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A Detailed Investigation of Particulate Dispersion from Kerman Cement Plant

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Abstract
The aim of this study was to investigate the particulate dispersion from Kerman Cement Plant. The upwind – downwind method was used to measure particle concentration and a cascade impactor was applied to determine particle size distribution. An Eulerian model, Gaussian plume model and an artificial neural network have been used to compute and predict concentration of PM_{10} from Kerman Cement Plant. Eulerian model incorporates source related factors, meteorological factors, surface roughness and particle settling to estimate pollutant concentration from continuous sources. The measured data have been used to create an artificial neural network for predicting suspended particle concentration from Kerman Cement Plant. The data includes particle concentration, distance from source, mixing height, lateral and vertical dispersion parameters and 10 meters wind speed. The performance of these models has been compared with the measured data. The AAPD (Average Absolute Percent Deviation) parameter for the results of the Eulerian model, Gaussian model and ANNs was 25.53%, 15.38% and 5.91% respectively.

Keywords: *Air Pollution, Particulate Dispersion, Gaussian Plume Model, Artificial Neural Networks (ANNs)*

Introduction
The deterioration of air quality in urban areas may be attributed to rapid industrialization. The ambient air quality has deteriorated to such an extent that it adversely affects the health and welfare of human beings [1, 3].
Kerman, a metropolitan city in the southeast of Iran is affected by increasing the air pollution level as a result of concentrated industrial activities and urbanization. One of these industries that has a particularly high rank on the list of pollutants is Kerman Cement Plant. The Kerman Cement Plant is located approximately 15 kilometers, south-west of Kerman. Portland cement dust is a gray powder with an aerodynamic diameter ranging from 0.05 to 10 µm. This size is within the range of sizes of respirable particles. Therefore, exposure of Portland cement dust has been long associated with respiratory symptoms [2].
Some attempts have been carried out to investigate particulate dispersion, as an instance, weekly average suspended parti-

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culate matter concentrations were measured in four locations in Shiraz, Iran [4]. The results of that study show that industrial pollution, especially particulate matter from an old cement plant located southwest of Shiraz, is exceeding international guidelines in some seasons. Also, in two localities of the Baltic costal macro-region in different seasons and weather conditions a cascade impactor was used for separation of solid urban aerosols [5]. Ten ranges of aerodynamic diameters between 0.009 and 8.11 μm were used.
Furthermore, to identify the origin of PM_{10} in the atmosphere of Shanghai, single PM_{10} particles from two environmental monitor locations and six pollution emitter sources were measured by scanning nuclear microscope techniques. The results of this investigation show that most of the measured PM_{10} particles are derived from building construction sites, cement factories, vehicles exhaust, coal boilers and steel mills [6]. In another study, atmospheric particle mass concentrations were measured at a site adjacent to Lake Hartwell, GA, during six dry sampling events in February–March 2003[7]. Particulate matter was collected on a deposition plate mounted onto a specially designed wind vane and was subsequently analyzed to determine the particle size distribution.
For modeling pollutant dispersion, as an instance, Olcese and Toselli [8] developed a model for reactive emissions from industrial stacks. Their model was based on the Lagrangian approach to the turbulent diffusion and estimated short–term concentration of primary and secondary pollutants resulting from point source emissions. Moreira et al.[9] presented an analytical solution for the nonstationary two dimensional advection–diffusion equation to simulate the pollutant dispersion in the planetary boundary layer. In their method the advection–diffusion equation was solved by the application of the Laplace transform technique.

In this study, a detailed investigation of particles dispersion from Kerman Cement Plant including measuring and modeling has been done. Measured data of PM_{10} concentration have been compared with the performance of a three dimensional Eulerian model, Gaussian plume model and artificial neural networks (ANNs).

Measurements

Particles Concentration

To measure PM_{10} from fugitive dust sources, upwind-downwind method was used [10]. In this method, ambient PM_{10} concentrations are measured upwind and downwind of a dust source. The difference between the two concentrations is considered to be the PM_{10} concentration due to the fugitive emission source.
To measure particle concentration we have used the Gravimetric method. In this method, a high volume pump is situated in an appropriate location preferably a little bit higher from ground level (2 m). The flow rate of the pump would be adjusted, considering the location of the pollutants dispersion in the environment. A fiber glass filter is placed in the filter holder and sampling is done at specific time intervals. Before using, the filters are kept for 24 hours in silica gel desiccators to insure equilibrium to the temperature and relative humidity held at constant values. Thereafter, the filters are weighed using an exact scale. After sampling, the moisture of filters are absorbed again, the differences between the filters' weights are measured and also the amounts of particles per volume unit are measured. The used pump model is HV1T, F&J specialty products, USA and the defined standard for existing particles in the working environment is based on WHO, 260 $\mu g/m^3$.

