PREDICTION OF DOWNWIND AIR POLLUTION LEVELS FROM AN INDUSTRIAL STACK IN JOS, NIGERIA.

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ABSTRACT: In this work the Gaussian Plume Dispersion Model is adopted to predict the concentration of pollutants in the windward direction of an industrial stack in Jos. The emission and atmospheric dispersion of air pollutants from the stack are considered in relation to such parameters as atmospheric stability, wind speed, mass flow rate of pollutants and the effective stack height from the ground level. The magnitude of ground level concentrations of identified pollutants such as SO_2, CO_2, NO_x and CO are evaluated for both an elevated source and a ground level source. The trend of the variation of pollutant concentration with downwind distance shows that the ground level concentration decreases downwind along the plum centre line. The maximum surface level concentration of the plum centerline occurs at 400m from the emission source. For a specific atmospheric stability condition and mass flow rate from the stack, the concentration of pollutants at a fixed downwind point decreases as the stack height increases.

INTRODUCTION

When pollutants are emitted into the atmosphere, they are subjected to the effects of transport, dilution, modification and removal. Therefore, the meteorological tools of analysis, prediction, monitoring and modeling are essential for the evaluation of air pollution (Meikap, 2007). Dobbins (1979) observed that it is practically impossible to measure the concentration of air pollutants everywhere they occur, hence the need to adopt a model that can be used to simulate the dispersion away from the emission source and to predict the ground level concentration. In the preparation of environmental impact assessment of pollutants, it is imperative that a reliable model be built to predict the impact of air pollutants on the environment of the industrial stack.

The most frequently and widely adopted models are the Gaussian models. They are analytically and conceptually appealing and computationally cheaper (Boutahar et al., 2004). They provide a mathematical simulation of how air pollutants disperse in the ambient atmosphere (Arya, 1999; Maduemezia, 2003). The models can easily be modified to account for different types of sources of emission, atmospheric stability and surface properties. Some of the applications include the study of the dispersion of ordour downwind from a livestock facility by Smith (1993). Also in the process of evaluating the horizontal pollution potential using wind data at Makurdi, Nigeria, Isikwue et al. (2010) applied the model to estimate the ground level concentration of some gaseous pollutants from an elevated source. The Gaussian plum equation has been used to estimate the impact of a single source pollutant over travel distances as large as 100km in some cases (Meikap, 2007).

In this work the ground level concentrations of gaseous effluents, SO_2, CO_2, NO_x and CO emitted from an industrial stack of a brewery at Jos (9°52′N, 8°52′E) are estimated at different locations downwind of the stack. The crosswind concentrations are also computed. It is intended to show how the variation of the stack height influences downwind air pollution levels on a local scale.

MODEL DESCRIPTION

The Gaussian plume dispersion model is given by the equation reported by Dobbins (1979) as:

$$C(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left(\frac{-y^2}{2\sigma_y{}^2}\right)\left[\exp\left(-\frac{(z-H)^2}{2\sigma_y{}^2}\right)+\exp\left(-\frac{(z+H)^2}{2\sigma_y{}^2}\right)\right] \quad (1)$$

Here C(x,y,z) is the concentration in mass per unit volume at the point (x, y, z), Q is the emission rate of the pollutant released and measured in kgs^{-1}, σ_y and σ_z are the crosswind and vertical dispersion coefficients respectively in metres, u is the mean wind velocity at the height H which is the effective height of the emission above the ground level.

At any point on the ground (x, y, o) the concentration due to an elevated source emission (ESE) along the X – axis is

$$C\,(x, y, o) = \frac{Q}{\pi\sigma_y\sigma_z u}\exp\left(\frac{-y^2}{2\sigma_y{}^2}\right)\exp\left(-\frac{H^2}{2\sigma_z{}^2}\right) \quad (2)$$

Also on the surface, in the windward direction, the Ground Level Concentration (GLC) is given by the expression,

$$C(x, o, o) = \frac{Q}{\pi\sigma_y\sigma_z u}\exp\left(-\frac{H^2}{2\sigma_z{}^2}\right) \quad (3)$$

For an assumed ductless emission when H = o, z = o, the concentration from the Ground Source Emission (GSE) is

$$C(x, y, o) \quad \frac{Q}{\pi\sigma_y\sigma_z u}\exp\left(-\frac{y^2}{2\sigma_y{}^2}\right) \quad (4)$$

