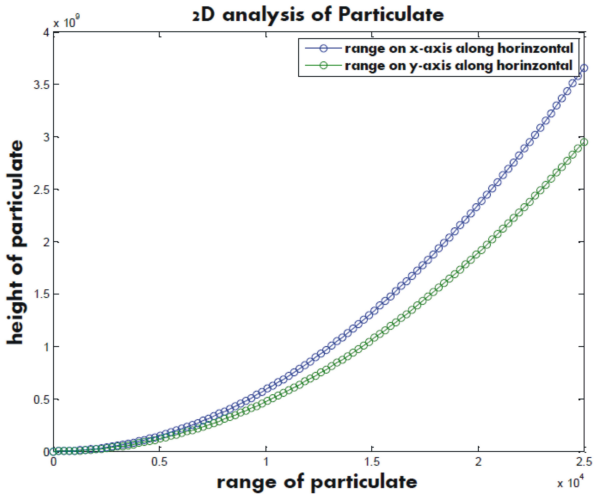

Figure 5 Two-dimensional analysis of radionuclide particulates within ten hours

ACKNOWLEDGEMENT

The authors appreciate the constructive contributions of Mrs J. Emetere.

REFERENCES

[1] Boubel RW, Fox DL, Turner DB, Stern AC. Fundamentals of Air Pollution, 3rd edition. New York: Academic Press, 1994.

[2] Wijeratne IK, Bijker W. ISPRS Technical Commission II Symposium, Vienna, 2006, 125-128.

[3] Carruthers DJ, Holroyd RJ, Hunt JCR, Weng WS, Robins AG, Apsley DD, Thomson DJ, Smith FB. A new approach to modelling dispersion in the Earth's atmospheric boundary layer. *J. Wind Eng. Ind. Aero.*, 1994, 52: 139-

153.
[4] Berkowicz R, Olesen HR, Torp U. The Danish Gaussian Air Pollution Model (OML): Description, Test and Sensitivity Analysis in View of Regulatory Applications. In: Air Pollution Modelling and its Application V (ed. De Wispelaere, Schiermeier and Gillani), 1987.
[5] Olukorede AO, Ewumi TO. Radiological impact survey of sites around two cement producing factories: Wapco and Purechem, Ewekoro, Southwestern Nigeria. *Report and Opinion,* 2011, 3: 37-42.
[6] Gbadebo AM, Amos AJ. Assessment of radionuclide pollutants in bedrocks and soil, Ewekoro Cement Factory, southwest Nigeria. *Asian J. Appl. Sci.,* 2010: 1-10.
[7] Jibiri NN, Olukorede OA, Kolawole AE. Variation of mean radiation Dose with distance of sites proximal to Purechem Cement Factory, Onigbedu, Ogun State, Nigeria. *Pacific J. Sci. Technol.* 2010, 11: 617-673.
[8] Morino Y, Ohara T, Nishizawa M. Atmospheric behavior, deposition, and budget of radioactive materials from the Fukushima Daiichi nuclear power plant in March 2011, *Geophys. Res. Lett.,* 2011, 38: 048689.
[9] Takemura T, Nakamura H, Takigawa M, Kondo H, Satomura T, Miyasaka T, Nakajima T. A numerical simulation of global transport of atmospheric particles emitted from the Fukushima Daiichi Nuclear Power Plant, *Sola*, 2011, 7: 101-104.
[10] Roberts OFT. The theoretical scattering of smoke in a turbulent atmosphere. *Proc. Roy. Soc.* (London), 1923, A104: 640.
[11] Soroka Y, Molchanov A, Isayeva N, Bednarik, O. Radioactive waste management and environmental remediation. Proc. 6th Int. Conf. Singapore, 1997, 773-776.
[12] Aribigbola A, Fatusin AF, Fagbohunka A. Assessment of health and environmental challenges of cement factory on Ewekoro community residents, Ogun State, Nigeria. *Amer. J. Human Ecol.* 2012, 1: 51-57.
[13] Chukwu MN. Impact of cement dust on *Chromolaena odorata* and *Manihot esculenta* around a cement factory in Nigeria. *Continental J. Water, Air Soil Pollut.* 2012, 3: 31-36.
[14] Otaru AJ, Odigure JO, Okafor JO, Abdulkareem AS. Model prediction of particulate dispersion from a cement mill stack: Case study of a cement plant in Nigeria. *IOSR J. Environ. Sci. Toxicol. Food Technol.* 2013, 3: 97-110.
[15] Oluseyi T, Kehinde O, Ismaila A. Assessment of ground water pollution in the residential areas of Ewekoro and Shagamu due to cement production. *Afric. J. Environ. Sci. Technol.* 2011, 5: 786-794.
[16] Olaleye VF, Oluyemi EA, Akinyemiju OA. Environmental disamenities produced by particulate and gaseous emissions from Ewekoro cement kilns on some strata of aquatic and terrestrial Ecosystems. *J. Appl. Sci.* 2005, 5: 428-436.
[17] Lushi E, Stockie JM. An inverse gaussian plume approach for estimating contaminant emissions from multiple point sources. *Atmos. Environ*. 2010, 44: 1097-1107.
[18] Uno EU, Emetere M E. Analysing the impact of soil parameters on the sensible heat lux using a simulated temperature curve model. *Int. J. Phys. Res.* 2012, 2: 1-9.
[19] Uno EU, Emetere ME, Eneh CD. Simulated analysis of soil heat flux using a temperature deviation model. *Sci. J. Phys.* 2012, 2012: 1-9
[20] Emetere ME, Akinyemi ML. Modeling of generic air pollution dispersion analysis from Ewekoro Cement Factory. *Analele Universitatii din Oradea–Seria Geografie*, 231123-628: 181-189.
[21] Turner DB.Workbook of Atmospheric Dispersion Estimates. Publication no. 999-AP-26, U.S. Department of Health, Education and Welfare. 1969.
[22] Hanna SR, Drivas PJ, Chang JC. Guidelines for Use of Vapor Cloud Dispersion Models. New York: AIChE/CCPS, 1996, 285 pp.
[23] El Desouky HJ, Moussa KF, Hassona HH. Impact of automobile exhaust on roadside-soils and plants in Sharkiya Governornate. *Egypt. J. Soil Sci.* 1998, 38: 137-151.
[24] Briggs GA. Plume Rise Predictions. In: Lectures on Air Pollution and Environmental Impact Analysis, American Meteorological Society, Boston, 1975.
[25] Ensor DS, Pilat MJ. Calculation of smoke plume opacity from particulate air pollutant properties. *J. Air Pollut. Cont. Assoc*. 1971, 21: 496-501.
[26] Lovejoy ER, Curtius J, Froyd KD. Atmospheric ion-induced nucleation of sulphuric acid and water, *J. Geophys. Res.*

2004, 109: D08204.
[27] de Gouw JA, Warneke C, Stohl A, Wollny AG, Brock CA, Cooper OR, Holloway JS, Trainer M. Volatile organic compounds composition of merged and aged forest fire plumes from Alaska and western Canada, *J. Geophys. Res*. 2006, 111: D10303.
[28] Rao PV. Textbook of Environmental Engineering. New Delhi: Prentice-Hall, 2002.

AES 130529(1134)