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Modeling the Dispersion and Atmospheric Mitigation of Pollutants in the Dibamba-Douala Thermal Power Plant

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Abstract

This work simulates the dispersion and atmospheric attenuation of pollutants from the Dibamba-Douala thermal power plant. The objective of this research is to study the dispersion of air pollutants and mitigate the impact of pollutants on the populations living around the power plant. The methodology used is as follows: the Gaussian model is used for the representation of the dispersion in the form of a plume, the finite difference method for digital resolution. Finally, dispersion charts are constructed which allow the heights of the chimneys to be fixed for which the concentrations of pollutants discharged comply with ambient air quality standards. The results obtained using the simulation made in the MATLAB software version 2016 show that, for a wind regime of 1.5 m/s; we have a predicted distance of 150 m at which the concentration is canceled out. Then, for the wind speed of 2 m/s; we had a predicted distance of 125 m and finally for a wind speed of 2.5 m/s; we observed the 120 m distance at which the concentration is canceled. In addition, for the same wind regimes, the attenuation of pollutants at ground level is obtained for a height of 60 m.

Keywords

Modeling, Atmospheric Pollution, Thermal Power Plant, Gaussian Model, Dispersion

1. Introduction

Air pollution is a serious danger to the environment. Indeed, its impacts affect the regional climate, the global climate, agriculture, natural ecosystems and human health. Air pollution is one of the important factors that influence the health and quality of life of urban and metropolitan populations. In this work, we will make a brief review of the work related to the modeling of the atmospheric dispersion of pollutants and a brief generality on the phenomenon of the dispersion, which will present the parameters implemented for the modeling of the dispersion. Many studies have been published on the transport and diffusion of air pollutants as part of the assessment of air quality in the urban area of Delhi, India, and in similar urban areas outside India (Li et al., 2006; Srimuruganandam & Shiva Nagendra, 2011; Goyal et al., 1994), simulated concentrations of SO_2, NO_2 and suspended particles (SPM) in Agra, India, using Gaussian plume models. Predicted monthly mean concentrations were found to be Consequential to observations. (Sharan & Gopalakrishnan, 2003) studied the dispersion of air pollutants under weak wind conditions using a mathematical model on Delhi, (Sharan et al., 2000) using a three-dimensional mesoscale model showed that urban weather conditions had no major influence on the dispersion of hazardous chemical gases during the Bhopal gas accident. (Abdoulaye & Sodré, 2007) modeled the attenuation on the ground of the concentration of emissions from a diesel thermal power plant. To do this, they designed a three-stage pollutant mitigation model to control atmospheric pollution caused by a thermal power plant in Ouagadougou. The first step consisted in carrying out an environmental audit then they applied a rehabilitation plan as a means of controlling and reducing emissions and so they sized the chimneys of the power plant for which the concentrations of pollutants discharged are attenuated. The results of this model could thus be used for the prevention and control of air pollution. In this work, we simulate the dispersion and atmospheric attenuation of pollutants from the Dibamba-Douala thermal power plant at the same time. For this, we will talk about the mathematical formulation of the dispersion problem and, before concluding we will present the results and discussion.

2. Methods and Description of Data

Dispersion modeling is the mathematical representation of the transport of pollutants in the atmosphere from one point to another. The pollutants emitted are simultaneously transported and dispersed further and further away from the source depending on the atmospheric conditions and the topography of the dispersion zone. Thus, at all times (t) and at all points (x, y, z) of the space around the source, the pollutants are present at a concentration which depends on both the direction of dispersion and the time considered. The problem of pollution control therefore boils down to ensuring that at any point in living space, the concentration of pollutants is less than or equal to the prescribed standards.

2.1. Mathematical Formulation of a Dispersion Problem

Atmospheric dispersion characterizes the future, in time and space, of a cloud of pollutant from a source released into the atmosphere. Modeling atmospheric dispersion requires coupling between these diffusion phenomena and advection phenomena.

2.1.1. General Advection-Diffusion Equation

Let us consider a scalar species transported in an incompressible turbulent flow and suppose that the dynamic behavior of this species is passive that is to say that the latter follows exactly the movement of the fluid particles. We then define its distribution in space using concentration $C_{(x,y,z,t)}$ (quantity of species per unit of volume). By applying the principle of conservation to the scalar quantity, we can write the advection-diffusion equation of the concentration Equation (1) (Srimuruganandam & Shiva Nagendra, 2011; Chen et al., 2011; Srikanth et al., 2016).

$$\frac{\partial C}{\partial t} + U \cdot \nabla C = \nabla \cdot \left(k \nabla C\right) + S \qquad (1)$$

With k being the diffusion coefficient of the species in the fluid and S a source term and U the velocity vector.

