Plume Model: A Simple Approach to Air Quality Control

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Abstract. Air is an essential element in the life of humans, and everyone deserves to breathe in clean air. But anthropogenic activities from industrialization and modernization, as well as some natural disasters such as earth quake and volcanic eruption pollute the air. Consequently, air pollution threatens the health of people living in close proximity to the source of pollution by causing or aggravating sicknesses like, heart problem, cancer and respiratory disorder. The dispersion of air from a point source tends to follow the shape of Gaussian or normal statistical distribution. The present paper aims at examining Gaussian plume model as the easiest and simplest model among the lists of air dispersion models evaluated, stating the various issues from the source to the receptors. Gaussian Plume model is mostly used in the analysis of air dispersion with the concentration of a given place, having function of the distance from the source, emission rate and the meteorological data, mostly temperature, wind speed and wind direction, with the help of some various assumptions, in order to estimate how much air has reduced or travelled from the source and the concentration at the ground level. The model uses Briggs coefficients sigma y and z to get both vertical and horizontal dispersion. Plume rise determines dispersion and transportation levels, and thereby affect the distance to maximum ground level concentration and the maximum ground level concentration, the taller the stack or chimney (source), the larger the plume and the lower the concentration at the ground. A week analysis on pollutants generated from Larfarge cement factory Sagamu, Ogun State was carried out. The result shows mathematical simulation of Gaussian plume model of pollutants concentrations from the source and the applicability of the model.

Keywords: Stack height, air quality, cement factory, meteorology, models, dispersion

1. Introduction
The control of Air Quality is a challenge of the present world especially for the industrial cities and towns. [1] defined air pollution as the “presence especially in the outdoor environment of contaminants such as dust, fumes, gas, mist, odour, smoke or vapour in quantities or characteristics and of duration which can cause injurious to human, plant or animal life or to property or which unreasonably interferes with the comfortable enjoyment of life and property.” Though the definition is outdoor specific, it is necessary to observe that indoor pollution from kitchen and faulty planning cannot be neglected. Air pollution importance cannot be over-emphasized because unlike others, an average adult consumes about 12 Kg of air per day which is about 12 times more than the food consumption [2]. A number of air pollution in the past such as London smog (1952) with about 4000 casualties and Bhopal India Dec. 1984, in Union Carbide industry where about 2500 people died when toxic gas methyl isocyanate leaked accidentally and over 100000 were severely affected. This defines the need for Air Pollution control especially in urban or Industrial cities [2].
Air pollution modeling is a computer/mathematical method for simulating air quality processes. It is the tool that describes the association among factors such as the atmospheric concentration, meteorological conditions, emissions and deposition. Estimation of air pollution gives necessary information about the air cluster, settling and it gives the description of air quality at particular times and position not stating the causes of the problem. Consequently, air pollution modeling gives sufficient description of the problem as well as the causes and factors responsible.

Air pollution modeling predicts both the past and the future consequences [3]. Subsequently, a simple model “The Gaussian Plume Model, is a reactive model developed to calculate the ground level and impact from the source. Gaussian model was derived practically from both horizontal and practical spread of the plume [4]. [5] and [6], concluded that understanding of the dispersion of plumes from stacks has been a challenge in air pollution modeling. Over the years, there have been several modeling used in solving air quality challenges, according to [7].

Air pollutants may be classified into Natural Contaminants such as pollen grains; Aerosols like dusts, smoke, mists, fogs and fumes; and Gases which include: Sulphur dioxide, Oxides of nitrogen, Carbon monoxide, Hydrogen sulphide, Hydrogen fluoride, Chlorine and hydrogen chloride, Ozone and Aldehydes. Also, Air pollutants are classified based on source as being stationary or mobile: Point source (large stationary source as power plants), Area source (small stationary sources like residential heating) and Mobile source (line source like highway vehicles or area source like Aircraft at airports) [2]. The aim of this work is to assess how to control point source pollutants such as in Cement factory with high Stack or Plume/Chimney and through that reduce air pollution.

