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Measuring and modeling particulate dispersion: A case study of Kerman Cement Plant

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Abstract

In this study to identify the origin of PM10 in the atmosphere of Kerman and investigate the dispersion conditions for these particles, the variations of the mass concentration and size distribution of PM10 have been measured. This study is focused on the local environmental impact of Kerman Cement Plant. All samples have been taken in the area between the plant and the city entrance at the wind direction. The result of this research shows that the PM10 concentration in the ambient air in distances about 590–1370 m from the stacks is higher than the WHO guidelines of annual average (260 $\mu g/m^3$). Also, concentration of PM10 is computed by using Gaussian plume model that incorporates source related factors and meteorological factors to estimate pollutant concentration from continuous sources. The performance of this model has been compared with the measured data.

Keywords: Air pollution; Particulate dispersion; Point source; Modeling

1. Introduction

According to the United Nation Environmental Program (UNEP), Suspended Particulate Matter (SPM) is the most significant source of air pollution affecting the world's largest cities [1]. Particulate matter, one of the six criteria pollutants regulated by the Environmental Protection Agency (EPA) through the National Ambient Air Quality Standards (NAAQS) is the generic term for dust and other diverse types of particles in the air. In 1987, EPA changed the indicator for the PM from Suspended Particulate Matter (SPM) to PM10 emissions (particles with an aerodynamic equivalent diameter less than or equal to a nominal 10 μm) [2].

Kerman, a metropolitan city in the southeast of Iran is affected by increasing air pollution level as a result of concentrated industrial activities and urbanization. Fig. 1 shows an aerial photograph of city of Kerman. 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 km, on south west of Kerman. Unfortunately, the location of this plant had been chosen without considering environmental impacts. Most of the times, wind direction is from the plant toward the city, therefore particulate matters are carried away toward the city. The major source of PM10 in this plant is the processing system which includes the kiln and the grinder exhaust stacks.

In this plant, raw materials, which consist mainly of limestone, silica, alumina and iron materials, after a complete grinding and mixing, are heated up to 1600 °C in a rotary kiln to produce Portland cement. The required heat is produced from combustion of the natural gas. The flue gas, consisting of nitrogen, carbon dioxide, water vapors, excess oxygen and some particulates, enters the electrostatic precipitator for final cleaning [3].

Due to continuous growth of industries the deterioration of air quality in urban areas has provided the impetus for comprehensive modeling and measuring air quality. Emissions from industrial stacks are regulated to protect human and environmental health.

Thus, industrial facilities are required to obtain permits to emit into the atmosphere and demonstrate their compliance with regulations. In the process of applying for permits, dispersion models are generally used to assess the impact of point source emission at ground level. Methods of estimating atmospheric

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Nomenclature

f	Coriolis parameter (s^{-1})
h_e	plume centerline height (m)
h_s	stack height (m)
k	summation limit for multiple reflections of plume
P	wind profile exponent
Q	emission rate (g/s)
u_{ref}	observed wind speed (m/s)
u_s	stack height wind speed (m/s)
u_{10}	10 m wind speed (m)
u^*	friction velocity (m/s)
x	downwind distance (m)
X	concentration ($\mu g/m^3$)
z_i	mixing height (m)
z_r	receptor height above ground (m)
z_{ref}	reference measurement height (m)
Z_m	mechanically mixing height (m)

Greek letters

σ_y	lateral dispersion parameter (m)
σ_z	vertical dispersion parameter (m)

dispersion have been studied for long time and undergone considerable revisions because of experimental results. Among the important parameters affecting dispersion are atmospheric stability, ground roughness and wind speed.

Some attempts have been carried out to investigate particulate dispersion, as an instance, weekly average suspended particulate matter concentrations were measured in four locations in Shiraz, Iran [4]. Instrumental Neutron Activation Analysis (INAA) and Atomic Absorption Spectrometry (AAS) methods were employed in this investigation. The results of that study show that industrial pollution, especially particulate matter from old cement plant located on the south west of Shiraz, is exceeding international guidelines in some seasons.

Also, in two localities of the Baltic costal macro-region in different seasons and weathers 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. The elementary composition for each diameter was obtained in a complex procedure consisting of laser ablation of deposits, then their successive ionization in an inductively coupled plasma generator, and finally mass selection in a quadruple spectrometer. Despite its complexity, the chemical element analysis method proved to be versatile, allowing the identification air pollution from natural and industrial sources, and road traffic.