By developing this equation while taking into account the different components of U and k and from the scalar gradient, we get Equation (2) the following form:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = K_x \frac{\partial^2 C}{\partial x^2} + K_y \frac{\partial^2 C}{\partial y^2} + K_z \frac{\partial^2 C}{\partial z^2} + S \qquad (2)$$

We made the choice on the Gaussian model for the dispersion modeling because, the parameters which we have at our disposal, are easily applied with the latter.

2.1.2. Modeling of the Dispersion

The study of the atmospheric dispersion of pollutants must make it possible to know at all times and in all points, the concentrations of the species released into the atmosphere (Jourdain., 2010).

The purpose of modeling is to simulate, using the assumptions of a Gaussian model, the dispersion of pollutants released into the atmosphere from a point source at any point in space and to estimate the concentration of pollutant at ground level. The simulation of such scenarios relates to the evolution of the dispersion according to a Gaussian model by a compilation of a program obtained from the discretization of the equation from the said model.

2.1.3. Gaussian Formulation of the Dispersion Equation

The Gaussian model is a representation of the concentration of pollutants in the air, the plume is emitted by a point source and is considered as a Gaussian distribution of the concentration.

Modeling according to the Gaussian model is only valid for the following simplifying hypotheses:

- A continuous punctual emission (therefore active for a long enough time to have a stable plume between the source and the most distant observed point), of constant flow Q;
- Uniform wind fields (in speed and direction) in time and space;

- The atmospheric turbulence is constant in space and in time;
- No obstacles, no relief.

By applying the above assumptions to the transport Equation (2), we have Equation (3):

$$u\frac{\partial C}{\partial x}=K_y\frac{\partial^2 C}{\partial y^2}+K_z\frac{\partial^2 C}{\partial z^2}+Q\delta(x)\delta(y)\delta(z-H) \tag{3}$$

where $\delta(.)$ is Dirac's function.

Equation (3), which ultimately only takes into account the pollutant concentration gradient, is classic and recalls the heat conduction equation with an animated source of speed U along the x axis. Its analytical solution is known and given by the following relation (Montazeri & Blocken, 2013).

$$C(x,y,z,t)=\frac{Q}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left[\frac{(x-Ut)^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}-\frac{z^2}{2\sigma_z^2}\right] \tag{4}$$

The standard deviations (σ_x, σ_y and σ_z), are determined by a statistical approach by describing the flow through speed regimes such that the components (U + u, v, w) fluctuate around the steady state (U, 0, 0) (Boeker & Grondelle, 1995). Then integrating Equation (4) with respect to time, we obtain an exact solution in the form:

$$C(x,y,z)=\frac{Q}{(2\pi)^{3/2}}\int_0^{\infty}\exp\left[\frac{(x-Ut')^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}-\frac{z^2}{2\sigma_z^2}\right]\frac{\mathrm{d}t'}{\sigma_x\sigma_y\sigma_z} \tag{5}$$

Neglecting diffusion in the direction of flow, the exact solution of Equation (5) is obtained as follows (Srikanth, et al., 2015):

$$C(y,z)=\frac{Q}{2\pi\sigma_y\sigma_z u}\left[\exp\left(-\frac{y^2}{2\sigma_y^2}-\frac{z^2}{2\sigma_z^2}\right)\right] \tag{6}$$

Now apply this Equation (6) to the specific case of a chimney of ascending z direction and coordinates (0, 0, H). Note in addition that when there is total reflection of the pollutants, as the case assumed here, it is necessary to superimpose on the real source, a fictitious source symmetrical of the real and of coordinate (0, 0, $-H$), so that leads to the Gaussian distribution of the total concentration at a given point which is the sum of the two:

$$C(y,z)=\frac{Q}{2\pi\sigma_y\sigma_z u}\left[\exp\left(-\frac{y^2}{2\sigma_y^2}-\frac{(z-H)^2}{2\sigma_z^2}\right)+\exp\left(-\frac{y^2}{2\sigma_y^2}-\frac{(z+H)^2}{2\sigma_z^2}\right)\right] \tag{7}$$

By neglecting the reflection of pollutants at ground level, the Equation (7) becomes:

$$C(y,z)=\frac{Q}{2\pi\sigma_y\sigma_z u}\left[\exp\left(-\frac{y^2}{2\sigma_y^2}-\frac{(z-H)^2}{2\sigma_z^2}\right)\right] \tag{8}$$

Equation (8) gives an analytical expression of the concentration emitted by a continuous point source at any point in space. With (σ_x and σ_y) the Gaussian standard deviations characteristic of atmospheric turbulence, according to the environmental stability class. It should be noted that these Gaussian standard deviations are related to the turbulent diffusion coefficients.