Particle Size Distribution

To measure PM during the extractive process, it is important to sample the gas isokinetically so that a representative sample of PM enters the sampling device. The parameter that must be controlled to establish isokinetics is the gas velocity within the sample probe, which must be equal to the actual gas velocity at the sample point in the source exhaust duct.

Cascade impactors generally can determine particle size between 0.3 to 16 µm [11], with low pressure impactors commercially available that measure particles between 0.02 and 10 µm [12,13]. The major limitation of cascade impactors is that only a small amount of PM (usually less than 10 mg) can be collected on each stage; therefore, the gas sampling volume/time must be adjusted to accommodate for this upper limit. Because of particle bounce and reentrainment and because of fracturing larger particles during impaction, cascade impactors may also be subject to biases towards small particles.

In this method, by using a pump, particles are passed into 8 stainless steel filters with different mesh (cascade impactor, Andersen sampler model AN200) then the particles are deposited on fiber glass filters. The used pump flow rate is 1 CFM (according to a previous conducted method).

The method of scaling particles is gravimetrical, in the way that filters are dried firstly and then weighed and thereafter are placed in Anderson Sampler containers. After sampling, the differences in weights for each filter are calculated by using the EPA standard and for the stack and the selected area the correcting factor of air density is also applied.

In the stacks the measurements are done based on the ISO-9096 standard and isokinetic sampling. With regard to the length of the probe, sampling has been done in different parts of the stack, in order to obtain an appropriate average from particles concentration in gas flow.

Raw materials and stack's dust analysis

In order to obtain components of Kerman cement stack's dust and compare it with raw materials, some samples of the stack's dust and raw materials have been taken and analyzed. Table 1 shows these analysis, it can be seen there is similarity between these two analysis, in both of them the main components are CaO, SiO_2 and Al_2O_3 but amount of these component in the raw materials are higher than dust. On the other hand, the amount of MgO, N_2O, SO_3, K_2O and Fe_2O_3 in the stack dust are considerable.

Table 1. Raw materials and stack dust analysis

Component	Dust	Raw materials
SiO_2	9.5%	14.09%
Al_2O_3	3.6%	3.86%
Fe_2O_3	3.87%	2.67%
CaO	40.3%	42.86%
MgO	1.95%	0%
SO_3	0.66%	0.03%
N_2O	0.41%	0%
K_2O	2.4%	0.37%

Mathematical model (Eulerian model)

In this study we have developed a mathematical model based on Eulerian method to predict particle concentration. In Eulerian method, the continuity equation of particles is solved to obtain particle concentration distribution considering the effect of gas turbulence is considered. The advantages of this approach are low CPU time and direct consideration of gas turbulence. In this model the particle velocity is equal to the gas velocity. This assumption is valid when the size of particle is fine. In the present work the average size of particle is 9 µm, so, that we can apply Eulerian method.

Establishing the continuity equation is the initial point of mathematical analysis of atmospheric distribution. For a point source, which disperse particles continuously, a 3D

model is used and a partial differential equation is presented by using Fick's law.
Pollutants chemical reaction is ignored in this analysis but their settling on the earth is considered. Pollutants move horizontally in wind direction and diffuse into atmosphere in y and z direction. Increasing the altitude, diffusivity and wind profile change and are functions of input pure heat flux into atmosphere and regional surface roughness.
In this study, continuity equation for particles based on the conventional diffusion equation can be represented as:

$$u\frac{\partial C}{\partial x}-\frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right)-\frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right)=0 \qquad (1)$$

Where x axis is on wind direction, y is vertical to wind direction in horizontal plate and z is vertical axis. Also, u is wind speed in x-direction, C is particles concentration in the ambient, K_y is the eddy diffusivity in y-direction and K_z is the eddy diffusivity in z-direction.
In this work, diffusion in x-direction (wind direction) is ignored. Boundary conditions include:

a- Particles are dispersed from point source and for point source, the term ″Q″ as a pollution source is added in the right hand side of the equation (1).
b- Particles settle on the ground with terminal velocity:

$$V_t=\frac{d_p^2\rho_p g}{18\mu} \qquad (2)$$

c- Particles diffusion in vertical direction (z) is ignored after mixing height.
d- Particles penetration in horizontal direction (y) is ignored after a certain distance which is computed due to different conditions of atmospheric stability.

