Evaluation of ground level concentration of pollutant due to gas flaring by computer simulation: A case study of Niger - Delta area of Nigeria

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Abstract

The disposal of associated gases through flaring has been a major problem for the Nigerian oil and gas industries and most of theses gases are flared due to the lack of commercial out lets. The resultant effects of gas flaring are the damaging effect of the environment due to acid rain formation, green house effect, global warming and ozone depletion.

This writes up is aimed at evaluating ground level concentration of CO_2, SO_2, NO_2 and total hydrocarbon (THC), which are product of gas flared in oil producing areas. Volumes of gas flared at different flow station were collected as well as geometrical parameters. The results of simulation of model developed based on the principles of gaseous dispersion by Gaussian showed a good agreement with dispersion pattern.

The results showed that the dispersion pattern of pollutants at ground level depends on the volume of gas flared, wind speed, velocity of discharge and nearness to the source of flaring. The results shows that continuous gas flaring irrespective of the quantity deposited in the immediate environment will in long run lead to change in the physicochemical properties of soil.

Keywords

Gas flaring, Niger – Delta, Modeling, Simulation and environmental pollution

Introduction

The presence of unaccepted levels of foreign gaseous and particulate matters in the atmosphere is referred to as air pollution (Odigure, 1999). The deterioration of the environmental quality, which began when man first collected into villages and utilizes fire, has existed as a serious problem under the ever-increasing impacts of exponentially increasing population and industrial society (Russel, 1976). Environmental contamination of air, water, soil and food has become a threat to continue existence of many plant and animal communities of ecosystem and ultimately threatens the very survival of the human race. Gas being flare into atmosphere is one of such indiscriminate discharge. Petroleum industry operation is characterized by sets of hazards (Onosode, 1996). The nature and magnitude of these hazards are dependent on series of factors and vary significantly from one sector to another. While it is true that Niger – Delta of Nigeria suffers a great deal from immediate impact of gas flaring. It is now increasingly recognized that the contribution of the petroleum industry to the environment degradation goes far beyond the immediate vicinity of the oil producing areas. The Nigeria oilfield in the Niger – Delta area produce about two million barrels of oil and most of this oil comes from reservoirs containing gas, which is produced with the oil (Ikelegbe, 1993). This associated gas, a by-product of the country's lifeline petroleum exploration activities is separated from the oil at flow station and more than 95% of it is flared. Currently are total sum of two billion standard cubic feet per day (scf/day), which is estimated to be about a quarter of the world gas flares (Onosode, 1996).

The impact of gas flared is of local and global concern. The main components of this flared include carbon (iv) oxide (CO_2), methane (CH_4), nitrous oxide (NO_2), water vapour and sulphur dioxide (SO_2). It is estimated that the Nigerian gas flared has released 35 million tons of carbon dioxide and 12 million tons of methane in a year. The low combustion efficiency of Nigerian flare stack (60 – 80%) results in a large portion of the gas emitted being methane and since methane has a higher global warming potential (64 against 1 for CO_2) (Sawaragi and Akashi, 1978). The Nigerian oil industry probably contributes more than any other company of these serious global commons environmental problems. As carbon dioxide and methane are the main green house effect and consequently, this phenomenon has been confirmed to raise the average global temperature by about 0.5°C within the last century (Thomas and Allen, 1999 and Penner, 1999). The flaring stations in the Niger – Delta area has been blamed for smoke and flames that damage the air and soil quality in the ecologically fragile delta and contribute to the global green house gases. The gas flaring in Nigeria have for years been criticized by environmental groups as the world's largest sources of global warming pollutants this acts, which experts attributes to the rise in sea level. In Nigeria however, environmental policies and regulations can be conveniently characterized as minimal and poor, as the Nigerian government puts profits ahead of the environment and the welfare of its citizens. Nigeria, which according to UN economic commission for Africa is categorized as a gas – surplus country, still has limited associated gas sales as 68% of the gas is flared and as a result has been associated with climate change and related warming, deforestation and acid rain with attendant impact on agriculture and other physical infrastructure (Onosode, 1996). Heat and noxious gases may contribute to environmental health problem in the Niger – Delta region. Also, there has been timely warming and an increasing global awareness on the need to protect our environment and improve our economy. Typical gas flare in Nigerian oil field are located at ground level and surrounded by thick vegetation, farmland and villages huts 20 – 30m from the flare. The heat radiation is a function of the flare temperature, gas flow rate and geometrical design of flare stack. There is a great physiological impact on crops planted in the vicinity of the gas flare. The soil mantle of the earth is indispensable for the maintenance of the plant life, affording mechanical support and supplying nutrient and water.