The last case considered is equation (4) when y = 0, we have the concentration due to the Ground Source emission (GSE in the X – direction as

$$C(x, o, o) \quad \frac{Q}{\pi\sigma_y\sigma_z u} \quad (5)$$

METHOD OF PREDICTION

Site and Emission Data

The Jos International Brewery was chosen as the site for the study. It is located in a major industrial area south of Jos city, off the old airport road, surrounded by other factories, the Nasco Fibre Plc, Cocacola Plc, and Standard Biscuit Plc. The brewery is on an expanse of land of about 2 hectares generally at an elevation of 1284m above mean sea level. It has two closely built identical stacks each of height 20m separated 2.5m from each other with an exit cross sectional area of $0.82m^2$. The stacks area usually operated one at a time, thus each constitutes an elevated point source of emission of air pollutants. The boiler in the factory uses low profile fuel oil which is known to produce identifiable effluent gases like Carbon dioxide CO_2, Carbon monoxide CO, Sulphur dioxide SO_2 and Nitrogen Oxides NO_x (USEPA, 2007). From the boiler manufacturer's booklet in the factory, the mass flow rate from the stack was given as $0.99kgs^{-1}$. The individual emission rates given in Table 1 were deduced from the principle of conservation of mass at the stack exit. With these flow rates, the common exit velocity of the gases was obtained as $0.15ms^{-1}$ by considering the product of density, velocity and exit cross sectional area of the stack (Benson, 2005). The molecular weights and the densities (Elsevier, 2007) of the pollutants are also listed in Table 1.

Meteorological Conditions

The meteorological data needed were wind speed, wind direction and ambient temperature which were obtained from the meteorological unit of the Department of Geography and Planning of the University of Jos, Jos in the month of June 2008. The wind measurements were taken from the anemometer mounted 2m above the ground level. At the period of measurements, the average wind speed was $3.3ms^{-1}$ from the southwest direction. The wind speeds at the vertical heights of 10m and 20m from the ground were computed as 5.2ms^{-1} and 6.3ms^{-1} respectively using the wind profile law of Counihan (1975) and the power law exponent of 0.28 for Jos (Sirisena et al., 1991). The wind speed at 10m was required for the classification of the atmospheric stability (Maduemezia, 2003). The daytime incoming solar radiation was moderate and the average ambient temperature was 25°C. Based on the Pasquill – Gifford stability classification (Dobbins, 1979), the stability class of the atmosphere over the brewery site was identified as class C(slightly unstable atmospheric condition, moderate daytime insolation and wind speed between 4ms^{-1} and 5.5ms^{-1}).

Table 1. Properties of the Pollutants and their emission rates

Pollutant	Molecular Weight kg/kilomole	Density kg/m^3	Mass flow rate kg/s
SO_2	65.054	2.927	0.3605
CO_2	44.001	1.980	0.2439
NOx	46.010	1.880	0.2316
CO	28.010	1.250	0.1540
		Total	0.9900

The vertical dispersion coefficient σ_z and the horizontal dispersion coefficient σ_y at specific distances X downwind of the stack were obtained from Briggs' interpolation formula for urban areas (Briggs, 1975) given as

$$\sigma_z = 0.20\,X \quad (6)$$

$$\sigma_y = 0.22X\,(1 + 0.0004X)^{-½} \quad (7)$$

The values of the coefficients which are increasing functions of downwind distance and related to the local turbulence intensity in the atmospheric stability (Meikap, 2007) (Table 2).

Table 2: Dispersion Coefficients and surface concentration from elevated (H=20m) and ground level (H=0) sources.

X(m)	**σ_y(m)**	**σ_2(m)**	**GLC(mgm^{-3})**	**ESE(mgm^{-3})**	**GSE(mgm^{-3})**	**GGC(mgm^{-3})**
100	21.5	20	70.54606	0.0014	0.0023	222.0479
200	42.3	40	26.08563	1.5952	1.8076	56.43061
300	62.4	60	12.63645	3.499	3.6989	25.50229
400	81.7	80	7.416598	3.5066	3.6179	14.60841
500	100.4	100	4.882799	2.9734	3.0334	9.510018
600	119.0	120	3.454048	2.4265	2.4605	6.686316
700	136.0	140	2.600099	1.9842	2.0046	5.014737
800	153.0	160	2.027142	1.6373	1.6501	3.900351
1000	186.0	200	1.337747	1.1577	1.1635	2.566682
1200	217.0	240	0.956995	0.8606	0.8636	1.833345
1400	247.0	280	0.721316	0.6646	0.6663	1.380575
1600	275.0	320	0.567228	0.5309	0.532	1.085007
1800	302.0	360	0.459313	0.4348	0.4355	0.878225
2000	328.0	400	0.380725	0.3634	0.3639	0.727748