In computing equation (1) for predicting particle concentration, one must obtain expressions for wind speed and wind eddy diffusivity [17]. These variables are recognized as a function of vertical distance from the ground and surface roughness. Eddy diffusivities and wind speed are related to atmosphere stability. In this study, the boundary layer is divided into two parts: surface layer which is up to about 100 meters above the earth and planetary boundary layer which can continue to 1000 meters or more. In surface layer, wind profile is considered logarithmic (due to the existence of surface roughness parameters) and for planetary boundary layer, an exponential profile is considered. Further details of evaluating these parameters are given elsewhere, Mohebbi and Baroutian [18].
The finite volume method incorporated with the power-law scheme and stretched grid in x-direction [14] was employed to obtain the numerical solution of equation (1). According to the atmospheric stability, the particles diffusion domain in y-direction is gained at about 2000 meters. For all presented results, the height of mixing layer was 250 m and the height of surface layer was 80 m. So, with Δy=20 m and Δz=10 m there are 100 and 25 elements in y and z directions respectively. In general, in each section we would have 25×100 cells (i.e. 2500 cells). The domain of particles dispersion in x-direction is 10000 meters. In order to reduce the time of calculations, the sizes of Δx would be diverse, meaning that at close points to the source which we have rapid changes of concentration, the sizes of Δx would be lower and on the distant points they would be higher.
Instead of solving the equation (1) directly, ambient atmosphere is divided into small elements and mass conservation equation is written for each element. In order to solve the equations concurrently, a computer program has been written in MATLAB software environment. First, the program receives

variable inputs from the user (the invariable inputs have been defined in the program). The variable inputs are: meteorological parameters (roughness, wind speed, surface layer height, mixing height, regional geographical width, atmospheric stability conditions, and ambient temperature), parameters related to the source (particles density, particles diameter, stack height, stack diameter, stack gas flow rate, stack gas temperature, emission rate) and size of Δy and Δz which the user should define them after calling the program. Subsequently, the program calculates the dispersion coefficients and wind speed profiles and after that concentration would be calculated.

Gaussian plume model

In this study a Gaussian plume model that incorporates source related factors and meteorological factors has been used to estimate pollutant concentration from continuous sources. It is assumed that the pollutant does not undergo any chemical reactions, and that no other removal processes, such as wet or dry deposition, act on the plume during its transportation from the source. The basic equation for determining ground level concentrations under the plume centerline from Gaussian model equations is [15]:

$$X = \frac{Q}{2\pi u_s \sigma_y \sigma_z}\left\{\exp\left[-0.5\left((z_r - h_e)/\sigma_z{}^2\right)^2\right] + \exp\left[-0.5\left((z_r + h_e)/\sigma_z{}^2\right)^2\right] + A\right\} \tag{3}$$

$$A = \sum_{N=1}^{k}\left[\begin{array}{l} \exp\left(-0.5(z_r - h_e - 2Nz_i)/\sigma_z\right)^2 + \exp\left(-0.5(z_r + h_e - 2Nz_i)/\sigma_z\right)^2 \\ + \exp\left(-0.5(z_r - h_e + 2Nz_i)/\sigma_z\right)^2 + \exp\left(-0.5(z_r + h_e + 2Nz_i)/\sigma_z\right)^2 \end{array}\right] \tag{4}$$

This equation is used to model the plume impacts from point source with a numerical integration algorithm.

The meteorological data required for this modeling effort were obtained from surface weather observatory stations located at Kerman's airport, close to the cement plant. Turner's stability classification method was used to determine atmospheric stability [16].

Neural networks

Artificial Neural networks (ANNs) are computing systems which can be trained to learn a complex relationship between two or many variables or data sets. Basically, they are parallel computing systems composed of interconnecting simple processing nodes.

The present work, applied the feed forward back propagation network with three layers [17]. The input, hidden and output layers had 6, 10 and 1 neurons, respectively. Each layer of this network has its own weight matrix, its own bias vector, a net input vector and an output vector.