Also, the soil constitutes a major storage location for heat, acting as sink for energy during the day and a source to the surface at night. Soil temperature is one of the most critical factors that influence important physical, chemical and biological processes in soil and plant. Soil temperature affects plant growth first during seed germination. Metabolically regulated plant processes, such as water and nutrient uptake can be diminished below optimum rates at both low and high temperature, resulting in temperature dependent growth and yield pattern. For instance, corn yields were observed to increase almost linearly as a function of soil temperature between 15 – 25°C, above 25°C the yield decreases (Allmaras et- al, 1964)). With respect to the gas flaring, its effect on vegetation, health and microclimate are equally searing. The free disposal of gas through flaring generates tremendous heat, which is felt over an average radius of 0.5 kilometer there by causing thermal pollution (Ikelegbe, 1993). It has been reported that there could be about 100% loss in yield of crops cultivated 200m away from the flares, 45% loss in yield of crops at 600m away and 10% loss in yield for crop planted 1000m away (Oyenkunle, 1999). This work focuses on the evaluation of ground level concentration of CO_2, SO_2, NO_2 and THC due to the flaring of associated gases during exploration of oil in the Niger – Delta area by computer simulation. This will be achieved via realization of the following objectives:

1. Develop a predictive model for the dispersion of pollutant from the flaring point;
2. Find interaction between various parameters that affects pollutant dispersion pattern i.e. volume of gas flared, temperature, wind speed etc;
3. Simulate the developed predictive model using computer program.

Experimental Methodology

The experimental methods carried out in this project aimed at quantifying the volume of gas flared at flow station in the Niger-Delta area for different stations. The experiments were performed by industries situated in the Niger-Delta. The data were collected from their logbook.

Conceptualization of the modeling technique

A pollutant concentration may be considered either as a climatological parameter in the same way as air temperature or humidity or as a complex resultant of "pure" climatological parameters (wind rise, stability wind rose, temperature, e.t.c.) Every population of climatological descriptors is essentially random. Since every function of a random variable is also a random variable, the concentration will be subject to random variation similar to that of a climatological series. The modeling is a resultant of pure climatological parameters. To compute base on climatological parameters an adequate amount of meteorological input about the state of the atmosphere as well as detailed data about emission were collected.

During the development of the mathematical model for the ground level concentration of pollutant using the Gaussian formula, the following assumptions were made:

1. A constant wind speed and turning of wind due to frictional effect is neglected;
2. Eddy diffusivities are constant throughout the space;
3. Flat topography;
4. Complete combustion and flare stack efficiency is 64% (46% of the flare gas are released as hydrocarbon while the remaining 64% undergo combustion);
5. Pollutants are chemically inert.

The resultant equation for pollutant concentration from an elevated continuous source is given by (Odigure and Abdulkareem, 2001):

$$C_i = \frac{Q}{2\pi\ x\ \left(K_{yy}K_{zz}\right)^{0.5}}\ \exp\left(\frac{-u_s Y^2}{4x\ K_{yy}}\right)\ \exp\left(\frac{-u_s\left(Z+H\right)^2}{4x\ K_{ZZ}}\right) \tag{1}$$

where: C_i - pollutant concentration in air at any point (x,y,z) (ug/m^3), Q - emission rate from the stack (gm/sec), U_s - wind speed at source height (m/sec),σ_y - horizontal dispersion coefficient (m), σ_Z - vertical dispersion coefficient (m), y - cross wind distance (m), z - vertical distance (m), H - effective stack height (m).

