Analele Universității din Oradea – Seria Geografie Year **XXIII**, no. **1/2013** (June), pp. **181-189**
ISSN **1221-1273**, E-ISSN **2065-3409** Article no. **231123-628**

MODELING OF GENERIC AIR POLLUTION DISPERSION ANALYSIS FROM CEMENT FACTORY

Moses E EMETERE*
Department of Physics, Covenant University Canaanland P.M.B 1023, Otta, Nigeria
e-mail: emetere@yahoo.com

M. L AKINYEMI
Department of Physics, Covenant University Canaanland P.M.B 1023, Otta, Nigeria
e-mail: marvel.akinyemi@covenantuniversity.edu.ng

Abstract: Air pollution from cement factory is classified as one of the sources of air pollution. The control of the air pollution by addressing the wind field dynamics was the main objective of the paper. The dynamics of dispersion showed a three way flow which was calculated and explained accordingly. The 3D model showed good level of accuracy by determining field values of air deposited pollutants. Mean concentration of diffusing pollutants was shown to be directly proportional to the plume angular displacement. The 2D model explained the details of the wind field dynamics and proffers a solution which may be relevant in controlling air pollution from anthropogenic sources.

Key words: contaminant, advection, drag force, semi-plume model

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INTRODUCTION

The introduction of harmful substances into the atmosphere (pollution) especially from the industrial sites has been condemned by various research institute and environmental regulatory agents globally. Many cement factories have employed various preventive measures such as 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. The wind field remains a great factor which seems to be inevitable. To a large extent, the cement factory may not control air pollution wind dynamics. Therefore, solving the wind field dynamics could go a long way not only to taming the air pollution dispersion around the cement factory but also ensuring a control measure of other pollutions from anthropogenic sources.

Dispersion of air pollution in and around any cement factory depends upon various factors including height of the stack, weather conditions, topography, air upthrust etc. Typically, air pollutant dispersion analysis should have taken care of source characteristics, terrain and meteorology feature of the polluting source. Theoretically, the concentration of contaminants and air pollutants in the environment is determined basically by four processes, which are advection, diffusion, ground deposition and chemical transformation. All these processes are frequently investigated and as such attracted different models (e.g dispersion model, photochemical model,

* Corresponding Author

particle model, odor model (Boubel et al., 1994), remote sensing dispersion model (Wijeratne, 2006)) to basically describe the dynamics of airborne pollutants, environmental impact assessments, risk analysis and emergency planning, and source apportionment studies. Models have been categorized into intermediary (e.g screen 3 model), advanced (e.g British model ADMS) (Carruthers et al., 1994), Danish model OML (Berkowicz et al., 1987), specialized (e.g dense gas dispersion model).

In this paper, the focus is the wind field dynamics which is believed to have a wide application to air pollution from most anthropogenic sources. The model concentrated on the mathematical modeling of the air pollutant dispersion from the Ewekoro cement factory. One of the striking highpoints of the paper is the introduction of the mild diffusion which is different from the turbulent diffusion as introduced by Roberts (1923).

LITERATURE REVIEW

The work is a theoretical work which was applied to existing experimental data from the most famous cement factory in Nigeria (Portland cement, Ewekoro). The study site has attracted most research write-up than any other in the country. Different research approaches have been adopted and with good results. For example, Aribigbola et al., (2012) investigated the health and environmental challenges of Ewekoro Cement Industry on the physical environment of the surrounding settlement of Ewekoro, Ogun State. The study confirmed the extensive incidence of land, air, and noise pollution within recommended minimum limits set by National Environmental Standard Regulation Authority (NESRA). Chukwu (2012) examined the effect of cement dust on photosynthesis apparatus of few cash crops such as Chromolaena odorata and Manihot esculenta. The farm at northern direction of the cement factory accumulated more cement dust than the southern direction. Obviously, the findings suggest the direction of impact. Oluseyi et al., (2011) worked on the Chemical and physico–chemical parameters of ground water samples from wells around Ewekoro cement factory. They adopted a multivariate statistical tool using pH, conductivity, dissolved oxygen (DO), total dissolved solids (TDS), biochemical oxygen demand (BOD), total hardness, acidity, alkalinity and anions. They discovered quantities of toxic metals (lead and cadmium) whose value exceeds the standards of World Health Organization (WHO). Olukorede et a., (2011) and Gbadebo et al., (2010) investigated the concentration of radio nuclei around the environs of the factory by extracting soil samples. The survey revealed that the radiation doses due to natural radio nuclides around Ewekoro are very low and insignificant to cause any serious health problems to the people living in the area. Olaleye et al., (2005) gave a detailed work on the suspended air particles around Ewekoro. The highest point of deposition was Wasinmi which was 9.4Km from the factory.