In the practical case, however, we are mainly interested in the concentrations of pollutants on the ground. They are obtained by making $z = 0$ in Equation (8) and we have:

$$C(y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u}\left[\exp\left(-\frac{y^2}{2\sigma_y^2} - \frac{H^2}{2\sigma_z^2}\right)\right] \quad (9)$$

For the plant, the greatest concentration will be at the foot of the chimney, that is to say by making $y = 0$ in Equation (9). Finally, we have Equation (10):

$$C = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (10)$$

where:

$$\begin{cases} C(y,z): \text{Concentration of pollutant at a point in space} \\ Q: \text{volume flowrate emitted by the source} \\ u: \text{wind speed along the } x\text{-axis} \\ \sigma_y \text{ and } \sigma_z: \text{standard deviations of the horizontal and vertical distributions} \\ H: \text{total elevation of the plume} \end{cases}$$

Considering the case of a point source, of coordinates (0, Y, H) for a constant flow Q in a non-isotropic medium. We have an analytical expression of the concentration of pollutants emitted from a chimney by Equation (11):

$$C(y,z) = \frac{Q}{2\pi\sigma_y\sigma_z u}\exp\left[\left(-\frac{(y-Y)^2}{2\sigma_y^2}\right)\right]\left[\exp\left(-\frac{(Z-H)^2}{2\sigma_z^2}\right)\right] \quad (11)$$

In practice, the plume does not extend over the entire space. Because there are boundary conditions on the ground and the inversion layer which is modeled as a ceiling. At this height, the temperature of the atmosphere increases with altitude instead of decreasing; thus preventing the plume from rising further.

2.2. Numerical Method

Transport Equation (1) the three-dimensional form of the advection dispersion equation is as follows:

$$\frac{\partial C}{\partial t} + U \cdot \nabla C = \nabla \cdot (k \nabla C) + S$$

As simplification hypotheses mentioned above and for a point source of coordinates (0, Y, H), we have Equation (12):

$$u\frac{\partial C}{\partial x} = K_y\frac{\partial^2 C}{\partial y^2} + K_z\frac{\partial^2 C}{\partial z^2} + Q\delta(x)\delta(y-Y)\delta(z-H) \quad (12)$$

where K_y and K_z represents the diffusion coefficients and Q the flow rate of smoke emitted from the source.

To solve such a problem it is necessary to define certain parameters.

2.2.1. Characterization of the Problem

1) Initial Condition

The concentration is maximum at the exit of the chimney for $x = 0$. So we have Equation (13):

$$C(0,y,z)=\frac{Q}{u}\delta(y-Y)\delta(z-H) \tag{13}$$

2) Domain of the Problem

We have as domain: $x\in\left]0;L\right[$, $y\in\left]0;L\right[$, and $z\in\left]0;L\right[$,

3) Boundary Conditions

The concentration decreases as we move away from the source, so the Equation (14):

$$\begin{cases} C(L,y,z)=0 \\ C(x,L,z)=0 \\ C(x,y,L)=0 \end{cases} \tag{14}$$

To eliminate the phenomenon of reflection in y and in z, we have the conditions for the following flow by Equation (15):

$$\begin{cases} \dfrac{\partial C}{\partial y}=0 \ \text{ for all } 0\le y\le L \\ \dfrac{\partial C}{\partial z}=0 \ \text{ for all } 0\le z\le L \end{cases} \tag{15}$$

2.2.2. Discretization of the Problem: Finite Difference Methods

In this simple approach, all derivatives are approximated by finite differences. The spatial derivatives are discretized on a grid with uniform rectangles of size $\Delta y\times\Delta z$. We assume that C is sufficiently smooth (differentiable). This is justified by the presence of the term of dissemination. We use the notation $C_{i,j}^{n}$ to approximate the values of $C(n\Delta x, \Delta y_i, \Delta z_j)$ at the nth time level and at the points of the grid (y_i, z_j). As a workable choice, we can use the central finite differences by Equation (16).

$$\frac{C_{i+1,j}^{n+1}-C_{i-1,j}^{n}}{\Delta x}=\frac{k_y}{u}\left(\frac{C_{i+1,j}^{n}-2C_{i,j}^{n}+C_{i-1,j}^{n}}{(\Delta y)^2}\right)+\frac{k_z}{u}\left(\frac{C_{i,j+1}^{n}-2C_{i,j}^{n}+C_{i,j-1}^{n}}{(\Delta z)^2}\right)+\frac{Q}{u}\alpha_{i,j}^{n} \tag{16}$$

By developing and applying the boundary conditions, we can determine the following approximations Equations (17) and (18):

$$C_{i,1}^{n+1}=(1-2R)C_{i,1}^{n}+2R_{xy}C_{I,2}^{n}+R_{xz}\left(C_{i+1,2}^{n}+C_{i-1,1}^{n}\right)+\frac{Q}{u}\delta(k)\delta(i)\delta(1) \tag{17}$$

and

$$\begin{aligned} C_{i,Nz}^{n+1}={}&(1-2R)C_{i,Nz}^{n}+2R_{xy}C_{i,Nz-1}^{n}+R_{xz}\left(C_{i+1z,Nz}^{n}+C_{i-1,Nz}^{n}\right) \\ &+\frac{Q}{u}\delta(k)\delta(i)\delta(Nz) \end{aligned} \tag{18}$$

These approximations allow us to observe the evolution of the concentration of pollutants from the source towards points where it tends to cancel itself depending on the weather conditions, the diffusion coefficient and the pollutant flow at the outlet for the current height of the fireplace.

