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Original Research Paper

Studies on Seasonal Variation in the Dispersion of Suspended Particulate Matter from a Point Source

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ABSTRACT

The present study focuses on the seasonal evaluation and short range dispersion of suspended particulate matter (SPM) emitted by a detergent manufacturing industry in Vadamangalam near Puducherry within a radius of 1.5 km of its source. The study was carried out using monitoring followed by modelling. Experimental measurements were obtained by conducting a spot sampling analysis during different seasons in and around the detergent manufacturing industry. Analytical calculations were carried out by employing the Gaussian plume point source model. SPM is considered to be the main pollutant emitted by detergent industry. Five years (1999-2003) of wind speed, wind direction and cloud cover data, recorded by Indian Meteorological Department (IMD), were used for concentration prediction. The predicted values of particulate matter in and around the industry, were used to evaluate the seasonal impact of detergent manufacturing industry on air quality. Comparison of modelling results with experimental data showed a marked seasonal trend in the study period, which is characterized by SPM levels that were higher in summer and decreased progressively through the monsoon, post-monsoon and winter seasons.

INTRODUCTION

The necessity for air pollution prediction has tremendously increased in the recent decade, especially with the increasing interest in the early pollution warning systems. Several attempts to develop different mathematical models describing the distribution of contaminants released into the atmosphere are available in the literature. The atmospheric dispersion of flue gas or pollutants from vents and stacks depends on many interrelated factors. These factors include the physical and chemical nature of the pollutant, the meteorological characteristics, source properties, location and the nature of the terrain downwind. The ability to predict the pollutant concentrations and relate them to their source is essential if the air quality standards are to be attained and maintained. Industrial pollutants decrease the electrical conductivity of air because large, slow moving particles tend to replace ions of higher mobility. Hence, atmospheric pollution is of serious concern to the meteorologists since it modifies not only the weather and climate, but has a profound impact on the rate of dispersion/ diffusion of the polluting agents. The air pollution play an important role in meteorological aspects, the atmospheric conditions that govern the behaviour of plumes. Dispersion of pollutants in the atmosphere is governed by the following two dominant mechanisms (Wark & Warner 1981).

1. Mean air flow that transports the pollutants downwind.
2. Turbulent velocity fluctuations that disperse the pollutants in all directions.

Among the various diffusion models, Gaussian model is still the most popular one as it is relatively easy to apply. The Gaussian plume model, first derived by Sutton (1953), and subsequently modified by Csandy (1973), Smith (1973) and Turner (1969), provides the primary method having widespread use in air pollution dispersion calculations. Viswanadhan (1980) applied Gaussian model for multiple sources for four major cities in India. Santosh (1997) applied the model to study the SO_2 concentration for four major urban centres in south India. The present study has been undertaken to evaluate short range dispersion of suspended particulate matter (SPM) emitted by a detergent manufacturing industry in Vadamangalam near Puducherry within a radius of 1.5 km of its source.

STUDY AREA

The site selected for investigation is a detergent manufacturing factory located between 11°56' north latitude and 79°50' east longitude, which is 15 km from Pondicherry in Vadamangalam. The industry consists of a boiler which utilizes three tonnes of furnace oil per day for its operation. The factory is surrounded by compact residential area, and hence, considered as an urban area. Since, no other factory is located within a radius of 5 km it is considered as a single and largest source of particulate matter in the study area. Puducherry is hot and humid throughout the year with temperatures ranging between 26°C and 38°C. March, April, May and June are the hottest months with temperatures touching 40°C. Puducherry region receives an annual average rainfall of 1000-1200 mm with a lowest annual average data of 784 mm during the year 1995-96.

The winter season starts in December and ends at the end of February. This season is marked by moderate to low cold winds with moderate to slight solar insolation. The average temperature is 25°C. The summer season starts during the month of March and last till the end of May. This season is marked by very strong solar insolation and high humidity levels due to its proximity to the Bay of Bengal. The average temperature shoots up to 38°C. The pre-monsoon season starts in August and ends in September. An average temperature of 35°C is recorded during this season. The monsoon season starts during October and lasts till the end of November. This season is marked by moderate temperature ranging between 26ºC and 29°C with slight showers to very heavy rainfall.