MATERIAL AND METHODS

Ewekoro cement factory is located five kilometers North of Ewekoro town (6º55′N, 3º12′E /6.93ºN, 3.2ºE). It is within the tropical rainforest belt of Ogun state, southwest-Nigeria. The topography of Ewekoro is classified as a southern upland (Gbadebo et al., 2010). It has an area of $594km^2$ and a population of 55,156 (at the 2006 census). The map of the towns and villages about Ewekoro is shown in figure 1.

THEORETICAL DERIVATION

From the research work of Chukwu (2012) and (Olaleye et al., 2005), the direction of flow of the pollutants from the stack is from the north of the cement factory. Therefore, the first step of our modeling was to know the direction of likely affected areas as shown in figure 2 below.

Previously, the wind speed have been measured and reported to be $1ms^{-1}$ and $0.72ms^{-1}$ respectively at 10m above the ground during the dry and wet seasons (Olaleye et al., 2005). The eddy diffusivity was measured by Lushi et al., (2010) as 2 -3 m^2/s, though it varies from place to place. The duration for the experiment was 4hours interval according to the author. All the assumption of the plume model was observed in the following derivation. The additional assumptions include:

- inclusion of the mild diffusion at the downwind plane as shown in figure 2;
- the angle of deviation (α and β) depends on the wind convection and it does not exceeds the angles. Therefore the cement dust noticed around the stack is as a result of the cement dust splash from the lower turbulent diffusion as shown in figure 2;
- the presence of air upthrust or viscous at the air layers. For simplicity of solving the equations, we made it negligible;
- the width of the plume (red and blue lines) varies with respect to angle of deviation (α and β).

Figure 1. Mapping of Ewekoro and its neighboring towns and villages (Microsoft World Map, 2009)

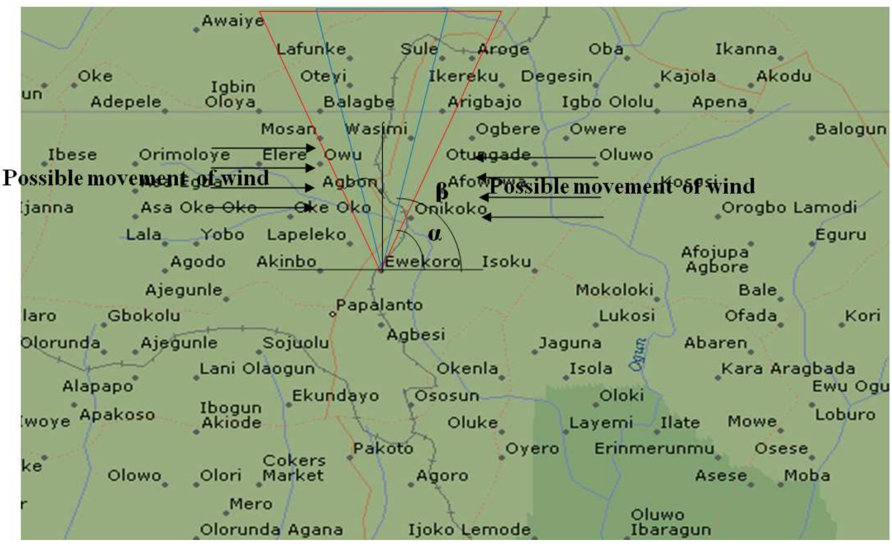

Figure 2. Directional view of air pollutant flow

$$V_x = V\cos\alpha \quad [1]$$

or

$$V_x = V\cos\beta \quad [2]$$

The second step is to examine a life pictorial view of the model as shown in figure 3 and the theoretical diagram of the Ewekoro cement plant stack as shown below in figure 4. The objective of the pictures is to enable the reader capture the derivation analysis of the advection-diffusion equation from the remodeled Gaussian plume model (Turner, 1994).