Furthermore, to identify the origin of PM10 in the atmosphere of Shanghai, single PM10 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 PM10 particles are derived from building construction sites, cement factories, vehicles exhaust, coal boilers and steel mills [6].

The size distributions of 16 Polycyclic Aromatic Hydrocarbons (PAHs) and particle mass less than 10 μm in aerodynamic diameter were measured by using a nine-stage low-volume cascade impactor at rural and urban sites in Tianjin, China in the winter of 2003–2004 [7]. The particles exhibited the trimodal distribution with the major peaks occurring at 0.43–2.1 and 9.0–10.0 μm for both urban and rural sites. The concentrations of the total PAH (sum of 16 PAH compound) at rural site were generally less than those of the urban site. The fine differences of concentration and distribution of PAHs at different levels at urban site suggested that the different source and transportation path of particulate PAHs.

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 [8]. 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.

Accordingly, the mass concentrations of PM10, SO_2, NO_x and O_3 at three sampling sites were observed in Beijing during dust storm occurrence period in April 2000 [9]. The PM2.5 samples were simultaneously collected. By comparing the hourly variations of the pollutant concentrations before, during and after dust storm events and haze pollution episode, the variation characteristics of the mass concentrations of PM10, SO_2, NO_x and O_3 during dust storm events were presented.

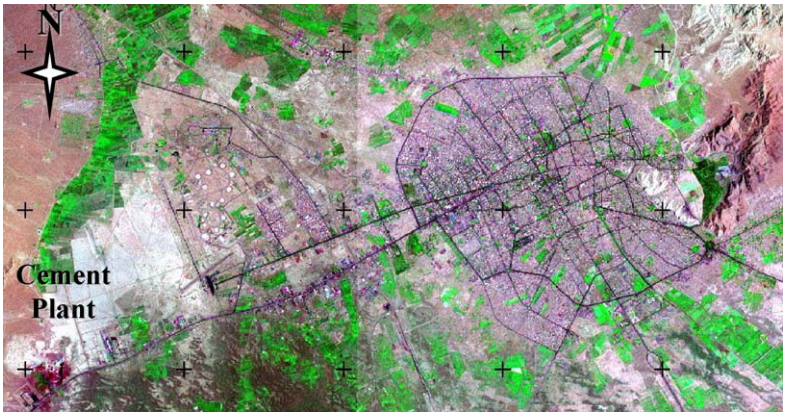

Fig. 1. Aerial photograph of city of Kerman.

Likewise, to analyze the elemental composition and the concentrations of PM10 and PM2.5 in the urban environment in South Brazil with HV PM10 and dichotomous samplers, three sampling sites were selected [10]. The mass concentrations of the samplers were evaluated, while the elemental concentrations of Si, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu and Zn were determined by using the particle-induced X-ray emission (PIXE) technique. Factor analysis and canonical correlation analysis were applied to the chemical and meteorological variables in order to identify the sources of particulate matter. Industrial activities such as steel plants, coal-fired power plants, hospital waste burnings, vehicular emissions and soil were identified as the sources of the particulate matter.

This case study included two main parts, measuring and modeling particulate dispersion. Measurements incorporated particle size distribution and particles concentration. In the modeling matter, Gaussian equation has been based to predict and identify particle mass concentrations in the atmosphere of Kerman.

2. Measurements

2.1. Particle concentration

To measure PM10 from fugitive dust sources, upwind-downwind method was used [11]. In this method, ambient PM10 concentrations are measured upwind and downwind of a dust source. The difference between the two concentrations is considered to be the PM10 concentration due to the fugitive emission source. Using wind speed, direction, and other meteorological data obtained during the PM10 sampling period and the emission rate is determined using dispersion models.

For measuring particle concentration we have used Gravimetric method. In this method, high volume pump is situated in an appropriate location preferably a little bit higher from the ground level (2 m). The flow rate of pump would be adjusted, considering the location of pollutants dispersion in the environment. A fiber glass filter is placed in the filter holder and sampling is done on certain time intervals. Filters before being used, are kept for 24 h in silica gel desiccators to equilibrate to the temperature and relative humidity held at constant values. Thereafter, the filters are weighted using an exact scale. After sampling, the moistures 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 working environment is based on WHO, 260 $\mu g/m^3$.