MATERIALS AND METHODS

Gaussian Plume Model (GPM)

The evaluation of the ground-level concentration field of an inert gaseous pollutant downwind of a point source is generally achieved by using a semi-empirical model based on Sutton's formulation (Sutton 1953) involving Taylor's statistical concepts, now commonly known as the Gaussian plume model. It takes the form:

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{h^2}{2\sigma_z^2}\right) \qquad ...(1)$$

Where C is the steady-state concentration, y is the cross wind distance from the source, σ_y and σ_z are the cross wind and vertical standard deviations of the pollutant distribution, u is the wind speed at the stack height, Q is the mass emission rate of the pollutant, and h is the effective source height (i.e., the geometrical height plus the plume rise). The reference frame is taken with its x axis parallel to the wind and with the origin of the same at the stack base. The wind speed at the stack level has been evaluated using the power law exponent. The buoyancy flux parameter is calculated by using Briggs (1973) equation. The Buoyancy flux equation is given by:

$$Fb = g\frac{d^2Vs}{4}\left(\frac{T_s - T_a}{T_s}\right) \qquad ...(2)$$

Where, F_b is the buoyancy flux parameter (m^4/s^{-3}), g is the acceleration due to gravity (g/m^{-2}), d is the inside diameter of the stack at the top (m), V_s is the exit velocity of the flue gas m/s, T_s is the absolute gas temperature (K), T_a is the absolute ambient air temperature (K).

Briggs (1972) plume rise formula is used for buoyant plumes during unstable condition, is given by:

$$H = c_1 Fb^{1/3} x^{2/3} / u \qquad ...(3)$$

Where c_1 = 1.6 (dimensionless constant), x is the downwind distance (m), and u is wind speed at the reference height (m).

Briggs (1973) formulas based on downwind distance x and stability have been used to estimate the dispersion coefficients σ_y and σ_z. Briggs urban σ-functions is given by:

$$\sigma_y = ax\,(1 + 0.0004x)^{-0.5} \qquad ...(4)$$

$$\sigma_z = bx\,(1+cx)^d \qquad ...(5)$$

Where, x is the downwind distance from the source (L) measured in meters (the X-axis is oriented along the transport direction), σ_y is the horizontal standard deviation of concentration distribution (L) measured in meters, σ_z is the vertical standard deviation of concentration distribution (L) measured in meters' c is the dimensional coefficient (L^{-1}) expressed in m^{-1}, the values that it assumes depending on the stability class. a,b,d are dimensional coefficients; the values they assume depend upon the stability class are given in Table 1.

Model Parameters

The existing formulations for the dispersion parameters can be broadly classified into the following three groups.

1. Methods based on power law functions (Briggs 1973)
2. Methods based on statistical parameters such as horizontal and vertical wind direction variances (σ_y, σ_z) (Briggs 1973)
3. Methods based on similarity theory (Hanna et al. 1977)

Methods based on similarity theory are difficult to use as they require the knowledge of parameters such as friction velocity (u_*), convective scaling velocity (w_*) and mixed layer height (Z_i). The formulation based on statistical methods involve σ_q and σ_ϕ which need large amount of meteorological data for their calculation. Thus, in the present study, we have adopted dispersion parameters for urban terrain by Briggs (1973), which are based on power law functions. These are analytical expressions depending upon downwind distance and atmospheric stability. The atmospheric stability has been calculated from Pasquill's turbulence typing scheme (Gifford 1976) based on wind speed, solar insolation, and cloud cover.

Experimental Setup for Validation

The field experiment was conducted at the detergent manufacturing company at various receptors selected based on the wind direction and the peak concentrations obtained at various downwind distances predicted by the model. The experimental site is a flat terrain with compact residential areas, and hence, it is considered as a urban terrain.

Measurement Procedure

SPM was measured gravimetrically. High volume air sampler with Whatman glass fiber paper filter paper was used at an average flow rate of 1.3 m^3/min. The samples were collected for 24 hours in four different days, in each representative month of the season. These days have been chosen randomly once in a week. August, November, January and April were chosen as representative months for pre-monsoon, monsoon, winter, and summer season, respectively. The monthly average concentration of SPM is compared with monthly averaged modelled results to ascertain the ground reality and test the accuracy of the model.

Assumptions of Gaussian Plume Model

There are few assumptions which have to be met with for getting accurate modelling results.