2.2.3. Dimensioning of the Height *H* of the Chimneys

Thus in this part of the model, it is a question of determining, an optimal height which, in addition to evacuating and rejecting the gases as high as possible, must be such that, the concentrations of pollutants on the ground remain within the limits prescribed by air quality standards in force.

Thus, we can write Equation (19):

$$C_{maxink} = \frac{Q_i}{(aU)_n (H_{ink})^2} \tag{19}$$

With Equation (20)

$$a = \frac{\sigma_y}{\sigma_z} \tag{20}$$

where, i designates the pollutants in order: CO, SO_2, NO_2, Particles; n represents the three wind regimes and k the number of iterations necessary for the concentration of each pollutant (i) on the ground to meet the air quality standards corresponding to a fixed height H_{in}. Thus, for each type of wind regime n = 1, 2 and 3, we must have. The sought height by Equation (21)

$$H = (\text{Sup})[H_{in}] \tag{21}$$

2.2.4. Description of Data

1) Numerical Simulation Parameters

The different simulations will be carried out with the following operating conditions and assumptions:

- The wind speed in the direction of the x-axis;
- The dispersion coefficient;
- Pollutant flows at the outlet of the chimney.

2) Wind Regimes Assumptions

To determine the standard deviations of dispersion we use the Briggs table in Table 1 and we estimate the distance x from the source at 300 m and we choose stability class B for this calculation.

Table 1. Briggs equations for dispersion parameters in urban terrain (Mcelroy-pooler parameters) (Sharan et al., 2000).

Stability Class	σ_y(m)	σ_z(m)
A-B	$0.32x(1+0.0004x)^{-0.5}$	$0.24x(1+0.0001x)^{0.5}$
C	$0.22x(1+0.0004x)^{-0.5}$	$0.2x$
D	$0.16x(1+0.0004x)^{-0.5}$	$0.14x(1+0.0003x)^{-0.5}$
E-F	$0.11x(1+0.0004x)^{-0.5}$	$0.08x(1+0.0015x)^{-0.5}$

The various meteorological measurements given by the RETScreen software indicate that the wind regimes are generally weak (between 1.5 and 2.5 m/s) in the city of Douala. For this model, and as (Abdoulaye & Sodré, 2007) in Burkina, we will take three standard speed regimes of 1.5 m/s respectively (unfavorable case), 2 m/s (average case) and 2.5 m/s (favorable case) to represent all the possibilities.

2.2.5. Calculation of Standard Deviations by the Briggs Table

The stability class to choose is B. The calculation of the values of σ_y and σ_z are given by Equations (22) and (23)

$$\sigma_y = 0.32x(1+0.0004x)^{-0.5} = 45.35\ \text{m} \tag{22}$$

$$\sigma_z = 0.24x(1+0.0003x)^{-0.5} = 40.22\ \text{m} \tag{23}$$

where x is the distance to the source, in the direction of the wind estimated at 300 m (Chen et al., 2011). The turbulent flux of the pollutant according to Oy and Oz are expressed by means of Coefficients k_y and k_z. Assuming k_y and k_z constant, find under which conditions on σ_y and σ_z (supposed to depend only on x). The following form is a solution Equation (24):

$$\sigma_y^2 = \frac{2xk_y}{u} \tag{24}$$

Thus Equation (25)

$$k_y = \frac{u \cdot \sigma_y^2}{2x} \tag{25}$$

2.2.6. Pollutant Flows Given by the Dibamba DPDC Thermal Power Plant

Table 2 informs us of the different emissions from the thermal power plant.

2.3. Results and Discussions

2.3.1. Dispersion of Pollutants According to Wind Regimes

The figures obtained show us the evolution of the concentration of pollutants under the influence of wind speed.

1) Concentration of Pollutants According to Wind Regimes

The curves of (**Figures 1-4**) allow us to show that, for a wind speed of 1.5 m/s, the concentration cancels at 150 m, then the wind speed of 2 m/s, allowed a prediction of a distance of 125 m and finally wind of 2.5 m/s; we have a predicted distance of 120 m at which the concentration tends towards a limit value. In addition, it should be noted that, this evolution of the concentration propagates progressively while gradually moving away from the source towards a limit value, which in fact translates a decrease in the concentration of pollutants until its

Table 2. Pollutant release rates at the chimneys of the power plant.