Sampling time duration is different according to pollutant dispersion. It should be noted that in sampling by filter, sampling time duration in respect to pollutant dispersion must be at a level which over load phenomenon does not occur. As the temperature increases and the altitude from the sea level heighten, the air density is lowered; therefore, in each sampling the air density must be modified. Correcting factor in cement plant environment, having 21 °C temperatures and the altitude of 1750 m, equals 0.82. By application of correcting factor, the achieved concentration is based on standard air density.

2.2. Particles size distribution

For measuring PM during extractive methods, it is important that the gas be sampled isokinetically so that a representative sample of PM enters the sampling device. The term "isokinetic" refers to the situation where the gas streamlines of the source gas are preserved within the sampling probe so that the concentration and size distribution of the PM in the sample probe is the same as in the source effluent duct. 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. Since the sample probe have a smaller diameter than the source exhaust duct and possibly a lower temperature, the actual gas flow rate used to extract gas through the sampling probe must be controlled to establish an isokinetic sampling velocity.

The size distribution of a particulate dust stream is sometimes desired to determine the emissions from a source or collection efficiency of a PM control device. Various measurement approaches are available to determine the size distribution of a particulate stream that includes cascade impactors, sampling cyclones, centrifugal separators, and more advanced techniques that utilize laser. Cascade impactors are a widely used method to size particles that have been commercially available for source testing since the early 1970s [12] and have a relatively well-developed theoretical basis [13,14]. Impactors collect particles by inertial impaction and utilization a series of plates (discs) or stages with various-sized holes (jets) that alter the velocity of the gas passing onto the next stage. Particles of a specific size or larger will impact each plate, while smaller particles will pass through the next plate.

Cascade impactors generally can determine particle sizes between 0.3 and 16 μm [13], with low pressure impactors commercially available that measure particles between 0.02 and 10 μm [15,16]. 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 a subject to biases towards small particles.

In this method, by using pump, particles are passed into eight 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 weighted and thereafter are placed in Anderson Sampler containers. After sampling, the differences in weights from 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 (see Fig. 2). With regard to the length of the probe, sampling has been done in different

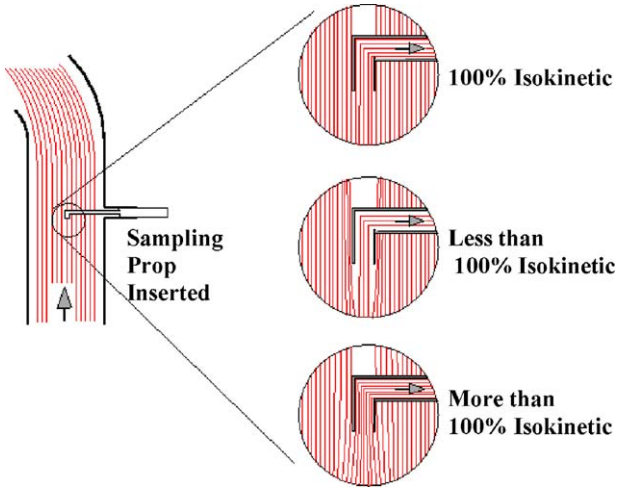

Fig. 2. Isokinetic vs. non-isokinetic sampling.

parts of the stack, in order to obtain an appropriate average from particles concentration in gas flow.

3. Modeling

3.1. Theory

This study uses a Gaussian plume model that incorporates source related factors and meteorological factors to estimate pollutant concentration from continuous sources (see Fig. 3). 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 [17]:

$$X = \frac{Q}{2\pi u_s \sigma_y \sigma_z}\left\{\exp\left[-0.5\left(\frac{z_r - h_e}{\sigma_z^2}\right)^2\right] + \exp\left[-0.5\left(\frac{z_r + h_e}{\sigma_z^2}\right)^2\right] + A\right\} \quad (1)$$

$$A = \sum_{N=1}^{k}\left[\exp\left(\frac{-0.5(z_r - h_e - 2Nz_i)}{\sigma_z}\right)^2 + \exp\left(\frac{-0.5(z_r + h_e - 2Nz_i)}{\sigma_z}\right)^2 + \exp\left(\frac{-0.5(z_r - h_e + 2Nz_i)}{\sigma_z}\right)^2 + \exp\left(\frac{-0.5(z_r + h_e + 2Nz_i)}{\sigma_z}\right)^2\right] \quad (2)$$