Equation above can be simplified for ground level concentration by setting Z = 0:

$$C_i = \frac{Q}{2\pi\ x\ \left(K_{yy}K_{ZZ}\right)^{0.5}} \exp\left(\frac{-u_s Y^2}{4xK_{yy}}\right)\ \exp\left(\frac{-u_s H^2}{4x\ K_{ZZ}}\right) \tag{2}$$

But Gwendolyn and Lewis, 1993 stated that:

$$\delta_y^2 = \frac{2K_{yy}x}{u_s} \tag{3}$$

$$\delta_Z^2 = \frac{2K_{ZZ}x}{u_s} \tag{4}$$

From equations 3 and 4:

$$K_{yy} = \frac{\delta_y^2\ u_s}{2x} \text{ and } K_{ZZ} = \frac{\delta_Z^2\ u_s}{2x} \tag{5}$$

Substituting equation 5 into equation 2:

$$C_i = \frac{Q}{\pi\ \delta_y \delta_Z} \exp\left(\frac{-Y^2}{2\delta_y^2}\right) \exp\left(\frac{-H^2}{2\delta_Z^2}\right) \tag{6}$$

where:

$$Q = \rho V, \tag{7}$$

$$H = h_s + \Delta h - h_t, \tag{8}$$

and h_s - physical chimney height, h_t - maximum terrain height between the release point and the point for which the calculation is made. In this case a uniform topography is assumed, therefore $h_t = 0$.

Then equation (8) becomes:

$$H = h_s + \Delta h \tag{9}$$

Note that Δh is the increase in stack height or the plume rise that occurs due to the effect of temperature and pressure and Δh can be calculated as function of temperature, pressure and other variables as follows:

$$\Delta h = \frac{V_s d}{U_s}\left[1.5 + 2.68\times10^{-3} pd\left[\frac{T_a - T_s}{T_a}\right]\right]C \qquad (10)$$

where: V_s - stack discharge velocity (m/s), d - stack diameter (m), U - wind velocity (m/s), T_s - Stack discharge temperature (°K) , T_a - Ambient temperature (°K), P - Atmospheric pressure (mbar), C - weather condition;

$$H = h_s + \frac{V_s d}{U_s}\left[1. + 2.68\times10^{-3} pd\left[\frac{T_a - T_s}{T_a}\right]\right]C \qquad (11)$$

Also:

$$\sigma_y = Ax^{0.903} \qquad (12)$$

$$\sigma_z = Bx^k \qquad (13)$$

The composition of associated flare gas is shown in table 1 below (Helen, 2003):

Table 1. Percentage by volume composition of flare gas

Component	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	Others
% Composition by volume	47	18	20	5	9	1

The above named compounds present in the flared gas undergo combustion during flaring to release CO_2, SO_2, NO and total hydrocarbon.

Amount of CO_2 released by flaring $1m^3$ of associated gas can be calculated from stiochiometry of burning. Total amount of CO_2 released by burning $1m^3$ of gas with 64% stack efficiency was calculated to be $1.3312m^3$. Consequently, the concentration of CO_2 released and dispersed at ground level is equal to:

$$C_{CO2} = \frac{1.3312pv}{\pi\sigma_y\sigma_z U_s}\exp\left(\frac{-H^2}{2\delta_Z^2}\right)\exp\left(\frac{-Y^2}{2\delta_y^2}\right) \qquad (14)$$

Also, on the basis of $1m^3$ of flared gas and 64% efficiency of flare stack with composition by volume of sulphur containing compound and nitrogen containing compound of 0.18% and 0.02% respectively. The volume of SO_2 and NO_2 produced are 0.001152 m^3 and $0.000128m^3$ respectively. Consequently, the concentration of SO_2 and NO_2 released and dispersed at ground level is equal to:

$$C_{NO2} = \frac{1.28 \cdot 10^{-4} \rho v}{\pi \sigma_y \sigma_z U_s} \exp\left(\frac{-H^2}{2\delta_z^2}\right) \exp\left(\frac{-Y^2}{2\delta_y^2}\right) \quad (15)$$

$$C_{SO2} = \frac{1.152 \cdot 10^{-3} \rho v}{\pi \sigma_y \sigma_z U_s} \exp\left(\frac{-H^2}{2\delta_z^2}\right) \exp\left(\frac{-Y^2}{2\delta_y^2}\right) \quad (16)$$

Also the volume of total hydrocarbon produced by flared $1m^3$ of associated gas with 64% efficiency of the stack is $0.365m^3$. The concentration of THC released and dispersed at ground level is equal to:

$$C_{THC} = \frac{0.356 \rho v}{\pi \sigma_y \sigma_z U_s} \exp\left(\frac{-H^2}{2\delta_z^2}\right) \exp\left(\frac{-Y^2}{2\delta_y^2}\right) \quad (17)$$

Results

Experimental results are presented in tables 1 and 2 below.