Figure 3. Pictorial view of the movement of the pollutants from the stack at Ewekoro

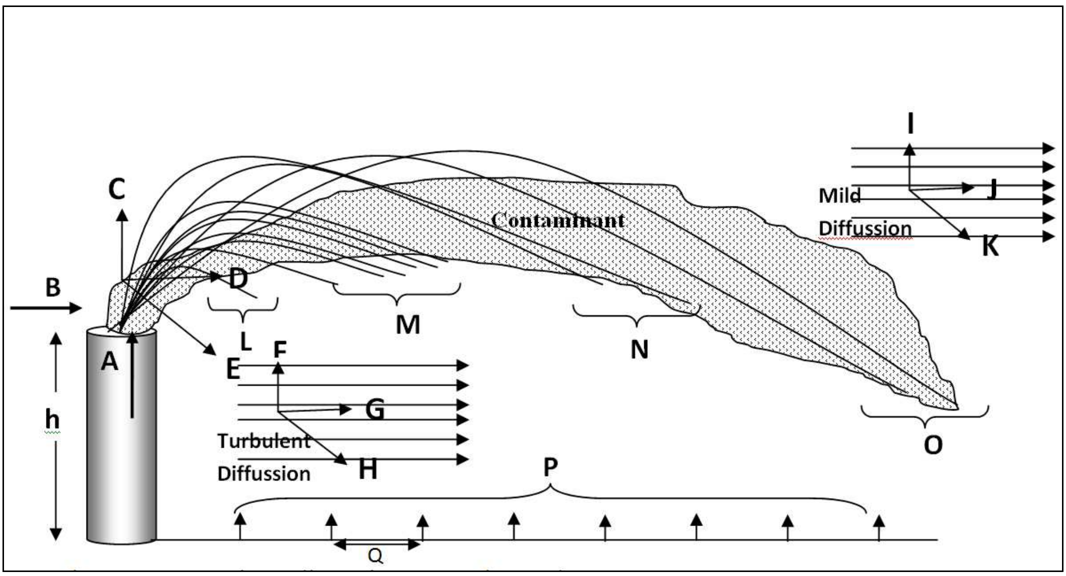

Figure 4. Contaminant dispersion pattern in Ewekoro cement Factory

The deterministic model generated from the diagram above for the dispersion of contaminants into the atmosphere based on the remodeled advection diffusion equation leads to the following sets of equations

$$A = \frac{\partial c}{\partial t}\ ; \qquad B = V_s \frac{\partial c}{\partial r}; \qquad C = V_z \frac{\partial c}{\partial z}; \qquad D = V_x \frac{\partial c}{\partial x}; \qquad E = V_y \frac{\partial c}{\partial y}$$

Where $= \sqrt[2]{x^2 + y^2 + z^2}$, and $V^2 = V_x{}^2 + V_y{}^2 + V_z{}^2$

$$F = \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right); \ G = \frac{\partial}{\partial x}\left(K_z \frac{\partial c}{\partial x}\right) = 0\ ; \ H = \frac{\partial}{\partial y}\left(K_y \frac{\partial c}{\partial y}\right); \ I = \frac{\partial}{\partial z}\left(K_{z2} \frac{\partial c}{\partial z}\right);$$

$$J = \frac{\partial}{\partial x}\left(K_{z2} \frac{\partial c}{\partial x}\right) = 0; K = \frac{\partial}{\partial y}\left(K_{y2} \frac{\partial c}{\partial y}\right); \ L \approx \frac{2V_{1x}^3 V_y}{gV^2}\ ; \ M \approx \frac{2V_{2x}^3 V_y}{gV^2}; \ N \approx \frac{2V_{3x}^3 V_y}{gV^2};$$

$$O \approx \frac{2V_{4x}^3 V_y}{gV^2}$$

Where $V_r{}^2 = V_{nx}{}^2 + V_y{}^2$ and L, M, N, O represents different points of cement dust deposition along its transmission. The parameters used for the modeling is defined as follows:

V = given wind velocity (m/s)

P= Air Upthrust

x = along-wind coordinate measured in wind direction from the source

y = cross-wind coordinate direction

z = vertical coordinate measured from the ground

C(x,y,z) = mean concentration of diffusing pollutants of diffusing substance at a point (x,y,z) [kg/m3]

K_y, K_x = eddy diffusivities in the direction of the y- and z- axes [m2/s]

S = source/sink term [kg/m3-s]

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

$$\frac{\partial c}{\partial t} + V_x \frac{\partial c}{\partial x} - V_z \frac{\partial c}{\partial z} - V_y \frac{\partial c}{\partial y} = \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{z2} \frac{\partial c}{\partial z}\right) + \frac{\partial}{\partial y}\left(K_{y2} \frac{\partial c}{\partial y}\right) - P + S$$

[3]

$$-V_z \frac{\partial c}{\partial z} = -\frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial c}{\partial y}\right) \qquad [4]$$

$$V_x \frac{\partial c}{\partial x} = \frac{\partial}{\partial y}\left(K_{y2} \frac{\partial c}{\partial y}\right) - \frac{\partial}{\partial z}\left(K_{z2} \frac{\partial c}{\partial z}\right) \qquad [5]$$

Equation 5 was solved using separation of variable i.e. C=X(x)Y(y) with the initial boundary condition are x=1, X=1; y=1, Y=1; z=1, Z=1.

