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Development of Site Specific Empirical Formula for Minimum Stack Height Estimation

K. V. George,[1] Krishnaprasad,[2] T. P. Mathew,[1] P. Verma[1]

[1] National Environmental Engineering Research Institute (NEERI), Nehru Marg, Nagpur, 440 020, India
[2] Fluidyn Software and Consultancy Pvt. Ltd., Bangalore, India

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In India coal is a cheap and abundantly available fossil fuel source used for energy extraction. 72% of the power plants are coal based thermal power plants generating particulate matter and sulfur dioxide as major pollutants. Particulate matter emissions are controlled at source using control equipments like electrostatic precipitator, cyclone, bag filter etc. and the regulatory requirements are that the emission rate of particulate matter at stack exit should not exceed the prescribed limits. For SO_2 emissions reduction, the alternatives suggested include usage of low sulfur fuel or desulfurized coal and flue gas desulfurization techniques. All these techniques are capital intensive and not practiced in developing countries and an optimal solution would be to take advantage of the dilution potential of the atmosphere wherein, the sulfur in fuel is converted to SO_2 and then released high into the atmosphere to effect higher dilution. Provision of tall stacks facilitates the discharge of pollutants at sufficiently greater heights in the atmosphere and the height should be chosen so as to ensure that the pollutants are discharged either above the mixed layer if the predominant mixing depth is shallow (inversion condition) or at a height which results in low ground level concentration of pollutants conforming to stipulated regulatory standards of ambient air quality if the mixing layer depth is very high (afternoon unstable superadiabatic condition).

Stack height for a desired ground level concentration (GLC) of pollutant can be estimated by using Gaussian dispersion model (Turner, 1994) for a given emission load and meteorological conditions. At different levels, either at the decision-making for air quality management or at the design/estimate of industrial setup, the physical stack height is required to be estimated. Meteorological data over a longer period of time is to be processed so as to make an input to the model and is a time consuming process. On such occasions, an empirical formula already developed for the region based on past meteorological data comes as a handy tool. A report on empirical formula for stack height of 110 MW and 500 MW coal based TPP is published by George et. al. (George, 2002). In this paper the empirical formula for minimum stack height as a function of SO_2 emission load is derived for coal based thermal power plants (TPP) of 60 MW and 210 MW capacities using meteorological variables of four regions (Jagdishpur, Panipat,

Correspondence to: K. V. George

Mathura, Satna) in northern India. Ground level concentration (GLC) of pollutant for different stack height is computed using Industrial Source Complex Short Term (ISCST3) model software developed by USEPA. The lacuna of empirical formula developed by Central Pollution Control Board (CPCB), the environmental law enforcing agency of Government of India is also discussed.

MATERIALS AND METHODS

The two main input data class for source dispersion modeling is emission source data and meteorology data. The source file requires information on location of source, pollutant emission rate, stack height, flue gas temperature, exit gas velocity, stack top diameter and receptor location. Stack height is estimated so as to meet the regulatory requirement on 24-hour average basis. Hourly GLC at each receptor is computed and then it is averaged out to find the one-day average GLC of pollutant. Four industrialized towns for which in the detailed meteorological data were collected have been considered and they are Jagdishpur, Panipat, Mathura and Satna in the northern India.

Wind velocity and ambient air temperature recorded at hourly intervals for a period of one month during extreme winter and summer season were considered as input data. The hourly data for one month is then averaged out to determine hourly mean predominant wind direction, wind speed, ambient temperature for one day. Thus 24 readings are available to represent the meteorology of the region for the given season. This along with the mixing height data and stability class data forms the meteorological data for prediction of ambient air quality. Vertical temperature lapse rate studies were carried out using minisonde technique to determine mixing height. Hydrogen gas filled balloon tied with minisonde were released for a period of three days at intervals such that hourly mixing data (24 readings) can be collected and was carried out at each station. The hourly mixing height data minimizes possible inaccuracy caused due to Holzworth method (Holzworth, 1967) of interpolation between twice daily radiosonde data.