Table 1. Volume of gas flared (m^3/s) at various times for station 1

Month	Volume of gas flared (m^3/s)	Discharge velocity (m^3/s)	Wind speed (m/s)	Surrounding temperature (°K)	Stack temperature (°K)
January	1.174	14.0	1.5	320	1000
February	4.480	14.0	2.0	325	950
March	1.121	13.5	1.5	318	1100
April	1.137	12.5	1.0	319	1000
May	0.622	12.5	1.3	325	900
June	0.877	12.0	2.0	320	1100
July	0.947	12.0	1.5	328	1150
August	1.126	12.5	1.8	320	900
September	1.103	14.0	2.0	318	1080
October	1.071	14.0	2.5	320	1000
November	1.092	12.0	3.0	320	950
December	0.977	13.0	2.8	328	1100

Height of the stack = 6.1m Diameter of the stack = 0.34m

Table 2. Volume of gas flared (m^3/s) at various times for station 2

Month	Volume of gas flared (m^3/s)	Discharge Velocity (m^3/s)	Wind speed (m/s)	Surrounding temperature (°K)	Stack temperature (°K)
January	0.831	12.5	2.5	328	1100
February	0.514	14.0	3.0	318	1000
March	0.582	13.0	3.0	320	900
April	0.497	14.0	1.5	320	900
May	0.485	13.0	2.0	320	1100
June	0.421	12.5	3.0	318	1000
July	0.365	12.5	3.0	328	1050
August	0.411	14	1.3	319	1000
September	0.372	13.5	3.0	325	980
October	0.336	12.0	1.3	328	900
November	0.307	12.5	2.0	318	1000
December	0.293	14.0	2.9	320	900

Height of the stack = 7.53m Diameter of the stack = 0.56m

Simulation Results

Simulation of the model means the use of computer codes to show the operation and behaviour of the system. The model equations were simulated using Q-Basic programme. The results obtained are presented in tables 3 and 4.

Table 3. Computed concentrations of pollutant (μg/m^3) for station 1 in the month of February

Distance (m)	Polluants concentration (μg/m^3)			
	CO_2	NO_2	SO_2	THC
100	02.03912E-4	3.268312E-8	2.0936374E-7	2.139874E-5
150	58.94978	9.448499E-3	8.488887E-2	6.186251
200	3443.891	0.5519885	4.959272	361.4054
250	18716.9	2.999954	26.95271	1964.171
300	41449.18	6.643494	59.68764	4349.719
350	61275.14	9.821209	88.23743	6430.276
400	73905.47	11.8456	106.4254	7755.716
450	79811.27	12.79219	114.9298	8375.477
500	80907.05	12.96782	116.5078	8490.469
550	79003.65	12.66274	113.7668	8290.724
600	75421.2	12.08855	108.608	7914.777
650	71021.76	11.3834	102.2728	7453.097
700	66333.98	10.63204	95.52226	6961.156
750	57188.73	9.883905	88.80071	6471.325
800	52986.82	9.166238	82.35292	6001.444

850	52986.82	8.492754	76.30209	5560.492
900	49095.85	7.869107	70.69901	5152.169
950	45521.98	7.296285	65.55256	4777.123

Table 4. Computed concentrations of pollutant (µg/m^3) for station 2 in the month of February

Distance (m)	Polluants concentration (µg/m^3)			
	CO_2	NO_2	SO_2	THC
100	1.167116E-9	1.87066E-13	1.680671E-12	1.224784E-10
150	6.808103E-2	1.091206E-5	9.803804E-5	7.144493E-3
200	25.14161	4.02971E-3	3.620443E-2	2.638386
250	319.5423	0.0512164	0.4601474	33.5331
300	1120.959	0.1796678	1.614203	117.6346
350	2185.434	0.3502824	3.147069	229.3417
400	3153.504	0.5054451	4.541109	330.9319
450	3850.266	0.6171225	5.544461	404.0509
500	4260.925	0.682943	6.135817	447.1458
550	4439.391	0.7115478	6.392812	465.8742
600	4452.173	0.7135964	6.411218	467.2155
650	4356.291	0.6982285	6.273147	457.1536
700	4194.348	0.6722721	6.039945	440.1591
750	3995.986	0.6404786	5.7543	419.3429
800	3780.928	0.606009	5.444613	396.7745
850	3561.841	0.5708936	5.129122	373.7832
900	3346.569	0.5363897	4.819126	351.1924
950	3139.744	0.5032369	4.521294	329.4879