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

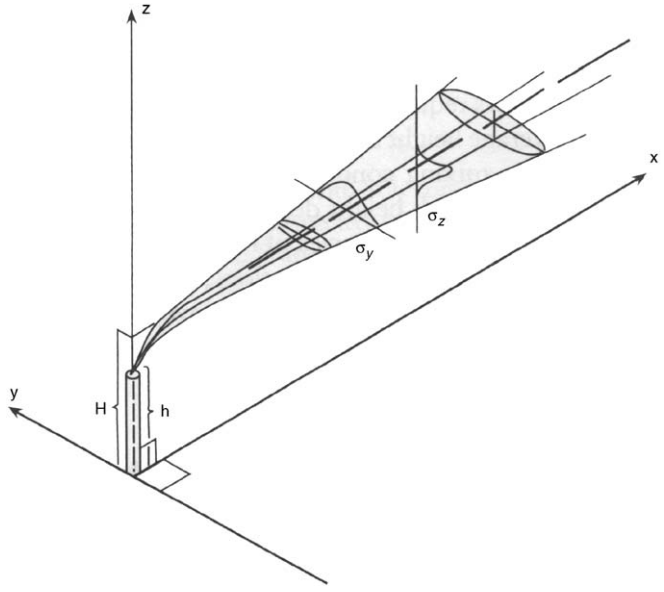

Fig. 3. Schematic illustration of a Gaussian plume model.

3.2. Meteorological conditions

Atmospheric conditions are a driving force in the formation, dispersion and transportation of pollutant plumes. 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 [18]. Stability of the atmosphere varies hourly, but for modeling purposes, for short time periods a constant representative atmospheric stability was assumed. This stability class combined with wind speed to identify the worst case meteorological condition that results in maximum ground level concentrations. Table 1 shows stability–wind speed combinations that are considered in this model.

The wind power law is used to adjust the observed wind speed, u_{ref}, from a reference measurement height, z_{ref}, to the stack height, h_s. The stack height wind speed, u_s, is found from

Table 1
Wind speed and stability class combination

Atmosphere stability	Wind speed					
	1.5 m/s	2.5 m/s	4.5 m/s	7 m/s	9.5 m/s	12.5 m/s
A	*	*				
B	*	*	*	*		
C	*	*	*	*	*	
D	*	*	*	*	*	*
E	*	*	*			
F	*	*				

the power law equation [19]:

$$u_s = u_{ref}\left(\frac{h_s}{z_{ref}}\right)^P \quad (3)$$

P, the wind profile exponent, is a function of stability category.

The volume available for diluting pollutant in the atmosphere is defined by the mixing height. The mixing height that used in this modeling for neutral and unstable conditions is based on an estimated mechanically driven from mixing height. The mechanically mixing height is calculated as [20]

$$z_m = \frac{0.3u^*}{f} \quad (4)$$

where u^* is a friction velocity (m/s) and f is the Coriolis parameter ($9.374 \times 10^{-5}\ s^{-1}$ at 40 °C). Using a log-linear profile of the wind speed, and assuming a surface roughness about 0.3 m, u^* is estimated from 10 m wind speed, u_{10}, as

$$u^* = 0.1u_{10} \quad (5)$$

3.3. Dispersion parameters

It is well recognized that the eddy diffusivity in the planetary boundary layer is neither stationary nor homogeneous. It changes significantly between day and night. In addition, the diffusivity above the planetary boundary layer is much smaller than that below this layer. Equations that approximately fit the Pasquill–Gifford curves are used to calculate σ_y and σ_z for the rural mode. The equations used to calculate σ_y and σ_z are of the form [19]:

$$\sigma_y = 465.11628(x)\tan(TH) \quad (6)$$

$$\sigma_z = ax^b \quad (7)$$

where

$$TH = 0.017452393[c - d\ln(x)] \quad (8)$$

In Eqs. (6)–(8), x is the downwind distance and the coefficients a, b, c and d have been calculated according to the Pasquill stability category.

4. Results

The downwind particle concentrations have been measured at different distances from the stack on a near layer to the ground surface and the results shown in Fig. 4. As can be seen in this figure, the point of maximum concentration is approximately 750 m downwind. Also in Fig. 4 the measured concentrations are compared with those predicted by the Gaussian plume model. It can be seen that there is good agreement between the results of model and measured data.