This exercise of empirical formula generation focuses only on emission characteristics of coal based thermal power plants. As the power plants of different capacities emit pollutant at different exit velocity, temperature and flow rate, the stack height requirement would be different. Since the stack height is derived as a function of only one parameter i.e., SO_2 emission rate, and the other factors like flue gas flow rate, temperature, exit gas velocity etc. are not included, there would be different formula for different capacities of TPPs. In this study, the stack height formula is derived for 60 MW and 210 MW capacity power plant. Data on flue emissions from TPPs were collected from available data/studies pertaining to TPPs (CPCB, 1994). Most of the TPPs have electrostatic precipitators for particulate matter collection, which are usually designed for flue gas temperature of 135^0C so as to, prevent condensation of SO_2. Further the temperature of flue gases recorded for TPPs are in the range of 135^0C to 200^0C. Lower value of exit gas temperature is considered (145^0C for 60 MW and 140^0C for 210 MW capacity TPP) for this study so as to simulate worst case (lower plume rise) scenario. Average flue gas flow rate considered for 60 MW and 210 MW TPP is 135 Nm^3s^{-1} and 370 Nm^3s^{-1} respectively. Data on TPP indicates that the exit gas velocity is found to be in the range of 15 ms^{-1} to 25 ms^{-1}. A value of 15 ms^{-1} is considered for 60 MW capacity and 18.8 ms^{-1} for 210 MW capacity TPP. Stack top diameter was computed using continuity equation while maintaining the exit velocity as mentioned above. Stack top diameter for 60 MW and 210 MW capacity power plant is estimated as 3.4 m and 5.0 m respectively.

Industrial Source Complex Short Term (ISCST3) model developed by USEPA was used for estimation of maximum ground level concentration of SO_2. Zannetti (Zannetti, 1990) has given detailed description of the mathematical modeling technique in air pollution. The ISCST3 model program was run with several known SO_2 emission rate under different source groups along with assumed stack height. The entire flue gas from the TPP is considered to be discharged through a single stack and is assumed to be at the center of the study area (center of co-ordinate system). Computation of GLC due to emission from each stack is carried out in its single run. The program was executed several times by varying the stack height till the output i.e., maximum ground level concentration of SO_2 meets with the ambient air quality norms for rural area (80 $\mu g/m^3$). At the run of the program when the GLC attains a value of 80 $\mu g/m^3$, the SO_2 emission rate in kg h^{-1} (on X-axis) Vs required stack height in meter (on Y-axis) graphs have been plotted. Regression analysis was carried out to derive equation for physical stack height as a function of SO_2 emission rate.

RESLUTS AND DISCUSSION

Central Pollution Control Board has suggested a "minimum stack height formula" in the year 1984 (CPCB, 1984) for coal based thermal power plants. The formula is $H = 14\ Q^{0.3}$, where H is the physical stack height (m) and Q is the SO_2 emission load (kg h^{-1}). This formula is considered applicable for the entire region (India) using meteorological data of three cities irrespective of the topographical variations. Meteorological data of two cities Mumbai and Kolkata were used to represent the coastal meteorology and that of Delhi was used to represent the inland meteorological features. The temperature of the flue gases and ambient air were considered to be the same. Hourly mixing height was determined using radiosonde data (two observations daily) with Holzworth interpolation technique. Dispersion is considered to take place at the level of physical stack height and plume rise effect is ignored. Ground level concentration (GLC) of SO_2 resulting from the estimated stack height needs to be conformed to National Ambient Air Quality Standards (NAQS) for industrial area (120 $\mu g/m^3$). Three stack height equations were derived for three cities following $H = aQ^b$ trend where "a" and "b" are the constants. In order to have a common formula for the entire region, the coefficient "a" and the exponent "b" derived for all the three cities were arithmetically averaged out and are considered valid for all capacity of TPPs.