In order to train and validate the neural network, several measured data of PM_{10} concentration have been used. To improve the learning process, mixing height, lateral and vertical dispersion parameters and 10 meters wind speed have been used. These meteorological parameters are related to atmospheric conditions.

Input vectors include distance from source, mixing height, lateral and vertical dispersion parameters and 10 meters wind speed. Also, target vector includes particles concentrations. The input vectors have been normalized randomly generated values ranging from -1 to 1. 75% of these data have been used to train the network and 25% have been used for simulation. The optimized number of hidden neurons has been determined during the learning and training processes by trial and error tests. After training of the three-layer, feed forward, back propagation network, the PM_{10} concentration can be found from the simulation of this network due to the suitable inputs. In the last step, after confidence about the results of the network, PM_{10} concentration in another distances have been predicted.

Results and Discussion

The downwind particle concentrations have been measured at different distances from the stack on a close layer to the ground surface and the results are shown in Fig. 1. As it is seen in this figure, the point of maximum concentration is approximately 750 m downwind. Also in Fig. 1 the measured concentrations are compared with those predicted by the Eulerian model, Gaussian plume model and ANNs. It can be seen that there is a good agreement between the results of these models and the measured data. Fig.1 also shows that for distances close to the source, the concentration of pollutants is lower and from this point on to 750 meter from the source, the particles concentration rapidly increases. Then the pollutants concentration is at first at a high rate and thereafter decreases to a slow rate. Also, the AAPD (Average Absolute Percent Deviation) parameter for the results of Eulerian model, Gaussian model and ANNs is 25.53%, 15.38% and 5.91% respectively according to the expression:

$$AAPD = \frac{1}{N}\sum_{i=1}^{N}\left|\left(\frac{C_{exp} - C_{cal}}{C_{exp}}\right)_i\right| \times 100 \quad (5)$$

Figures 2 and 3 show the particle size distribution in the stack for two samplings. These figures indicate that the particles with 1.1-3.3 μm diameters have maximum weight percent and concentration in the stack.

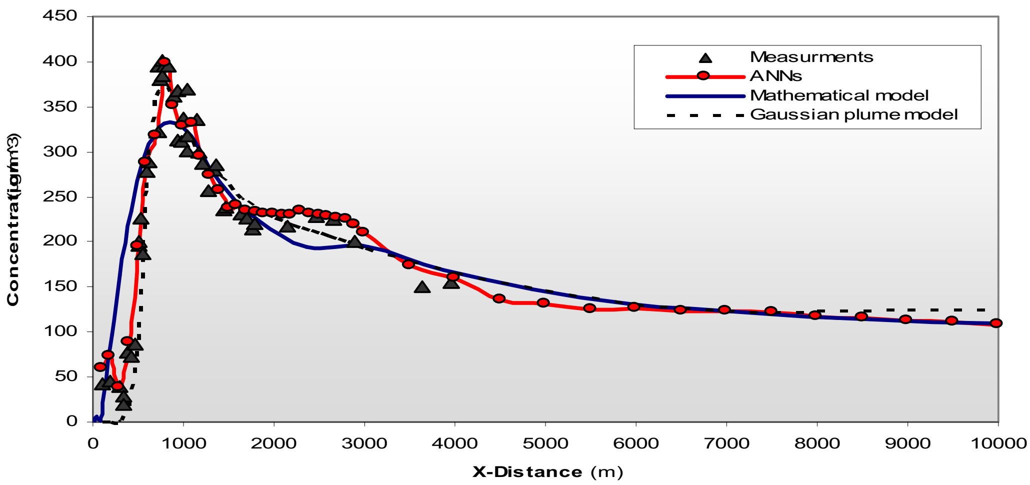

Figure 1. Comparison of measured concentration with those predicted by the mathematical model(Eulerian model), Gaussian Plume model and ANNs.

Figures 4 and 5 illustrate particle size distribution versus weight percent and concentration in the plant ambient air for the downwind and upwind of the source.