1. Steady state conditions: This assumption requires that concentrations at all points in space are constant with time, i.e., local meteorology and source strength are constant.
2. Wind blows in *x*-direction and is constant in both speed and direction.
3. Transport by mean wind turbulent transport in *x*-direction.~
4. The source emission rate (*Q*) is constant.
5. Eddy diffusion coefficients are constant in both time and space.
6. Inert pollutants (this is sometimes modified by assuming a simple first-order decay).~
7. Mass within a plume follows a Gaussian distribution in both the *y* (crosswind) and *z* (vertical) directions. This is often a reasonable assumption for the *y*-direction

Above all the Gaussian-type models work well in simple situations, i.e., flat terrain, best for inert pollutants and work best for elevated point sources and for short travel times from the source, i.e., less than 10 km.

RESULTS AND DISCUSSION

Concentrations have been computed from Gaussian plume model equations (1), (2) and (3). Sigma functions were calculated by using the Briggs (1973) urban σ-function by Equation (4) and (5). Peak concentrations of SPM emitted from the source are measured at various receptors located downwind of the stack and the monthly averaged concentrations of SPM were compared with the monthly averaged predicted values for the four seasons. The comparison of the observed versus the model predictions are taken up for analysis to ascertain the dispersion pattern and to validate the model results. They are presented in Fig. 1.

Table 1: Values of the coefficients to be introduced in the formula (4) and (5).

Stability class	*a*	*b*	*C*	*d*
A	0.32	0.24	0.0010	0.5
B	0.32	0.24	0.0010	0.5
C	0.22	0.20	0.0000	0.0
D	0.16	0.14	0.0003	-0.5
E	0.11	0.08	0.0015	-0.5
F	0.11	0.08	0.0015	-0.5
G	0.11	0.08	0.0015	-0.5

Source: Briggs (1973)

The concentration of suspended particulate matter (SPM), emitted from the detergent factory is predicted at various downwind distances for the month of January which is considered as winter season for the year 1999-2003, using Gaussian plume dispersion equation.

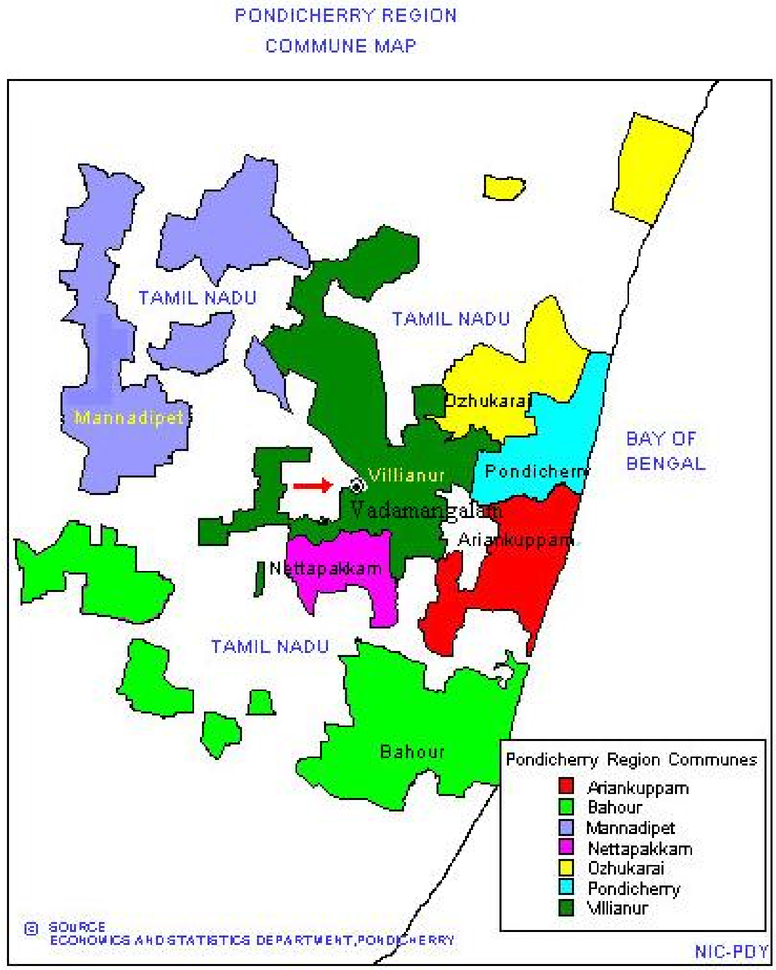

Fig. 1: Pondicherry region commune map.