Evaluation of pollutant concentration

Equations (2) and (3) provided the basis of computation of pollutant concentration at the ground level due to the elevated stack because the environmental impact of interest is at the ground level. For the crosswind concentration on the ground level, the coordinate y in equation (2) was 100m and the wind speed u equal to 6.3ms^{-1} at the stack height. The symbol ESE in Table 2 represents the surface concentration at the crosswind distance of y = 100m from the centre line. The symbol GLC represents the ground level concentration downwind of the stack. The effective stack height H of the pollutant source was taken as the physical height since the expected plume rise due to momentum release technique of Rama Krishna et al. (2007) applied at the exit velocity of 0.15ms^{-1} was negligible compared to the physical height. The assumption therefore is that as the effluent enters the atmosphere the plume attains its equilibrium altitude instantaneously and maintains it at all downwind distances considered here. The computed values of ESE and GLC are given in Table 2.

For purposes of comparison, a ductless emission was considered (i.e. the dispersion of the pollutants without the use of the industrial stack). In this case the effective height H was taken as zero and the surface wind 3.3ms^{-1} corresponding to that measured at the height 2m. The computations for the assumed ground source emissions, GSE in the crosswind and GGC in the downwind directions respectively, are shown in Table 2. To illustrate the variation of the ground level concentrations with the stack height H, equations (3) was evaluated for a fixed downwind distance X = 100m with H ranging from 20m to 60m.

RESULTS AND DISCUSSIONS

Downwind and Crosswind Concentrations of Pollutants

On the surface, in the direction of the wind, the concentration of pollutants GLC decreases as the distance X increases. This direction is generally referred to as the centre line or the plume axis. The variation on this axis is shown graphically on fig. 1 for the elevated source. The concentration from an assumed ground source GGC follows a similar trend but it is observed to be greater in magnitude than the stack emission. The effect of the stack is amply demonstrated as it carries the gaseous pollutants high into the atmosphere where they are released and dispersed by the wind thereby reducing the ground level concentration that would have existed around the neighbourhood of the industry. Moreover, at the stack height, an increased wind speed and invariably more atmospheric mixing and turbulence prevail. These conditions enhance more dispersion of pollutants in the air than on the ground (Beychok, 2005).

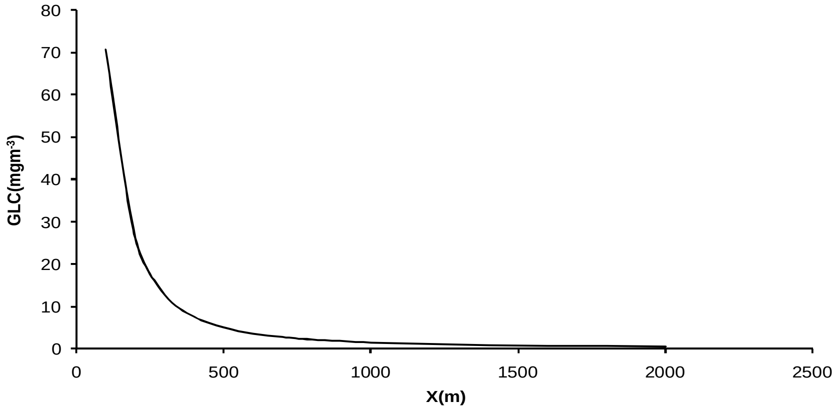

Fig. 1: Variation of GLC (mgm^{-3}) with x(m)

The crosswind concentrations at y = 100m off the X-axis give lower values compared to those obtained on the plume axis. This observation is applicable to both elevated and ground level sources. Unlike the downwind ground level concentrations GLC and GGC, the crosswind values ESE and GSE have peaks at about X = 400m from the stack (Fig. 2).