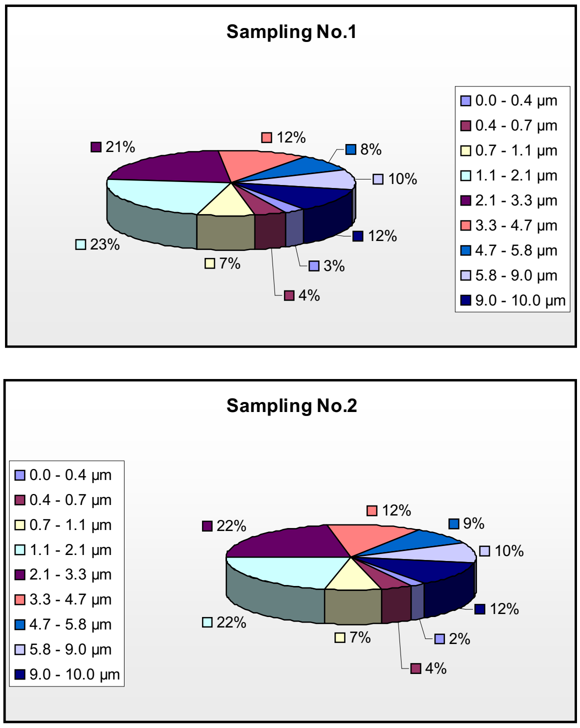

Figure 2. Particle size distribution versus weight percent in the stack.

Figure 6 compares the particle size distribution versus weight percent and concentration in the plant ambient air. It can be seen clearly that the particle concent-ration with a size range of 3.3-9 µm and less than 0.7 µm in the downwind of the source is more than the upwind.

Three dimensional views of the concentration profile in the ground surface layer that were predicted by the Eulerian model have been shown in Fig. 7. As the figures show the maximum concentration is in the direction of emission from the stack at y=1000. Also the extent of pollutant dispersion in y-direction increases as it gets farther from the source.

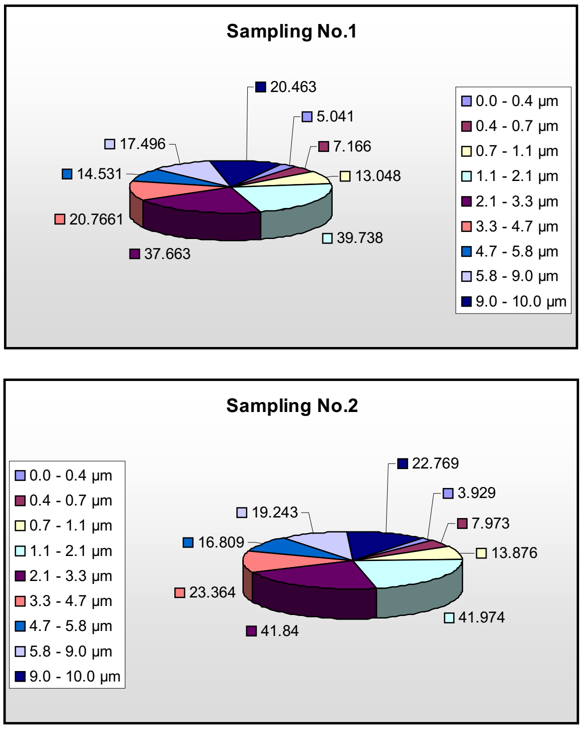

Figure 3. Particle size distribution versus particles concentration in the stack.

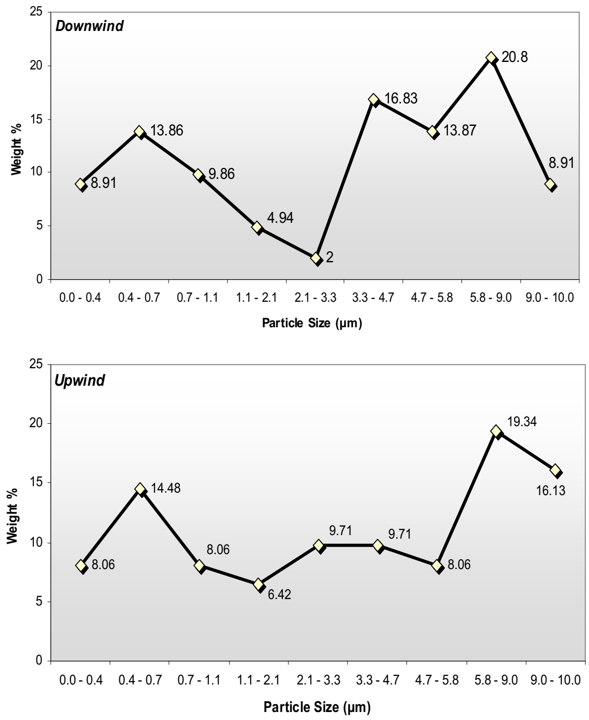

Figure 4. Particle size distribution versus weight percent in the plant ambient air (Upwind and downwind of the source).