Therefore, this figure provides a good validation for the Gaussian plume model and we can use this model for estimating particle concentration for distances more than 4 km downwind of the source. As can be seen in Fig. 4 there is no measured data for these distances.

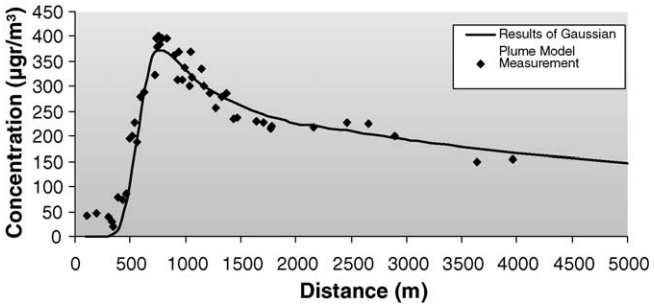

Fig. 4. Comparison of measured concentration with those predicted by the Gaussian plume model.

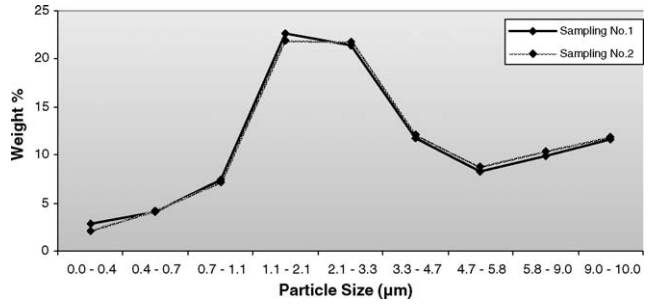

Fig. 5. Particle size distribution vs. weight percent in the stack.

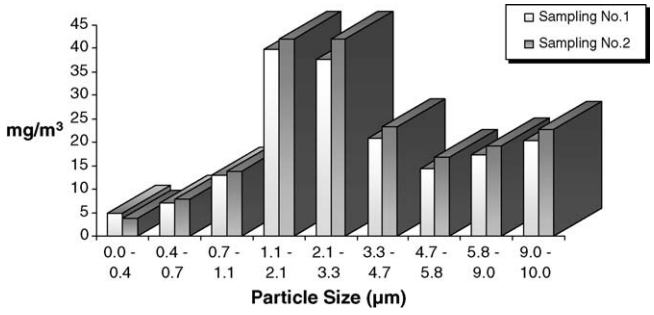

Fig. 6. Particle size distribution vs. particles concentration in the stack.

Figs. 5 and 6 show the particle size distribution in the stack for two samplings. These figures indicate that the particles of 1.1–3.3 μm diameters have maximum weight percent and concentration in the stack.

Figs. 7–10 illustrate particle size distribution versus weight percent and concentration in the plant ambient air for the downwind and upwind of the source, respectively.

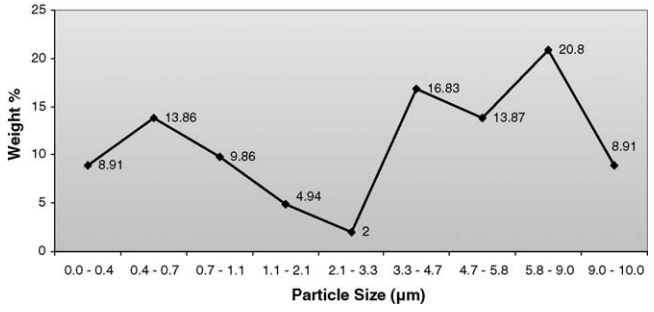

Fig. 7. Particle size distribution vs. weight percent in the plant ambient air (downwind of the source).

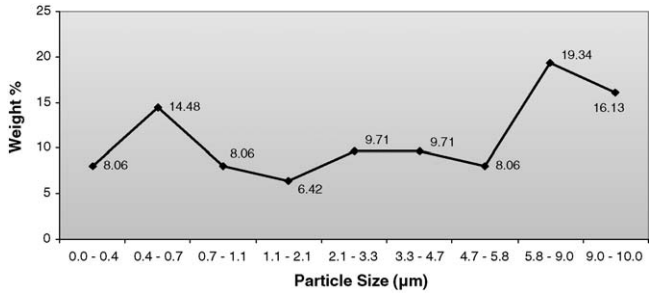

Fig. 8. Particle size distribution vs. weight percent in the plant ambient air (upwind of the source).