Discussion of results

The operation at gas plant and flow station in the Niger – Delta area of Nigeria involves flaring of excess gas on twenty-four hourly basis. Combustion of gas flare contributes to the atmospheric content of carbon, nitrogen, sulphur and total hydrocarbon. Most pollutant is emitted into the atmosphere from elevated sources such as chimneystacks and transported through the atmosphere by wind currents from their point of release to downwind receptors (Gwendolyn, 19993). The major meteorological parameters controlling atmospheric dispersion are atmospheric stability and wind speed (Gavriel, 1991). One of the major issues in Nigeria is the flaring of gas that is produced with oil in the Niger – Delta area. The flaring of gas has been an integral part of the operation associated with the exploitation of crude oil and natural resources in Nigeria since inception. Flaring of gas has been as a result that most of Nigerian's oil facilities were built in 1960s and 1970s (Kuranga, 2002). This implies that they were built to environmental standard of those days. Gas flaring has exposed the people of Niger – Delta area to a lot of hazard.

From experimental results shown in tables 1 to 2, it could be observed that the volume of gas flared varies from station to station and month. This could be attributed to the fact that the production rate and well properties are not constants for all stations. The simulation results of the predictive model are presented in tables 2 to 4. It could be seen from the tables that the most dangerous zone is within the 200 – 600m radius from the flare station (figs. 1-4). However, effect of gas flared are felt within the radius range of 1000m away from the flaring source depending on the volume of gas flared, wind speed, surrounding temperature, velocity of discharged and height of stack. It could be observed from the results that the concentration of pollutant in the ground level increases as the volume of gas flared increase and vice versa. This implies that the concentration of the pollutant is directly proportional to the volume of gas flare. Simulation results of the predictive model shows that cross wind distance and distance across the x – axis affect the concentration of the pollutants at the ground level.