1.1 Types of Air Quality Models:

The three types of models used in Air Quality are:

1.1.1 Photochemical Models

They are mathematical quality model in large scale used in simulating the changes in the atmosphere. This kind of model can be used at multiple spatial scales with local, region and global, it is also used in regulating policy and simulating the impacts from source by giving/circulating pollutant concentrations and deposition from inert and chemically reactive pollutants over large spatial scales. There are two of photochemical air quality models commonly used in air quality evaluation: the Eulerian grid model that makes use of a fixed coordinate system with respect to the ground and the Lagrangian trajectory model. Community Multi-scale Air Quality (CMAQ)-Model is an active open source project form U.S. EPA that is used in determining the impact of air quality for multiple pollutants at multiple scales and to deduce and simulate physical interactions in the atmosphere [8]. Comprehensive Air quality Model with extensions (CAMX) - This is an open source computer comprehensive air quality model, it is for gaseous and particulate air pollution. The computer aid is easy to work with, simulates to use over geographical scales and it deals with inert and chemically active pollutants. It is also a plume-in-grid and source apportionment capabilities. Urban Airshed Model Variable Grid (UAM-V)-The UAM-V is the pioneering effort in photochemical modeling in the early 1970s in staging ozone, is the most used photochemical air quality model, that is technically okay and reliable, it is a three-dimensional grid model developed in calculating the inert and chemically reactive pollutants in order to simulate both physical and chemical processes in the atmosphere. Regional Modeling System for Aerosol and Deposition (REMSAD)-REMSAD was developed to calculate the chemically and inert pollutants concentration by simulating the physical and chemical processes in the atmosphere that affect pollutant concentrations over regional scales. The processes include particulate matter, haze and airborne pollutants, like mercury and soluble acidic components [8].

1.1.2 Meteorological Models

Meteorology is important for the dispersion of pollutants because it is the primary factor that determines the diluting effect of the atmosphere, for the purpose of air quality, meteorological grid models are used with chemical interaction models. Meteorological grid models use mathematics to formulate and simulate processes like wind speed, wind direction and temperature.
California Meteorological model (CALMET)-This reconstruct the 3D wind and temperature fields; it also determines the 2D of micro meteorological variables that is used for dispersion simulation. The Fifth Generation Penn State University/National Centre for Atmospheric Research mesoscale model (MM5) - This is a regional mesoscale model used in creating weather forecasts and climate projections, it can also be used in research by comparing it to other model. MM5 can also be used for air quality models. Plate 1 shows weather station used to obtain Data on wind speed and direction, rainfall volume, relative humidity and air pressure for weather forecasting.

Weather Research Forecasting model (WRF)-Numerical weather prediction system used for research and forecasting applications. WRF produces the actual atmospheric conditions for researchers (observation to analyses).

Plate 1: Airport weather station used to obtain Data on wind speed and direction, rainfall volume, relative humidity and air pressure.

1.1.3 Dispersion Models
Dispersion models are computer programs that use mathematical algorithms to simulate how pollutants disperse and react in the atmosphere, it estimates mainly based on Gaussian plume model which deals with the stable wind speed and turbulent and height [9]. Dispersion modeling allows estimating concentration of pollutants at specific ground level receptors surrounding the emission source; it is used for planning and managing existing emission. The most commonly used dispersion models are the steady state Gaussian plume models. Examples include AUSPLUME, ISCST3, AERMOD and CTDMPLUS [10].

America Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) - A steady type of Gaussian plume model that uses wind in transmitting emission, it is been used to substitute ISCST3, the model is based on atmospheric boundary layer. It employs flat or complex, rural or urban terrain. Gaussian dispersion is used for stable conditions while non Gaussian is used for the unstable conditions.

California Puff Model (CALPUFF)-An advanced non steady state Lagrangian puff model that can simulate dispersion in quiet and advanced all coastal terrain. It is used for long range coverage above 50miles. This takes care of visual impact plumes [11].

Industrial Source Complex for Short Term Version 3 (ISCST3)-This is a Gaussian model used in assessing pollutant concentration in sources from industrial complex. It takes care of the plume rise, point source, deposition of particles and settling.