The first solutions of C by equation [4 and 5],

$$C(y,z) = \frac{Q}{2} e^{\sqrt{\left(y^2 + \frac{1}{yk_y}\right) + z}} \left(e^{\left(\frac{V_z + \sqrt{V_z^2 - 4k_z}}{2k_z}\right) z} - e^{\left(\frac{V_z - \sqrt{V_z^2 - 4k_z}}{2k_z}\right) z} \right) \qquad [6]$$

$$C(x,y,z) = Q\sqrt{\frac{y^3 z^3}{K_y K_z V_x^2}}\exp(xV_x) + In\left(\sqrt{\frac{K_y}{y}}\right) + In\left(\sqrt{\frac{K_z}{z}}\right) \quad [7]$$

Equation 3 was also solved using separation of variable with the 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 solution

$$C(x,y,z) = \frac{V_x V_y}{V_z} e^{\left(\frac{4x}{k_z+k_{z2}}\right)^{\frac{1}{2}}} e^{\left(\frac{4y}{k_y+k_{y2}}\right)^{\frac{1}{2}}} \quad [8]$$

$$C(x,y,z) = \frac{V\cos(\beta-\alpha)V_y}{V_z} e^{\left(\frac{4x}{k_z+k_{z2}}\right)^{\frac{1}{2}}} e^{\left(\frac{4y}{k_y+k_{y2}}\right)^{\frac{1}{2}}} \quad [9]$$

$$C(x,y,z) = \frac{V\cos(\beta)V_y}{V_z} e^{\left(\frac{4x}{k_z+k_{z2}}\right)^{\frac{1}{2}}} e^{\left(\frac{4y}{k_y+k_{y2}}\right)^{\frac{1}{2}}} \quad [10]$$

Hanna et al., (1996) defined the following terms, W = worst case cloud width [m] (usually assume W = 0.1x, where x is distance from the source). The value for W was substituted in the modeling for either x and y in the solutions. Further on the velocities ratio,

$$V^2(1-\cos(\beta)) - V_z^2 = V_y^2 \;;\; V^2(1-\cos(\beta-\alpha)) - V_z^2 = V_y^2 \quad [11]$$

Equation 11 will be used subsequently to substitute for $\frac{V_y}{V_z}$ when implementing the model.

From the analysis of point L,M,N,O equation[11] becomes

$$\left(V^2(1-\cos(\beta)) - \frac{gW}{2\cos^2(\beta)}\right)^{1/2} = V_z \;;\; \frac{gW}{2\cos^2(\beta)} = V_y \quad [12]$$

Different deposition points were documented by Olaleye et al., (2005), the Junior Staff Quarters (JSQ) (1.1 km South), Olapeleke (1.0 km West), Itori (4.8 km North), Wasinmi (9.5 km North) and Alaguntan settlements (1.5 km East) was the sampling points. We shall assume K_z=200m^2/s, K_{z2}=100m^2/s, K_y=120m^2/s, K_{y2}= 150m^2/s

RESULTS AND DISCUSSION

The validity of equation 6 - 12 was confirmed in table 1, the mean concentration of diffusing pollutants at a point is dependent on the directional wind flow velocity which have been proven to be almost accurate to the experimental air pollutants deposition at various sampling points reported by Olaleye et al., (2005). The large percentage error noticed in the theoretical reading may be as a result of the inclusion of domestic air pollutants around the sampling points (El Desouky et al., 1998). Also, it could be explained that the percentage error testifies of the accuracy of the non Gaussian model (Van Ulden, 1978) which was accounted for in our derivations. The low air pollutant deposition on the west side of the Ewekoro cement factory was due to the minute angular displacement of the plume (β=5). It is also interpreted that wind speed at the time when the deposition was made at each sampling point, the average shift of the plume which was an effect of the wind field dynamics, was more to the north-west than to the north- east.

Table 1. Total Deposited air particles
(Data source: Olaleye et al., 2005)

	Experimental Air deposition	Theoretical Air deposition	% error
Alaguntan	23.51	23.27(β=30)	1.20
Itori	27.89	25.30(β=60)	9.20
Junior staff qtrs	10.35	10.34(β=40)	0.97
Olapeleke	15.84	12.75(β=5)	19.5
wasinmi	5.34	5.89(β=0)	10.2

Also from the solutions, it is reported that $\frac{V_y}{V_z} \geq 1$ at the source point and $\frac{V_y}{V_z} \ll 1$ at the farthest deposit points. The relationship of V_y & V_z to the resultant wind speed V is shown in figure 4.