Pollutants	CO	SO_2	NO_2	Particles
Discharge Rate at Chimneys Q (kg/s)	3.9×10^{-3}	2.5×10^{-4}	0.017	5.5×10^{-4}

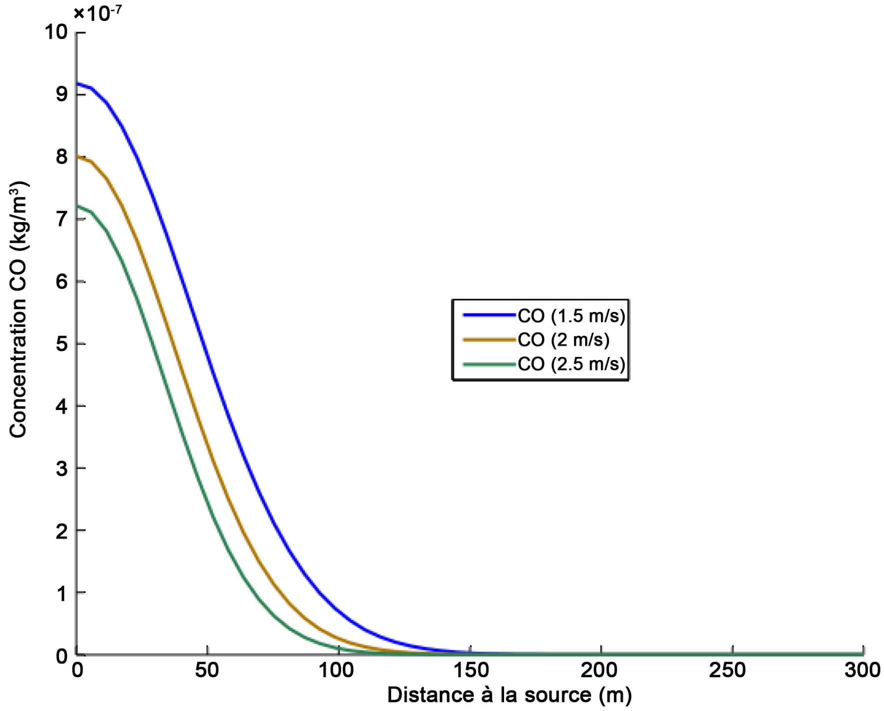

Figure 1. CO concentration as a function of wind regimes.

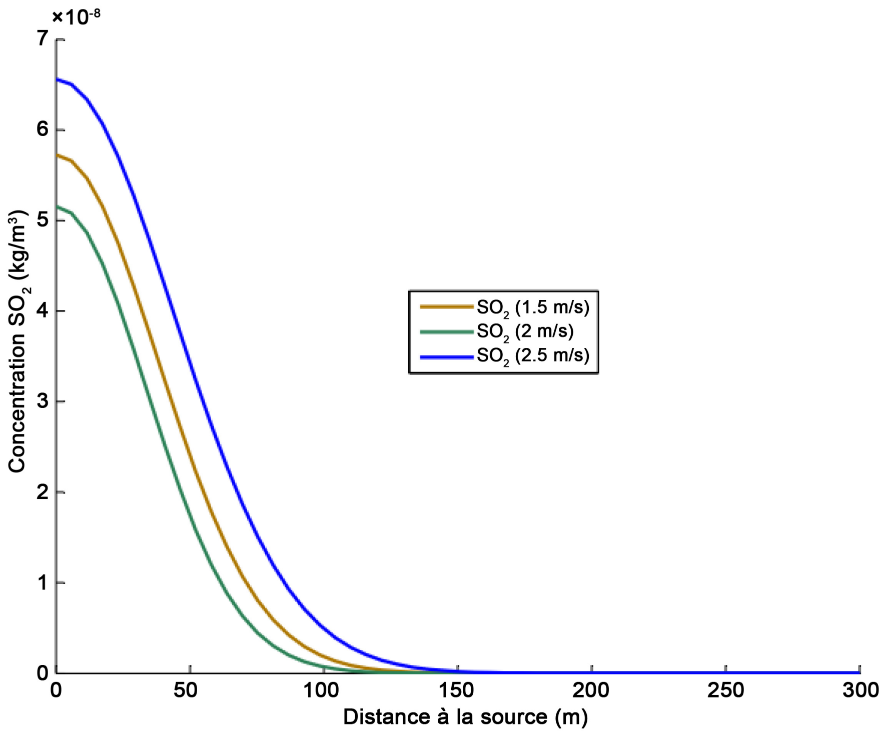

Figure 2. SO_2 concentration as a function of wind regimes.

total dilution in the atmosphere depending on the nature of the pollutant. From this, the individuals located in the interval [0; 150 m] are the most exposed to inhalations of chemical species released into the atmosphere. On the other hand,