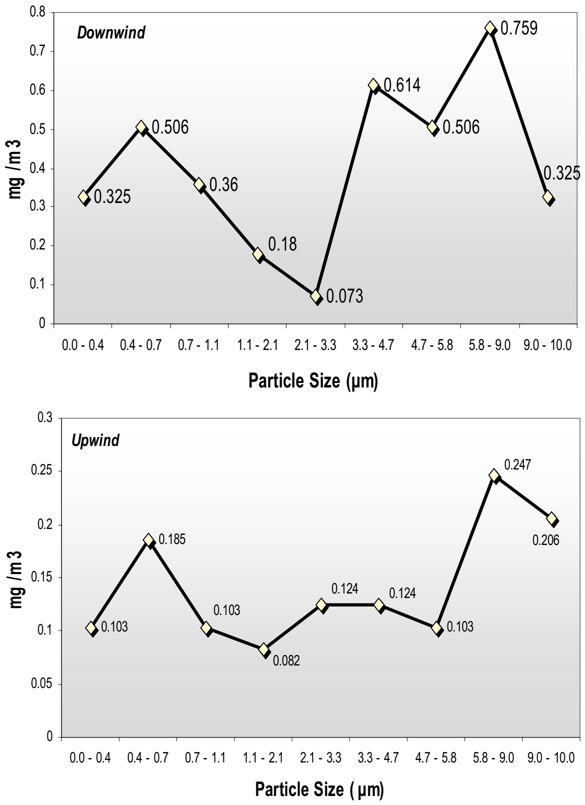

Figure 5. Particle size distribution versus particles concentration in the plant ambient air (Upwind and downwind of the source).

Conclusions

In the present study, a detailed experimental and theoretical investigation was carried out to find out the pattern of particulate dispersion from Kerman Cement Plant. The measurement result of this work shows that the PM_{10} concentration in the ambient air at distances of 590 – 1370 m from the stacks is higher than the WHO guidelines of an annual average of 260 μg/m^3. Particle size distribution from a cement plant stack has a wide range. It includes PM_{10}, $PM_{2.5}$, $PM_{1.0}$ and ultra fine particles. These particle size ranges have shown to a significant contribution to respiratory problems. Finally, good agreement between measured data and Eulerian model, Gaussian plume model and ANNs show that these models can be a powerful model for predicting particle concentration for the downwind of a source. In distances, 400 - 2900 meters from the source, using the Gaussian plume model or ANNs is more accurate. For the regions far from 2900 meter either the Eulerian model or ANNs is recommended.

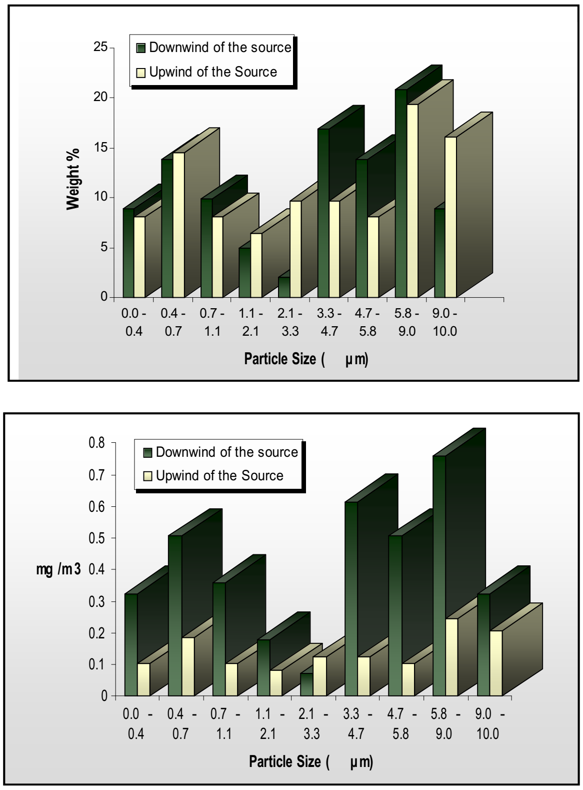

Figure 6. Comparison of particle size distribution versus particles concentration and weight percent in the plant ambient air.