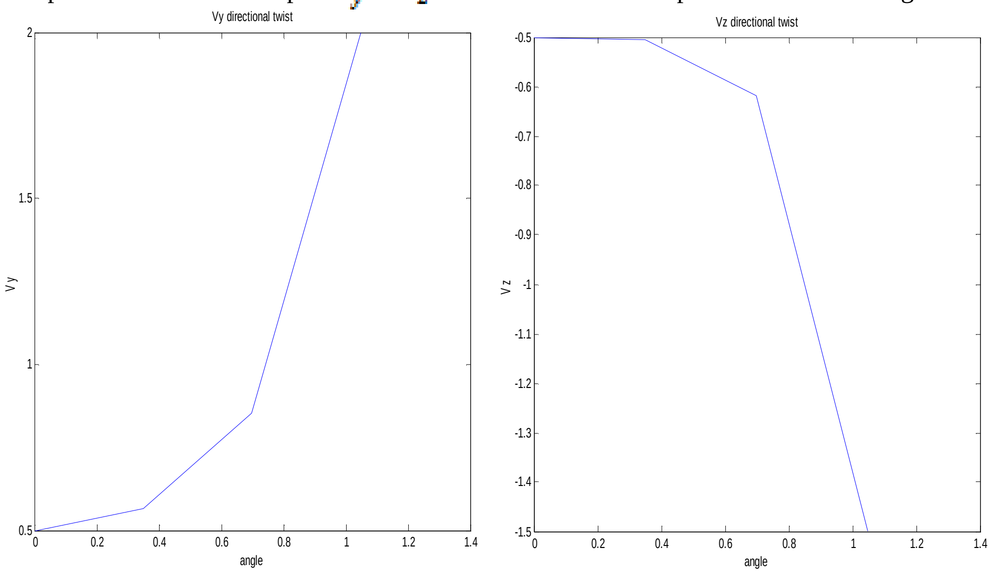

Figure 5. Directional changes of V_z and V_y in a plume model of Ewekoro cement factory

It is also shown in figure 5 that the maximum wind speed along the z-direction is $V_z = 1.0m/s$ at an angle $24 \geq \beta \leq 90$ (at 10m above the earth surface) while the maximum wind speed along the y-direction is $V_y = 2.0$ at an angle $0 \geq \beta \leq 37$. This result conforms to the measured wind speed (Lushi and Stockie, 2010; Olaleye et al 2005).The V_z component of the wind speed shown in figure 4 confirmed the final directional movement of the air pollutants which agrees with the principles of deposition (Carruthers et al., 1997; Berkowicz et al., 1987; Briggs, 1975; Ensor et al., 1971). The mild diffusion (which is quite different from the known turbulent diffusion) was generated in equation 4 and its solution given in equation 6. Equation 4 was derived to analyze regions close to the final deposition point where a rather mild diffusion is experienced. Even though Olaleye et al's data showed a reduced deposition of contaminants, equation 4 explains that there is the possibility of highest chemical transformation at the final deposition point because air particles at this point is the lightest by mass and energetic to interact with atmospheric current (Lovejoy et al., 2004; de Gouw et al., 2006). Therefore, the three dimensional semi-plume model determines rather the deposition points and two dimensional semi- plume model determines the wind field dynamics. Therefore, the solution to controlling the flow of air pollutants from any anthropogenic sources, is calculate the mathematical inverse of equation 6 and 12.

CONCLUSION

The validity of the model – juxtaposing it with field work showed that it was accurate. The dependence of the wind speed on plume angular displacement (as shown by the solutions and diagram) should be incorporated into the computer translation of this model. The diffusivity was of two types i.e. the turbulent diffusion at the source of dispersion and mild diffusion at the point of deposition. The solution of equations 3-5 shows that the diffusivity at the deposition point supports high chemical transformation. The semi-plume model determines rather the deposition points and two dimensional semi-plume model determines the wind field dynamics. From Figure 4, mean concentration of diffusing pollutants is directly proportional to the plume angular displacement which has been explained to be due to the spreading of the plume and the variational wind speed (Rao, 2002). The solution to wind field dynamics from anthropogenic sources was simply to calculate the mathematical inverse of equation 6 & 12.

ACKNOWLEDGEMENT

The paper enjoyed the part funding of Covenant University.

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