For the month of January the monthly averaged concentration of 30.484 $\mu g/m^3$ was predicted during the year 1999 at a down wind distance of 500m, which is the highest concentration during the winter season. The concentration was found be decreasing further downwind distance of 500m in all the seasons. The stability class 'C' which denotes unstable condition is seen during the month of January. The stability category is fixed based on the incoming solar radiation, cloud cover and the surface wind speed which is denoted in Pasquill stability class in Table 2. Concentration predicted for the month of January is found to be lesser than pre-monsoon and summer seasons. SPM concentration of 27.838$\mu g/m^3$ and 27.969$\mu g/m^3$ was obtained for January 2000 and 2001, while the concentration of SPM was found to be 21.667 $\mu g/m^3$ during January 2002 at a downwind distance of 500m which is the lowest predicted concentration of the winter season during the study period. The SPM concentration was found to be 22.321 $\mu g/m^3$ during January 2003 at 500 m downwind from the source. Similarly concentration of SPM was predicted for the month of April for five years from 1999-2003,

Table 2: Meteorological conditions that define the Pasquill stability classes.

Surface windspeed		Daytime incoming solar radiation			Night time cloud cover	
m/s	mi/h	Strong	Moderate	Slight	> 50%	< 50%
< 2	< 5	A	A-B	B	E	F
2-3	5-7	A-B	B	C	E	F
3-5	7-11	B	B-C	C	D	E
5-6	11-13	C	C-D	D	D	D
> 6	> 13	C	D	D	D	D

Class D applies to heavily overcast skies, at any windspeed day or or night.
Source: Turner (1969)
Notes:
(1) m/s = meters per second; (2) mi/hr = statute miles per hour
The ground-level concentrations are calculated at different receptor points by using equation (1), and the concentration predicted is compared for seasonal variations.

which is considered as the summer season, the highest concentration during the month of April was 84.865 µg/m^3 during the year 2000. Higher concentrations were also obtained during the years 2001 and 2002 and the concentrations are found to be 82.954µg/m^3 and 84.551 µg/m^3. The stability category 'A', which denotes highly unstable condition, prevailed during the month of April. The higher concentration during the month of April could be attributed to the high humidity levels prevailing in the region which can prevent the efficient dispersion of air pollutants and strong convective conditions. The physical modelling works of Willis & Deardoff (1976) indicate that elevated releases under convective conditions will tend to have the centerline of the plume eventually descend rather than maintain the constant height of elevated plumes, resulting in higher concentration of air pollutants. Higher concentrations during highly unstable conditions could be attributable to the dispersion phenomenon prevailing in the region. Surface air is transported in columns to great elevation. In turn, downdrafts bring the aloft air to the surface. Updrafts cover about 40 percent of the area while downdrafts cover about 60 percent of the area. This atmospheric state is termed 'unstable'. One effect in these vertical motions is to cause the wind direction to meander quite widely. The downdrafts also transport pollutants emitted aloft to the surface with only a modicum of dilution and hence increasing the ground level concentration of the pollutant. This shows the importance of meteorological variables in the dispersion of pollutants in the atmosphere. The concentration of SPM during the pre-monsoon season (August) is 86.073 µg/m^3 during the year 200, which is the highest predicted concentration of all the seasons. The atmospheric stability category 'B' is seen during the month of August during all the years taken up for study. Peak concentration of SPM was found to be 79.354 µg/m^3, 80.325µg/m^3, 84.64µg/m^3 and 85.881 µg/m^3 at a downwind distance of 250m from the source during August 1999, 2000, 2001 and 2002 respectively. Higher concentrations are obtained during summer and pre-monsoon season, and lower con-

Table 3: Emission characteristics.

Parameter	Value
Product details	Soap & Detergent
Stack height (m):	
From ground level	57
From roof level	47
Stack diameter (m)	2.1
Flue gas exit velocity (m/sec)	17.9
Flue gas temperature (°C)	120
Gas flow (m^3/h)	4,05,437
Type of fuel	Furnace oil (3TPD)
Type of air pollution control systems	Wet scrubber

Table 4: Observed concentrations of SPM ($\mu g/m^3$) at various receptors.

Day	Winter	Summer	Pre-monsoon	Post-monsoon
1	24.478	82.34	82.76	22.765
2	26.535	80.53	79.84	21.654
3	28.655	85.87	83.23	24.435
4	32.562	84.23	83.00	18.698

Table 5: Observed levels of air pollutants around the site.