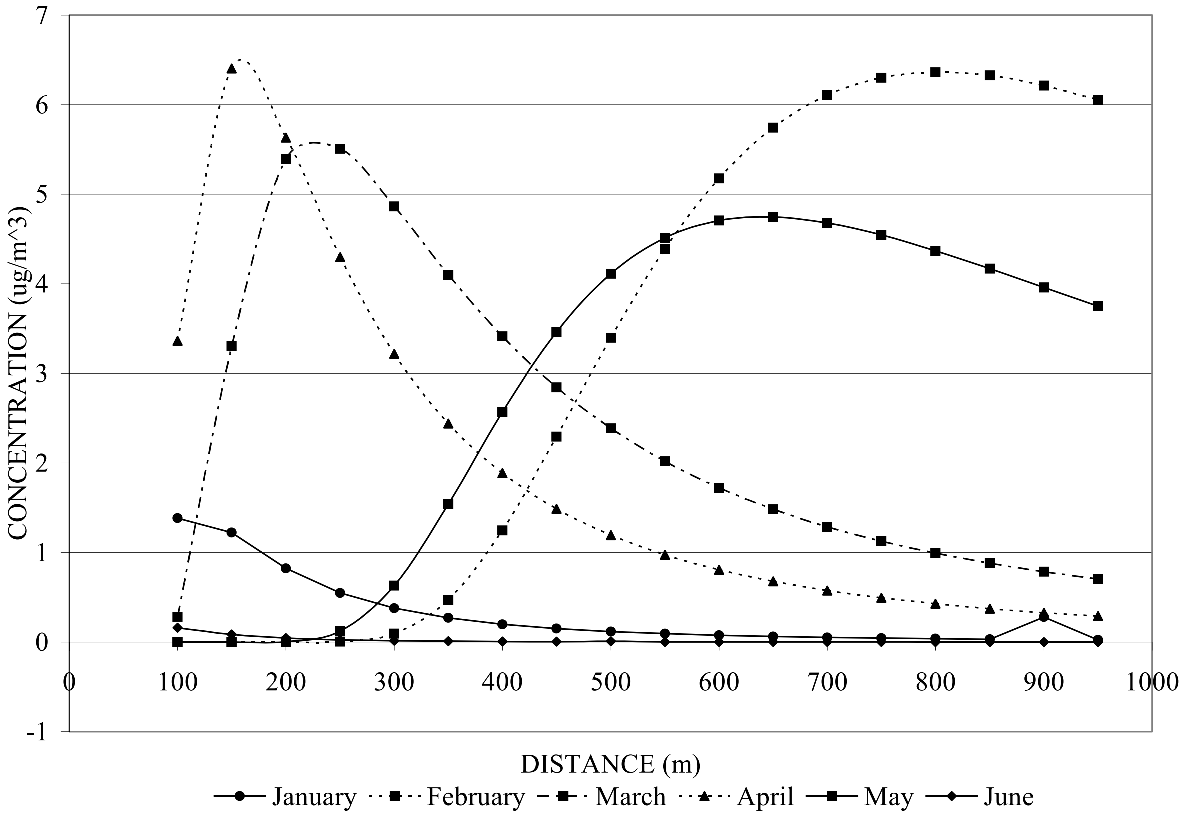

Figure 1. SO_2 concentration for station 2

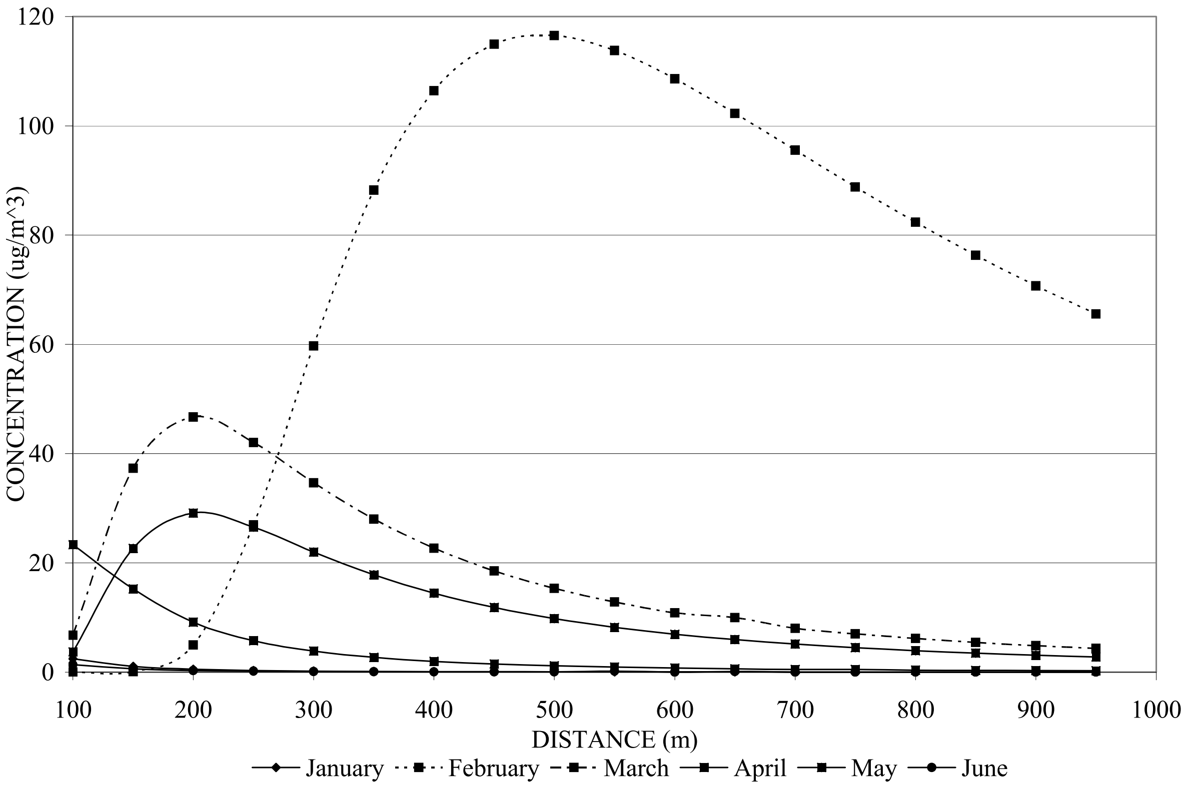

Figure 2. SO_2 concentration for station 1

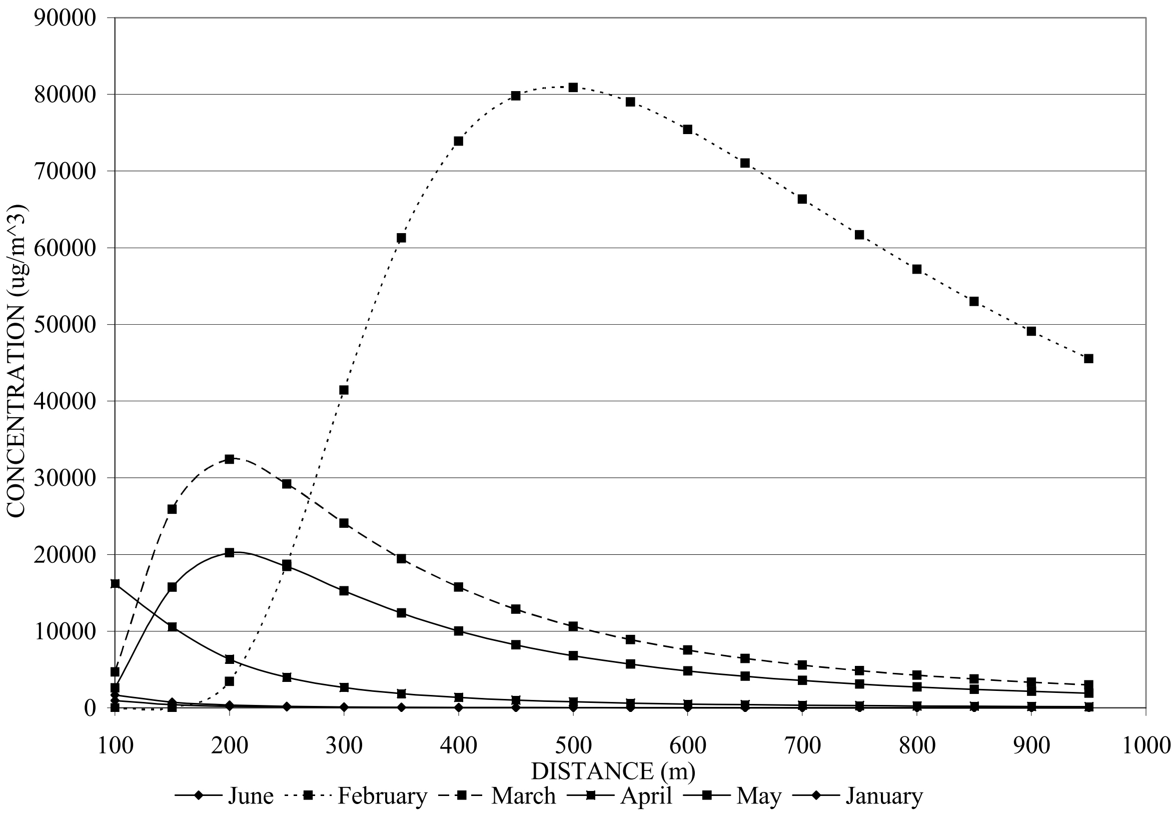

Figure 3. CO_2 concentration for station 1

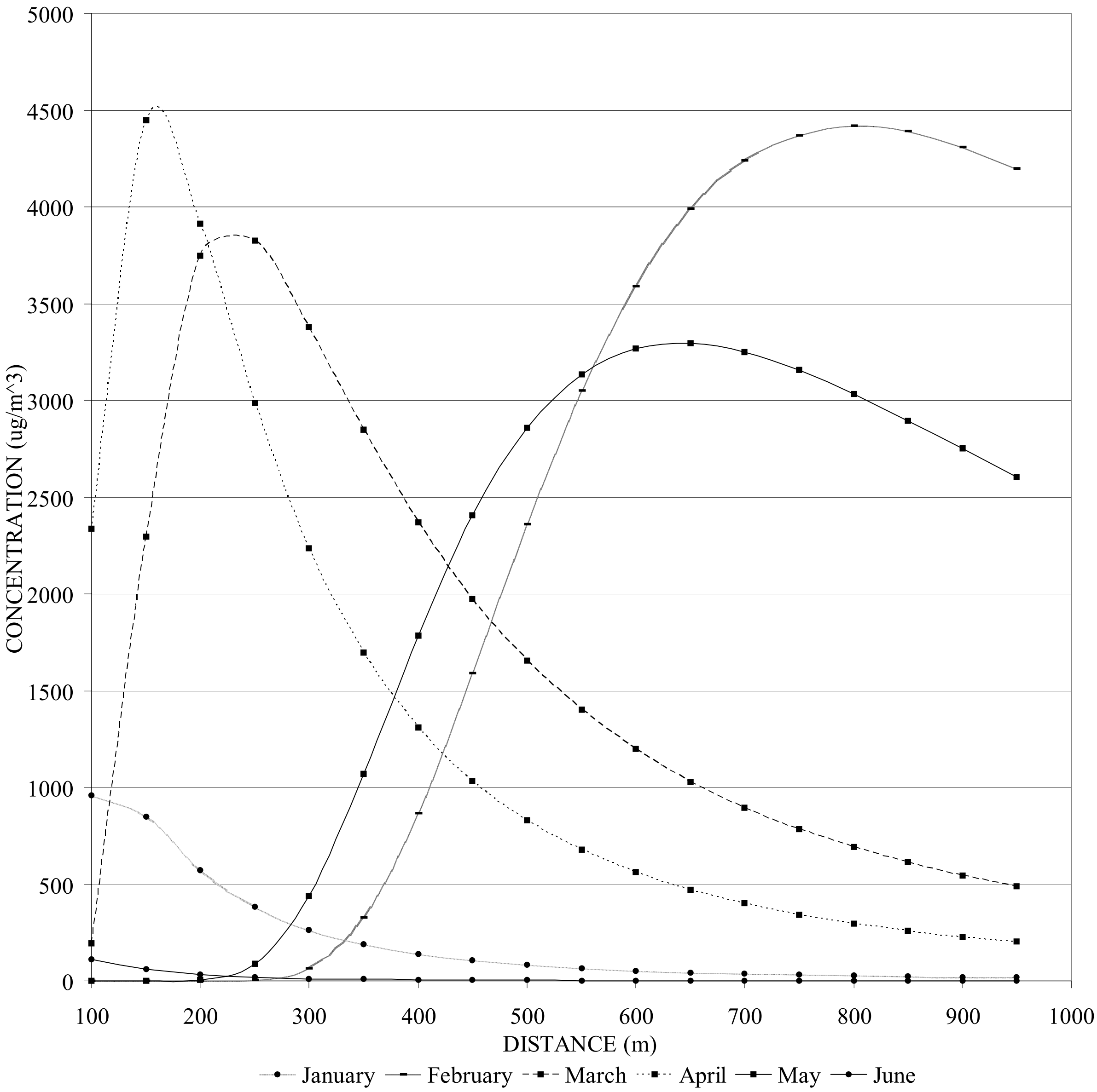

Figure 4. CO_2 concentration for station 2

Note that at the further distance, lesser concentration of the pollutants (figs. 1-4). This could be attributed to the fact the pollutants are engaged in other reaction due to dispersion of pollutants and other components. Results show that the people of Niger - delta area are exposed to danger due to