In terms of magnitudes, the plum axis concentrations, at times referred to as the ‘worst-case’ scenario (Maduemezia, 2003, Isikwue et al., 2010), are the maximum ground level concentrations occurring in the x-z plane passing through the plume centre line at y = 0. In Figure 2 it is also seen that within a relatively short distance, the concentration of the pollutants rises suddenly to the peak and thereafter decreases exponentially for a very long distance. This is accounted for in terms of the emission rate which dominates the dispersion nearer the stack, while the dispersion further away from the stack increases with the distance in the windward direction. In conformity with the theory and as previously observed above, all the cross wind concentrations (ESE and GSE) are lower in value than the downwind ground level concentrations (GLC and GGC). Wolak et al. (1996) attribute this to sharing motions perpendicular to the mean flow that contribute significantly to enhanced horizontal dispersion.

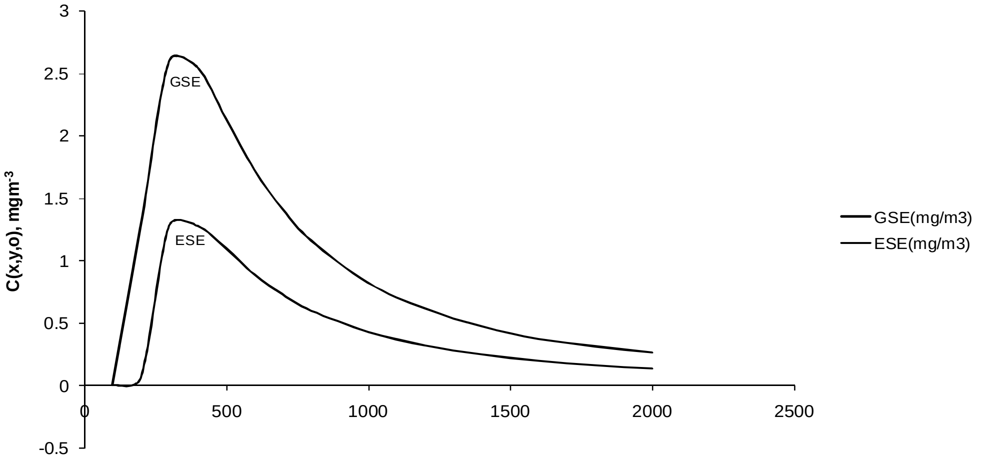

Fig. 2: Variation of SO^2 concentration ESE (mgm^{-3}) with X (m) at exit velocity of 0.15m/s

Variation of Pollutant concentration with height

The solution of equation (3) for the concentration at a fixed value of X relates the concentration with the stack height H. At X = 400m, the concentration decreases as the effective height H increases for a given value of mass flow rate. Fig 3 depicts this variation for H ranging from 20m to 60m and assuming a constant wind speed at these heights. Through this type of calculation for each of the atmospheric stability classes, it is possible to deduce the most appropriate stack height for the environment.

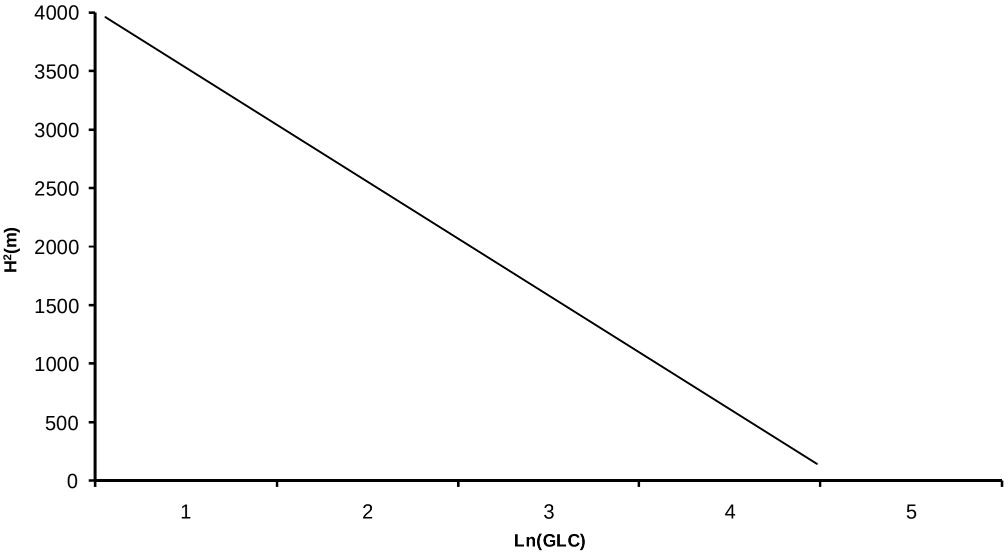

Fig. 3: Log linear variation of H^2 with concentration at a fixed downwind location