Date	Location	Parameters			
		SO_2 in $\mu g/m^3$	NOx in $\mu g/m^3$	SPM in $\mu g/m^3$	CO in $\mu g/m^3$
09.12.2005	Ariyur	6.1	12.6	62	650
12.12.2005	Koodapakkam	3.7	10.5	33	284
14.12.2005	Uruvaiyar	3.0	9.8	21	198

centrations during winter and monsoon season. Remarkable difference is seen in change in the concentration during various seasons. The concentration of SPM during the month of April and August was almost similar, since the weather conditions are similar. Concentration of specific pollutant chosen for the study is found to be increasing from 200m downwind of the source and decreasing further at 500m downwind of the source. The concentration of SPM for the month of November for five years 1999-2003 is predicted, which is considered as monsoon season. The concentration of particulate matter was found to be 28.203 $\mu g/m^3$ at a downwind distance of 500m during November 2000. The lower concentration could be due to the atmospheric stability category ‘C’ which denotes slightly unstable conditions prevailing during that period. Similarly, the concentration of SPM was 24.144$\mu g/m^3$, 14.359$\mu g/m^3$ and 21.795$\mu g/m^3$ during November 1999, 2001, 2002. The concentration of SPM was found to be 5.096$\mu g/m^3$ during November 2003, which is the lowest of all the seasons. The concentration of SPM was lowest during monsoon season, the lower concentrations could be due to the wet deposition of pollutants by rain since the region receives monsoonal rainfall during that period. Precipitation plays an important role in the removal of pollutants from the atmosphere. Heavy rain fall washes the atmosphere and this results in the removal of particulate matter from the atmosphere by wet deposition resulting in lower concentrations of SPM. The SPM concentration at different receptor points was compared with CPCB’s National Ambient Air Quality Standards (1994), which was found below the CPCB standard, i.e., 200 $\mu g/m^3$ at all the times. Fig. 2 indicates that the observed and predicted concentrations follow the same trend at all receptors.

Concentrations can be expected to be higher from 250m downwind distance from the source but decreasing beyond 500 m. The region around 500m from the source will have higher concentrations under the normal meteorological condition. Concentration of the pollutant of interest is least at 50-150 m and 700-1500 m downwind of the stack due to dispersion and eventual dilution of the specific pollutant. The concentration was found to be very less near the source but gradually increases and attains the highest level at 250 m during summer and pre-monsoon seasons and at 500m during winter and monsoon seasons. Since the plume rise behaviour depends upon the stability category, the plume is bent and descends forming a looping fashion during highly unstable conditions, which is denoted by stability class ‘A’ and ‘B’, therefore, the pollutant reaches the ground nearer to the source, whereas during slightly unstable conditions, which is denoted by stability category ‘C’ the plume rise is higher and the pollutant reaches the surface farther from the source. But in stable climatic conditions the concentration of pollutants is generally higher near the source due to slower diffusion and gradually decreases away from the source. The modelled results are compared with the monitored data which is slightly higher during summer and pre-monsoon and lower during winter. The monthly average observed values of SPM during January is 28.057 $\mu g/m^3$ which is lesser than the predicted values but without much deviations. The monthly averaged value of SPM during April