Nomenclature

C	Concentration (μgr/m^3)
d_p	particles diameter (m)
g	gravity acceleration (m/s^2)
h_e	plume centerline height (m)
k	summation limit for multiple reflections of plume (dimensionless)
k_y	eddy diffusivity in y-direction (m^2/s)
k_z	eddy diffusivity in z-direction (m^2/s)
Q	emission rate (gr/s)
u	wind speed in x-direction (m/s)
u_s	stack height wind speed (m/s)
v_t	particles terminal velocity (m/s)
X	concentration (μ gr/m^3)

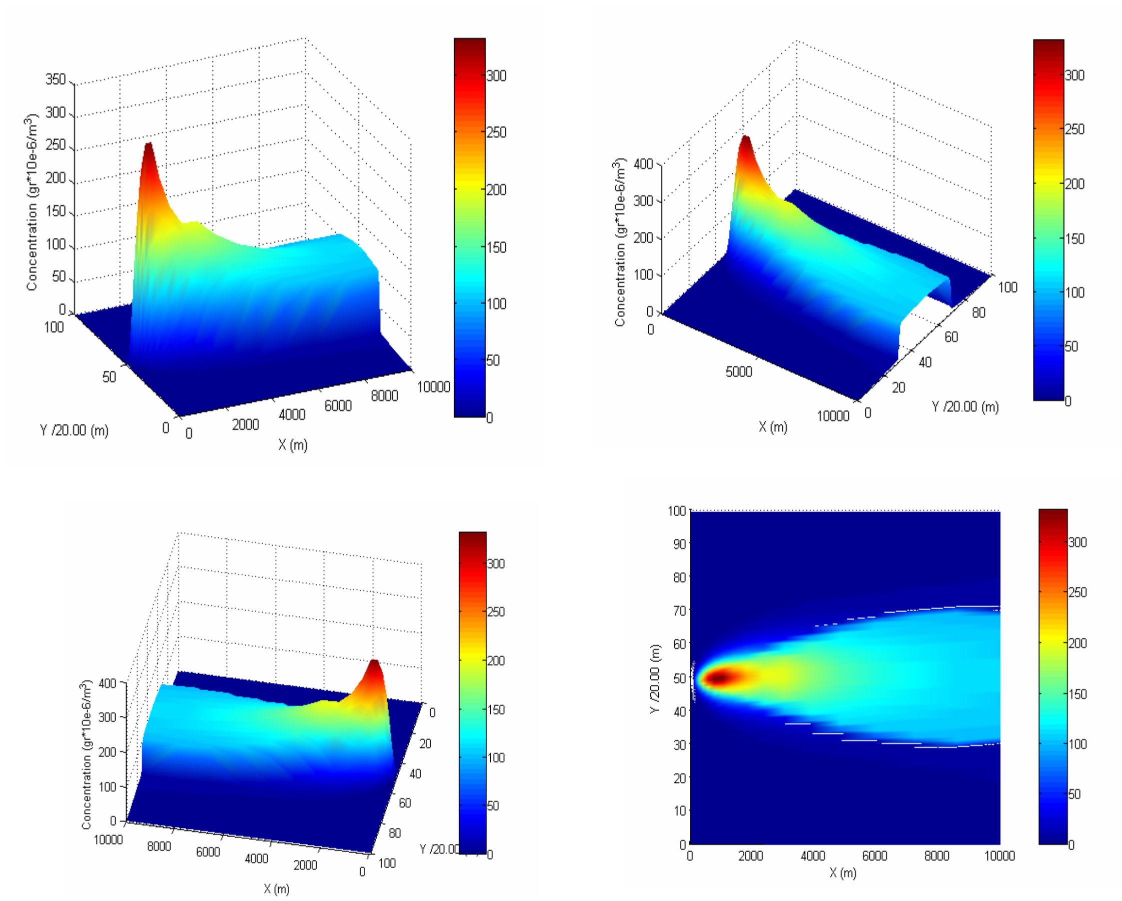

Figure 7. Three dimensional views of the concentration profile in the ground surface layer predicted by the mathematical model (Eulerian model).

Δx element size in x-direction (m)
Δy element size in y-direction (m)
z_i mixing height (m)
z_r receptor height above ground (m)
Δz element size in z-direction (m)

Greek letters

ρ density (kg/m^3)
ρ_p particles density (kg/m^3)
μ viscosity (kg/m.s)
σ_y lateral dispersion parameter (m)
σ_z vertical dispersion parameter (m)

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