The Emission of SO_2, CO_2, NO_x and CO from the stack

The predicted ground level concentrations of the gaseous effluent components using the Gaussian dispersion model for various values of X downwind of the stack are shown in Table 3. In the computation it is assumed that there is no loss of mass, the effluent is composed of only the gases listed above and there is no interaction between them from the point of emission to the downwind point of measurement. Using the individual mass flow rates shown in Table 1, the gaseous concentrations on the ground for distances of X = 100m to X = 2000m are as follows: for SO_2, the range is between 26mgm^{-3} and 0.14mgm^{-3}, for NO_x the range is 17mgm^{-3} – 0.09mgm^{-3} while the CO concentration is between 11mgm^{-3} and 0.06mgm^{-3}.

Table 3: Predicted Concentrations of SO2, CO2, NOx and CO at various ground level locations downwind of the stack.

X(m)	**SO_2*(mgm^{-3})***	**CO_2*(mgm^{-3})***	**NO_x*(mgm^{-3})***	**CO*(mgm^{-3})***
100	26.00	17.38	16.50	11.00
200	9.60	6.43	6.09	4.06
300	4.60	3.11	2.95	1.97
400	2.70	1.82	1.73	1.15
500	1.80	1.21	1.14	0.76
600	1.30	0.85	0.81	0.54
700	1.00	0.64	0.61	0.40
800	0.80	0.50	0.47	0.32
1000	0.49	0.33	0.31	0.21
1200	0.36	0.24	0.24	0.15
1400	0.26	0.18	0.17	0.11
1600	0.20	0.14	0.13	0.09
1800	0.17	0.11	0.11	0.07
2000	0.14	0.09	0.09	0.06

Comparing these with the safety limits of 365μgm^{-3} for SO_2, 100μgm^{-3} for NO_x and 10mgm^{-3} for CO concentrations (WHO, 1994), the SO_2 concentrations at 1km and above from the source are within the specified standard. The NO_x concentrations at 1.2km and above are within the recommended limits while for CO the safe zone lies 100m away from the source. The concentration profile of CO_2 is also given in table 3 though carbon dioxide is not an air pollutant; it is a major constituent of greenhouse gases responsible for global warming (Malgwi et al., 2002, Abimbola et al., 2011). However these predicted concentrations are recommended for experimental verification because the concentration at any point from the source depends not only on the variability of weather patterns and pollution emission conditions but also on the presence of trees, building and other structures in the area. Furthermore additional work should be done to establish the chemical nature of the effluent and to establish the hazardous effluent conversion techniques adopted by the factory. In this work it has been assumed that no removal of pollutants has taken place in the plant and all the pollutants are emitted into the atmosphere. Actually a fraction of the pollutants is removed before they are injected into the atmosphere from the stack. In a bid to reconcile actual measurements with theoretical predictions, the United States Environmental Protection Agency has developed the Industrial Source Complex Short Term (ISCST) model (Lorber et al., 2000, Yegnan et al., 2002) which incorporates appropriate scaling factors and decay terms in the steady state Gaussian Plume equation to take care of the shortcomings mentioned above. If the emission from the stack posses some health challenges to the people living along the plume spread, the government should prohibit human habitation in such areas and compel the factory to comply with internationally accepted safety standards in its stack effluent emission.

CONCLUSION

The Gaussian plume model for a point source has been used to theoretically predict the pollution concentration levels downwind of an industrial stack. The ground surface concentrations of identified air pollutants along the plume centre line are greater in magnitude than the values off the axis. The maximum concentration of pollutant emission off the plume axis is observed at a downwind distance of about 400m. The concentration at any given point on the centre line decreases as the height of the stack is increased for a specific weather stability class and mass flow rate from the stack. The theoretically predicted concentrations alone are not sufficient to determine the safety limits of the gaseous emissions; in-situ measurements are recommended at the industrial site.

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