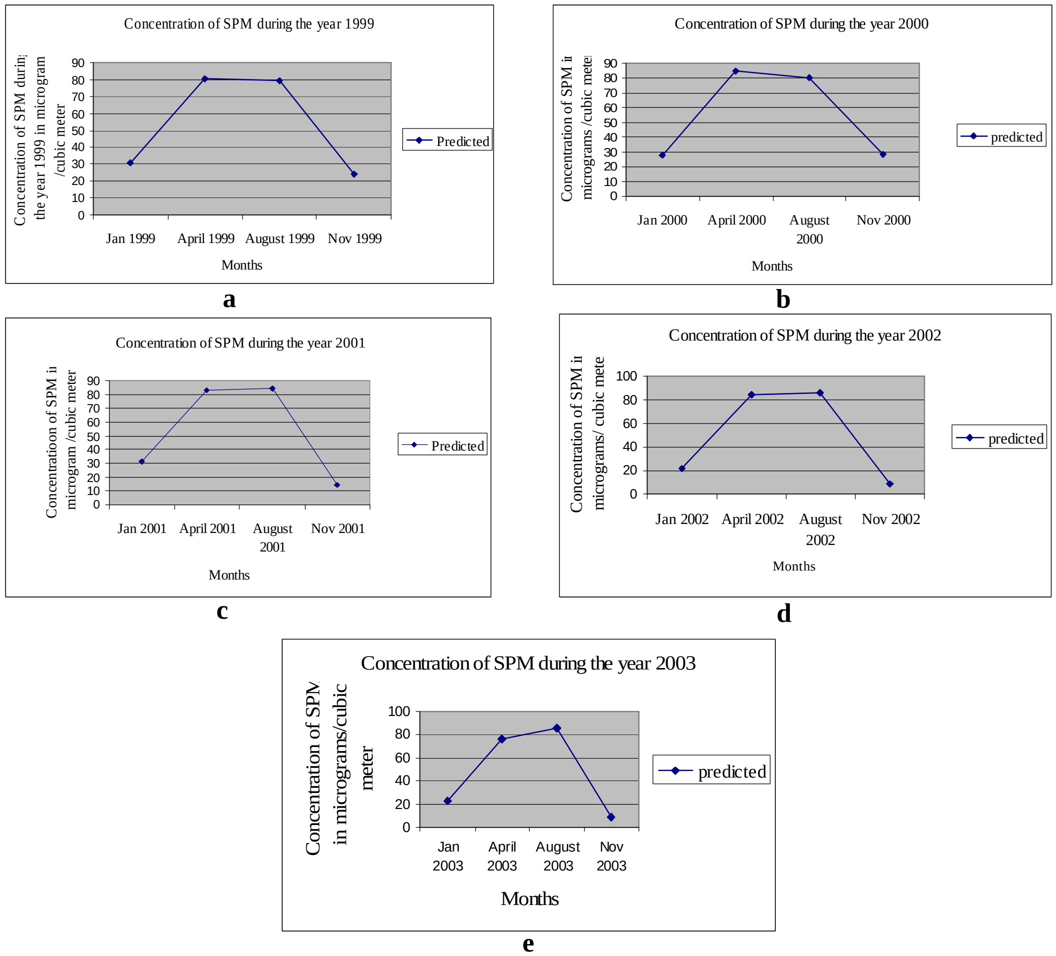

Fig. 2: (a) Predicted concentration of SPM during the year 1999; (b) Predicted concentration of SPM during the year 2000; (c) Predicted concentration of SPM during the year 2001; (d) Predicted concentration of SPM during the year 2002; (e) Predicted concentration of SPM during the year 2003

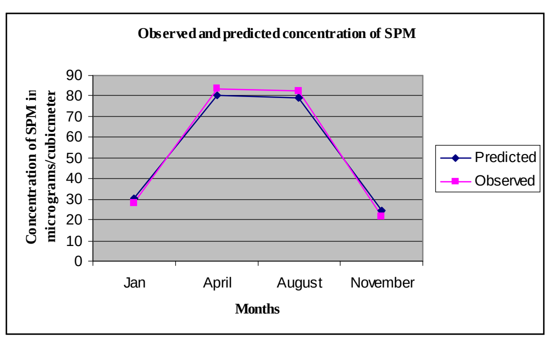

Fig. 3: Observed and predicted concentrations of SPM emitted from the detergent factory.

is 83.242µg/m^3. The observed values are slightly higher than the predicted values, which could be due to the addition of SPM generated by resuspension process from soil, which can have an effect on the model prediction. The monthly averaged observed value of SPM during August is 82.207 µg/m^3. The monthly averaged observed value of SPM during November is 21.888 µg/m^3. The observed values are only marginally higher than the predicted values. Stack tip downwash is not seen since the velocity of the exiting gas is 17.9 m/s which is very much high enough for discharge of flue directly into the atmosphere (Vs > 1.5 U). Since, there is no building within a distance of 2.5 times the height of the stack the chances of building downwash is nil. As long ago as 1932 the thumb rule for stack design was that stack should be at least 2.5 times the height of the surrounding buildings. The atmospheric condition was never stable during the periods taken up for modelling, the meteorological data showed zero calm period since the region is very close to Bay of Bengal.

CONCLUSIONS

It is concluded that there is a substantial concentration of SPM around the industry. The hourly concentration of SPM predicted by the Gaussian Plume model was high during day time and lower during the night hours.

The seasonal evaluation of the monthly average concentration of SPM, predicted by the model, showed a remarkable trend. The SPM levels were maximum during strong convective and highly unstable conditions, i.e., during summer and decreased progressively towards pre-monsoon, winter and monsoon seasons. Peak concentrations was predicted at a downwind distance of 250m during highly unstable conditions and at 500m downwind of the source during winter and monsoon seasons. People residing in this distance are expected to be exposed to higher levels of SPM. The 24-hourly average concentrations of SPM obtained experimentally and daily average concentration of SPM predicted by the model do not exceed the National Ambient Air Quality Standards, i.e., 200 µg/m^3 for residential, rural and other areas.

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