Table 1. Empirical formula for stack height of 60 MW TPP

Place (Season)	Equation	Range of SO_2 Emission (kg/h)	R^2
Mathura (Summer)	$h = 0.0866\ Q - 68.952$	1260 to 3240	0.9986
Panipat (Summer)	$h = 0.1084\ Q - 109.68$	1080 to 3240	0.9982
Jagdishpur (Winter)	$h = 0.9454\ Q^{0.6037}$	1080 to 2700	0.9967
Satna (Winter)	$h = 0.1453\ Q^{0.8222}$	720 to 2160	0.9913
	$h = 8e\text{-}09\ Q^{2.9988}$	2160 to 2880	0.9819

Variation of stack height requirement with SO_2 emission rate for different places for the two cases of 60 MW and 210 MW TPP are presented in Figure 1. The dots in the curve are the stack height obtained by modelling exercise. Hard line presents the curve obtained by regression analysis. Regression analysis is carried out to determine the equation, which best fits the data points and the curve that gives a regression coefficient (R^2) more than 0.9 is accepted. Table 1 & 2 presents the equation for stack height, the regression coefficient and the range of SO_2 emission rate within which the equation is valid for 60 MW and 210 MW TPP respectively. It is observed that the regression curve of stack height estimation follows different trends in order to obtain a regression coefficient of more than 0.9 (R^2>0.9) under different meteorological conditions. Since this is development of an empirical relationship, the nature of the curve does not affect the estimation of stack height provided it is applied within the range of its validity. The nature of stack height curve indicates the vertical variation in the dilution potential of atmosphere averaged over 24-hour period.

Comparing the curves for 60 MW and 210 MW for each place, two observations are made. First, at each place, the 60 MW and 210 MW curves shows a similar trend. This indicates that change in exit velocity of gas, stack top diameter, exit gas temperature does not cause any change in the trend of curve instead the difference in trend is observed from one place to the other indicating that, it is the meteorology that governs the trend of stack height curve. Second, for the same emission rate, the stack height required for 60 MW is more than that needed for 210 MW. This is attributed to the higher plume rise gained by the emitted flue gas from the stack of 210 MW owing to its higher exit velocity (Turner) compared to 60 MW.

Comparing the equation for two seasons, summer and winter, it is found that in order to obtain a GLC of 80 $\mu g/m^3$ of SO_2, the stack height needed during winter season is less than that needed during summer season. For air quality assessment studies, winter season is considered critical due to observations of higher ambient air pollutant levels compared to that of summer season. This is the condition when the pollutant sources are found to be near the ground level. Due to higher frequency of inversion during winter season, the ground level emissions are