continuous pollution of soil from these sources. Also, the results obtained showed that dispersion pattern conform to the modified principles by Gaussian.

Conclusions

From this research, the following conclusions can be deduced:

1. It was observed that the result of the simulation of model developed based on the modified principles of gas dispersion showed a remarkable agreement with dispersion pattern;
2. The dispersion pattern of pollutant showed that the concentration of pollutant from the flare source depends on the volume of gas flared, height of stack and wind speed;
3. Model equation that represent ground level concentration of pollutants are:

$$C_{CO2} = \frac{1.3312\rho v}{\pi\sigma_y\sigma_z U_s}\exp\left(\frac{-H^2}{2\delta_z^2}\right)\exp\left(\frac{-Y^2}{2\delta_y^2}\right)$$

$$C_{NO2} = \frac{1.28\cdot 10^{-4}\rho v}{\pi\sigma_y\sigma_z U_s}\exp\left(\frac{-H^2}{2\delta_z^2}\right)\exp\left(\frac{-Y^2}{2\delta_y^2}\right)$$

$$C_{SO2} = \frac{1.152\times 10^{-3}\rho v}{\pi\sigma_y\sigma_z U_s}\exp\left(\frac{-H^2}{2\delta_z^2}\right)\exp\left(\frac{-Y^2}{2\delta_y^2}\right)$$

$$C_{THC} = \frac{0.356\rho v}{\pi\sigma_y\sigma_z U_s}\exp\left(\frac{-H^2}{2\delta_z^2}\right)\exp\left(\frac{-Y^2}{2\delta_y^2}\right)$$

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