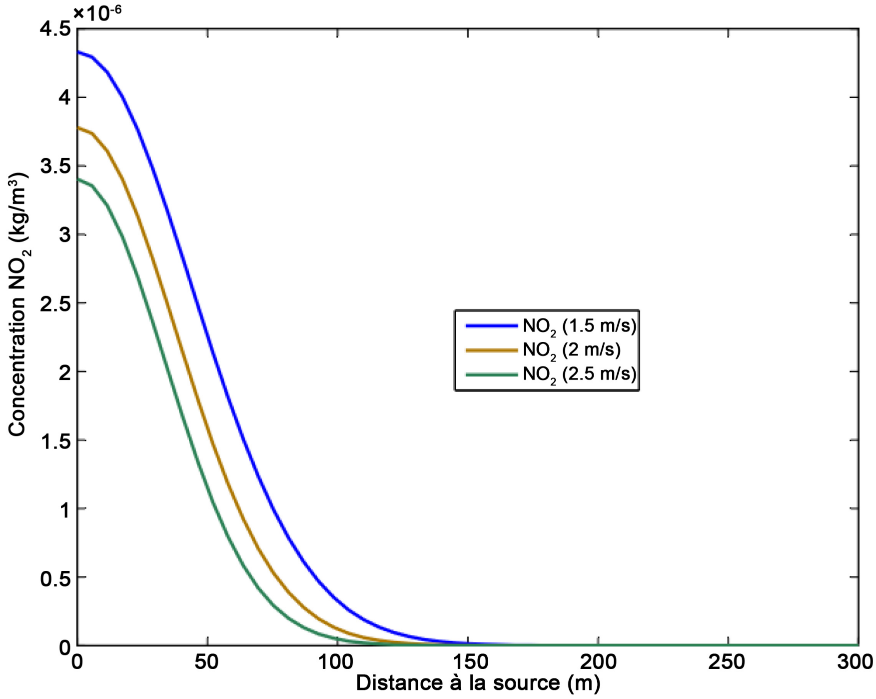

Figure 3. NO_2 concentration depending on wind regimes.

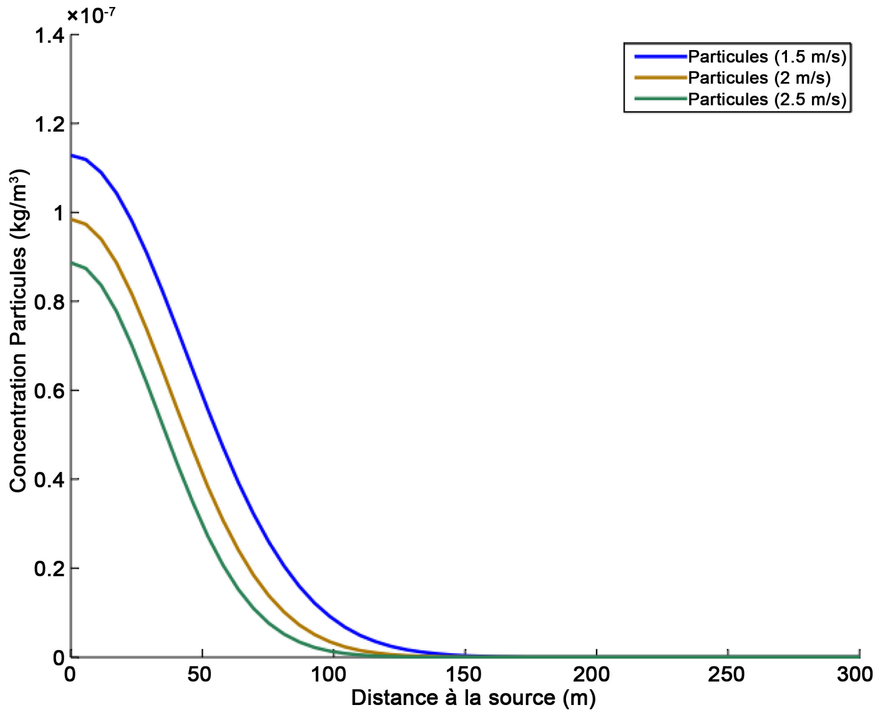

Figure 4. Concentration of Particles according to wind regimes.

those located beyond this interval are out of danger because we observe a total dilution of pollutants. In addition, we note that at this interval the most exposed individuals are the employees of the plant, hence the proposal for the following height.

2.3.2. Determination of the Concentration of Pollutants at a Given Height of Chimneys

The curves of (**Figures 5-8**) are plotted by the function $H_{in} = f(C_{maxin})$, these plots made it possible to obtain a set of dispersion curves for the four pollutants