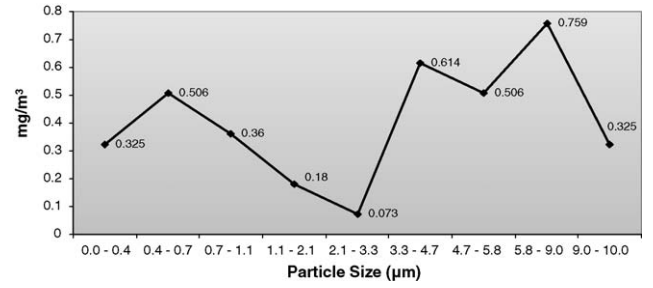

Fig. 9. Particle size distribution vs. particles concentration in the plant ambient air (downwind of the source).

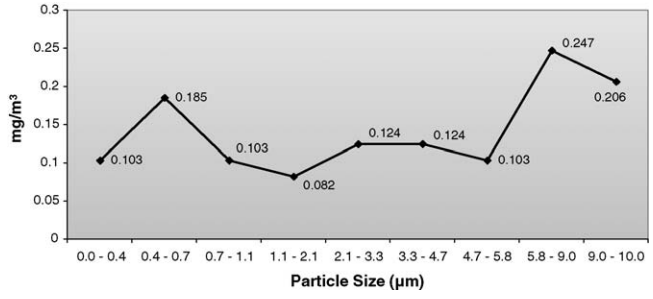

Fig. 10. Particle size distribution vs. particles concentration in the plant ambient air (upwind of the source).

Figs. 11 and 12 compare the particle size distribution versus weight percent and concentration in the plant ambient air, respectively. It can be seen clearly that the particle concentration with the size range 3.3–9 μm and less than 0.7 μm in the downwind of the source is more than the upwind. Also, Fig. 12 shows particulate concentration difference between the plume and background of the source.

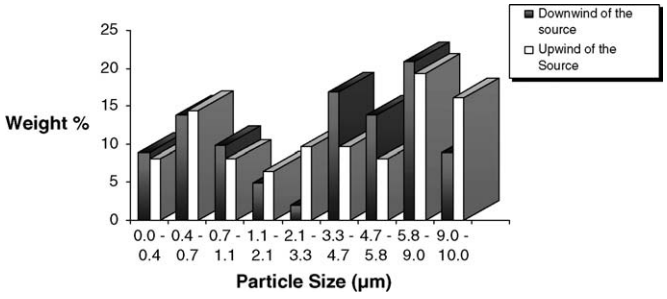

Fig. 11. Particle size distribution vs. weight percentage in the plant ambient air.

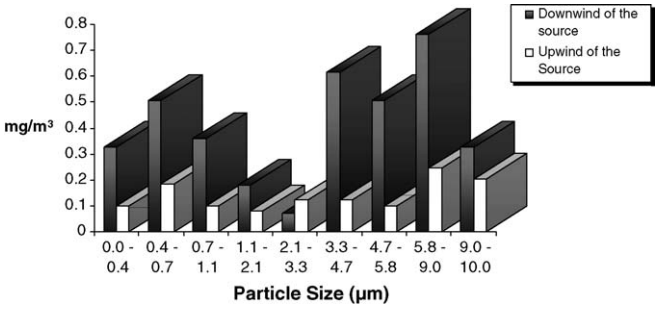

Fig. 12. Particles size distribution vs. particles concentration in the plant ambient air.

5. Conclusions

In the present study, a detailed experimental investigation was carried out to find out the pattern of particulate dispersion from Kerman Cement Plant. Based on the results obtained in this study the amount of particles has been emitted in the ambient air in distances about 590–1370 m from stacks is higher than the standard level. Particle size distribution from a cement plant stack has a wide range. It includes PM10, PM2.5, PM1.0 and ultrafine particles. These particle size ranges have shown to contribute significantly to respiratory problems. Finally, good agreement between measured data and Gaussian plume model show that this model can be a powerful model for predicting particle concentration for the downwind of a source especially in the regions far from the source.

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