Atmospheric Dispersion Modeling System (ADMS)-An advanced dispersion model designed for calculating concentrations continuous pollutants from line, point area sources from point source or discrete from point sources. Plate 2 shows the dispersion of pollutant through the point source of a Stack.
Plate 2: Cement factory Stack showing the discharge of pollutants into the atmosphere from waste generated by the plant following the Gaussian model.

2. Methodology

2.1 Nature and Causes of Air Pollution

There are many forms of environmental pollution, and the resultant health risks include diseases of all kinds affecting almost all organ systems of the body. According to [12], this variation in forms of environmental pollution makes each pollutant have its own health risk profile, which makes summarizing all relevant information into a difficult task. Air pollutants are usually categorized into suspended particulate matter (PM) (dusts, fumes, mists, and smokes); gaseous pollutants (gases and vapors); and odours. Outdoor air pollution is caused mainly by the combustion of petroleum products or coal by motor vehicles, industry such as cement factory, and power stations [12].

2.2 Location of Study

Sagamu is a city in Ogun State, South-west of Nigeria, Figure 1. It is located between the cities of Ibadan and Lagos and on Coordinates 6°50′N 3°39′E on Area of 614 km², with Population 253,412 [13]. Sagamu has many industries, of which the Larfage cement factory is the major in region.

Figure 1: Map of Nigeria Showing Ogun State and Sagamu [14]

Larfarge cement factory is one of the major contributor of air pollution in Sagamu environs, thereby threatening the health of people living or working around the factory. [15] established that there were contamination and impacts on air, land and noise pollution conducted at Ewekoro area of Ogun and through the study investigated on health and environmental challenges of the Cement Industry on Physical surrounding settlement of Ewekoro, Ogun State.

Data collection was done on the three (Ikorodu, Ijebu-ode and Abeokuta) major routes to Larfarge cement factory Sagamu using Aeroqual 500 series. Concentration of four different gases, CO2, SO2, VOC NO2 and particulate matters were collected on weekly basis over a period. Meteorological data such as Relative humidity, Temperature, Rainfall, Wind speed and Wind direction were also determined. All data collected were used in calculation in other to obtain the concentration levels of the pollutants.
2.3 Controlling Pollutants with Plumes

The aim of air pollution control is to reduce to the minimum the release of pollutants to the atmosphere and hence promote sufficient dispersion and dilution of released pollutants within the atmosphere. Efficient Stack height determination ensures optimal release condition of pollutants that will limit ground level concentration [16]. Air pollution is therefore controlled in an Industrial plant by means such as the nature and height of Plumes, changing the raw material, the process conditions, procedure and by ensuring preventive maintenance. Pollutants are being controlled through different plume behaviours, and it depends on the degree of instability of the atmosphere and the wind turbulence in form of:

Looping: It is an unstable condition which occurs with heat and light conditions, it moderates wind speed during hot weather in the presence of eddies, Eddies carry plume to the ground level for a while by causing surface concentration of pollutants near the stack.

Coning: A neutral lapse rate condition which occurs within cloudy skies both in the day and night, shape of plume is vertically symmetrical, pollutants concentrations are fairly carried downwind before reaching the ground, it also works between moderate and high wind.

Fanning: This is an inversion condition which occurs during the dispersion of plume in the presence of light wind. If the density of the plume is different from that of the surrounding atmosphere, then the plume travels parallel to the ground when stable plume is within 10 to 20 km downwind.

2.4 Effect of Stack Height on Pollutant Removal

The height of the stack or chimney is governed by such factors as meteorological parameters, height of the nearest building or structure, prevailing wind direction, height of natural landforms, location of air intake, type of equipment draft (natural or forced), type of fuel and local and/or national ambient air quality requirements. Stack height is the most important parameter which highly affects transportation and dispersion of pollutants [17]. Stack height can affect pollutant removal by: Limiting pollution at ground level in order to make pollution stay within acceptable limits; Preventing downwash during periods of high wind velocity; Lowering ground level concentrations near the source; Increasing the amounts of pollutants emitted to the atmosphere.