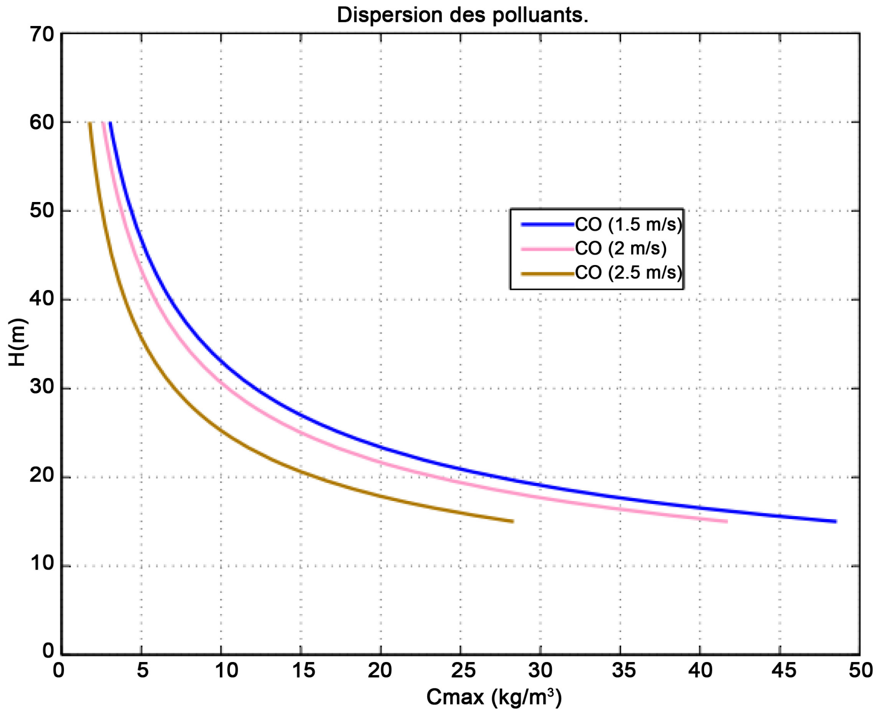

Figure 5. CO dispersion according to wind regimes.

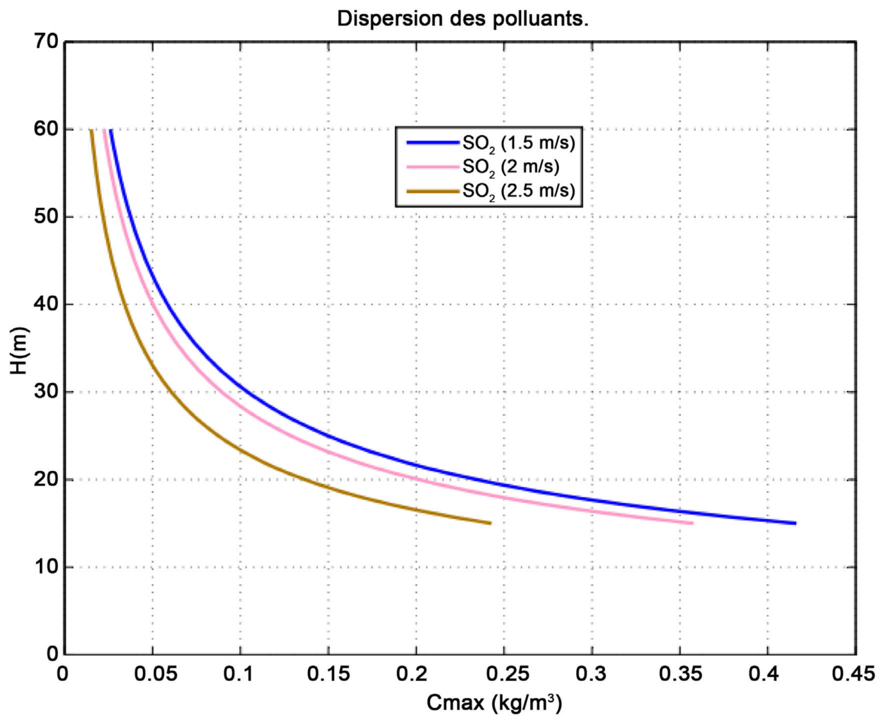

Figure 6. Dispersion of SO_2 according to wind regimes.