2.5 Application of Gaussian Plume Model

The application and the use of the model under review are enormous, Gaussian plume can be used in the day to day activities. The model can be used in predicting the impacts of pollutants from the industry/factories, to disseminate pollen in agriculture.[18], it is also used in wind control (pheromones) during insect entomology behaviour[19]

3. Result and Discussion

Gaussian plume model is used in determining or predicted ground level concentration of particulate matters long downwind of the factory. Simulation of the effects of deposition and fumigation is best done by Gaussian plume model.

![Figure 2: Schematic figure of a Gaussian plume. The \( He \) effective stack height and the crosswind and vertical deviation of the profile are the key parameters of the model [20]](image)
The equation for a Gaussian plume is

\[ c(x, y, z) = \frac{Q}{2\pi \sigma_y \sigma_z} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \left[ \exp\left(\frac{-(x-h)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-(x+h)^2}{2\sigma_z^2}\right) \right] \]

where \( c \) is a concentration at a given position, \( Q \) is the source term, \( x \) is the downwind, \( y \) is the crosswind and \( z \) is the vertical direction and \( u \) is the wind speed at the \( h \) height of the release. The \( \sigma_y, \sigma_z \) deviations describe the crosswind and vertical mixing of the pollutant. The following assumptions are made to develop emission from cement factory [21]: (i) A continuous and point source emission (ii) Eddy diffusion, advection/diffusion equation (iii) Diffusion in the downwind direction is negligible, presence of vertical and crosswind only (iv) Wind speed from point source to receptor is constant (v) Atmospheric turbulence is constant (vi) Plume reflection

The Gaussian plume is derived by assuming steady state conditions. The formulae do not depend on time, the meteorological conditions are also assumed to remain constant from source to receptor instantaneously. Although, the plume characteristics will not change over time, and they depend on emission change and meteorological conditions. Gaussian plume model can be used when: (i) the pollutants are chemically inert (ii) the terrain is not complex (iii) the meteorology may be considered uniform spatially and (iv) there few periods of calm or light winds.

The concentrations of the pollutants and the meteorological data results for the two weeks period were obtained to calculate the emission rate, which were used as input data for the Gaussian plume modeling for the point source.

**Table 1:** Shows the typical parameters measured and used for the modeling of concentration of pollutants at the site of a Cement factory

| Point | Landmark/ Name | Location/Coordinates | Time (Hr) | Temp °C | RH (%) | Light Ft-cd | Wind Speed (m/s) | P.M2.5 µg/m3 | CO2 ppm | SO2 ppm | VO C ppm |
|-------|----------------|----------------------|-----------|---------|---------|-------------|-----------------|-------------|---------|---------|-----------|
| 1     | Regal Height s | 754285 569503        | 11:50     | 29.9    | 73.6    | 980.2       | 0.7             | 8.6         | 650     | 0.00    | 1104      |
| 2     | UBA            | 755062 570785        | 12:28     | 30.3    | 69.4    | 1245.1      | 2.1             | 16.9        | 677     | 0.02    | 736.6     |
| 3     | OPC-Standard   | 756754 571896        | 12:46     | 29.6    | 71.5    | 824.5       | 2.2             | 62.7        | 687     | 0.00    | 1089      |
| 4     | Terrazo House | 758071 572669        | 13:07     | 30.5    | 72.3    | 723.3       | 0.4             | 37.5        | 665     | 0.00    | 624.1     |

4. **Conclusion**

This paper presents a description of Gaussian plume mathematical model as a flexible model applicable for dispersion from source to receptor; it is based mainly on assumptions developed for simulation. In the current study, wind speed controls the dispersion of air pollutants released from the point source as well as the vertical height above the eddy diffusion (vertical and horizontal). From the research it is established that Stack height affects the dispersion of pollutants in a Cement factory and hence optimally designed chimney height influence the air quality around the location of the factory.
Acknowledgements
The authors wish to thank the Chancellor and Management of Covenant University for the platform made available for this research. The authors also acknowledge the reviewers for their valuable comments.

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