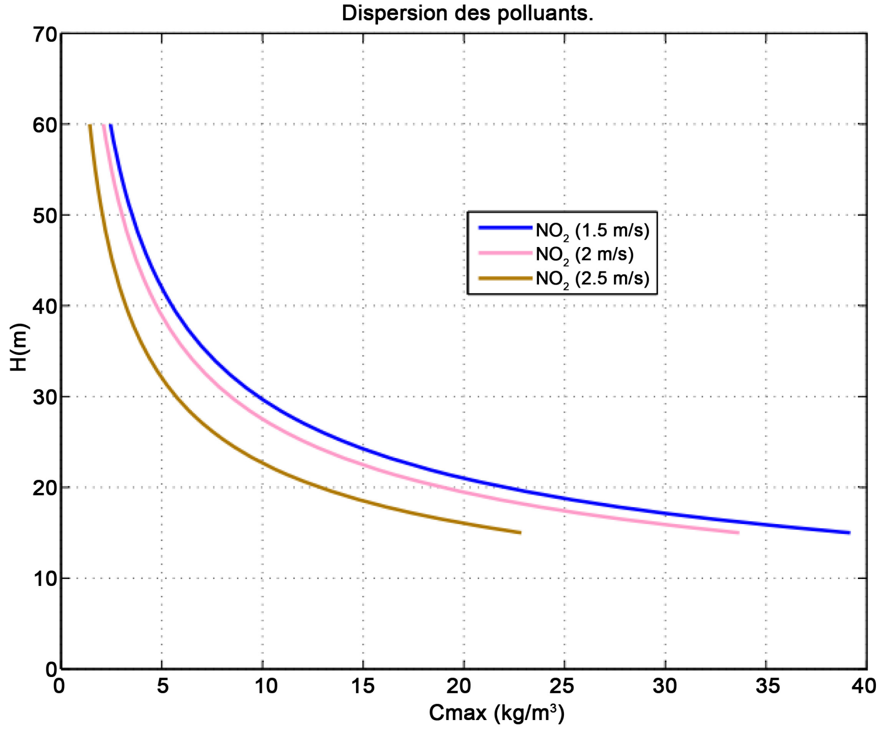

Figure 7. NO_2 dispersion according to wind regimes.

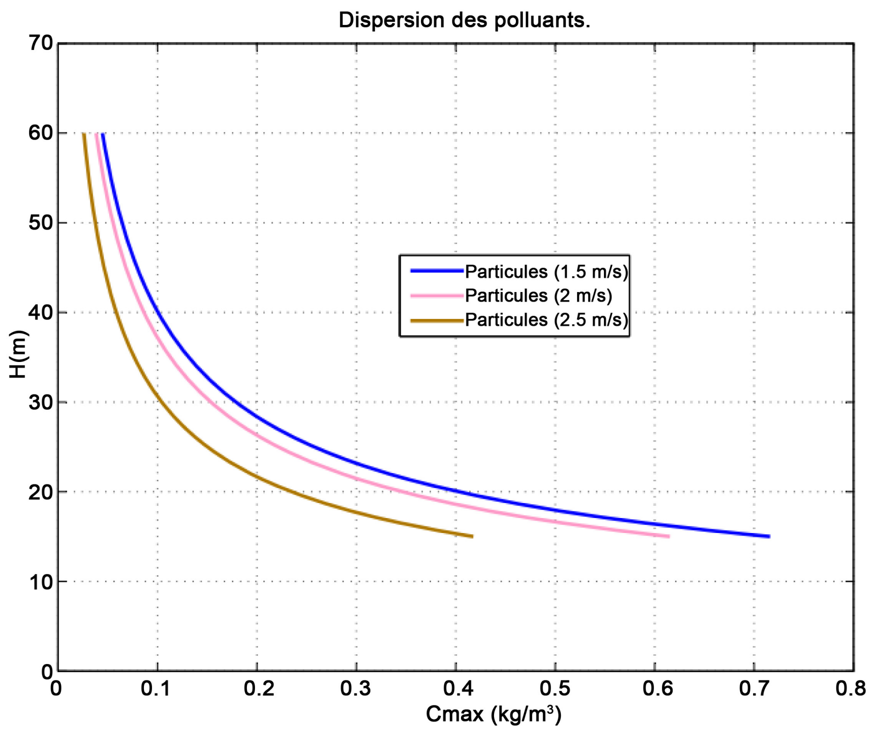

Figure 8. Dispersion of particles according to wind regimes.

as a function of wind regimes. Taking as reference the height of 15 m from the ground at which the attenuation of pollutants is made according to (Abdoulaye et al., 2007). We have carried out iterations in order to obtain a fixed height for which the concentration of pollutants at ground level is attenuated for the wind regimes chosen. These curves clearly show the role of wind dispersion. During the iterations, it was found that pollutants such as: SO_2 and particles are attenuated on the ground for a chimney height of 45 m from the ground. On the other hand, for the others, namely CO and NO_2, iteration continues up to the height of the chimneys of 60m to observe a good attenuation of these two pollutants on the ground. The heights of the chimneys will therefore depend on the attenuation of the ground concentrations of NO_2 and CO, because these pollutants evolve more slowly than the others do. We can therefore say that the dispersion is indeed better for high wind speeds, requiring only chimneys of average height. However, weak winds will depend on long chimneys for the same results.

3. Conclusion

The results of the simulation study allowed us to observe the distribution of the concentration of the source towards a limit value. From this we could see that for a wind regime of 1.5 m/s the concentration cancels at 150 m, then the wind regime of 2 m/s allows a prediction from a distance of 125 m and finally wind of 2.5 m/s; we have a predicted distance of 120 m at which the concentration is canceled out. From this, the individuals located in the interval [0; 150 m] are the most exposed to inhalations of chemical species released into the atmosphere. On the other hand, the one located beyond this interval is out of danger because we observe a total dilution of pollutants and we have determined an average height of 60 m for better attenuation of ground concentration. Better results could be obtained by designing a complete dispersion model. To do this, it is necessary to measure parameters such as temperature, parasitic sources of rejection, gas emission speeds and the heights of obstacles around the Power Plant.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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