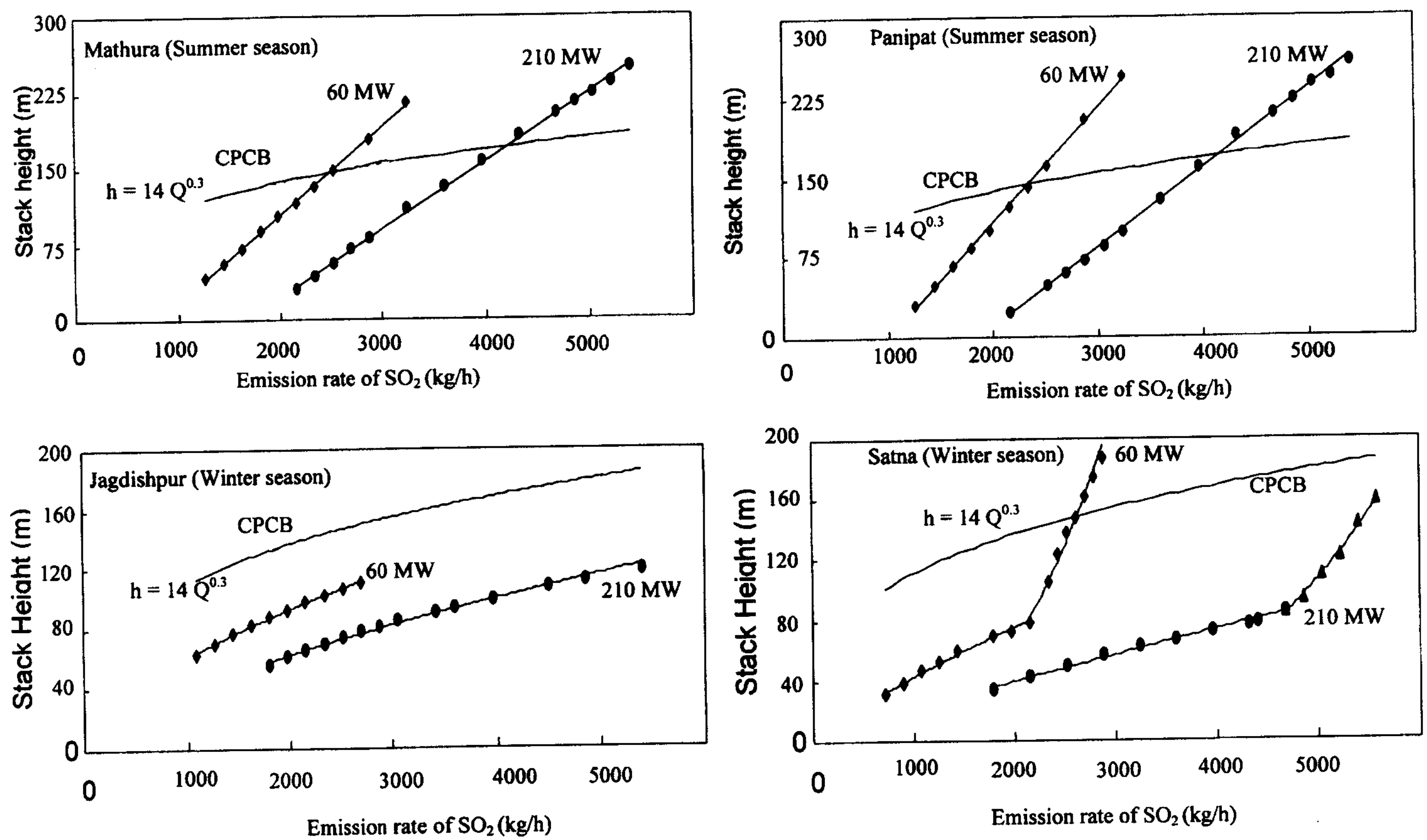

Figure 1. Variation of Stack Height with SO_2 Emission Rate

Table 2. Empirical formula for stack height of 210 MW TPP

Place (Season)	Equation	Range of SO_2 Emission (kg/h)	R^2
Mathura (Summer)	$h = 0.0673\ Q - 111.97$	2160 to 5400	0.9988
Panipat (Summer)	$h = 0.0743\ Q - 139$	2160 to 5400	0.9981
Jagdishpur (Winter)	$h = 0.3714\ Q^{0.6744}$	1800 to 5400	0.9936
Satna (Winter)	$h = 0.0419\ Q^{0.9002}$	1800 to 4680	0.9898
	$h = 3e\text{-}12\ Q^{3.6807}$	4680 to 5580	0.9939

trapped in the lower atmosphere thus increasing the ambient air pollutant level. In the case of TPP, the flue gas emission is at higher elevation at high exit velocity causing plume to penetrate through the low level mixing layer of winter season and thus lesser contribution of pollutant to ground level ambient air. During summer season, the mixing heights are high and the plume remains within this boundary layer causing build up of ambient air pollutants. This feature leads to a conclusion that, for a given region, if stack height formula is to be generated for elevated emissions, the meteorology of summer season should be considered.

The stack height formula for Satna during winter season shows an entirely different trend. For both the cases of 60 MW and 210 MW, the stack height trend changes after it attains 78 m. Up to 78 m the stack height trend is curvature downward and above 78 m the trend is not curvature downwards. This indicates that the overall dilution potential of atmosphere at higher levels (above 78 m) is less compared lower atmospheric layer. In this case it is also observed that for stack height below 78 m, the maximum GLC of 80 $\mu g/m^3$ is found at 25000 m from the source, indicating the dominance of stable atmospheric layer, where as at emission above 78 m, the maximum GLC is very near the stack indicating the dominance of unstable layer. This is the reason why two formulas are generated for the same place under same capacity of TPP. It is preferable that these stack height formula be used within its range of validity.

The study demonstrates that a single empirical formula for physical stack height of TPP as a function of only one independent parameter (SO_2 emission load) excluding other factors (stack top diameter, flue gas exit velocity and temperature) for a region (India) marked by non-uniform meteorology as suggested by CPCB formula cannot be considered appropriate. An air shed that can be represented by a reasonably uniform meteorology, a stack height formula can be developed as a function of source parameters. If source parameters can be categorised as in the case of TPP (60 MW, 210 MW) separate formula can be generated for each source category. Since the new formula takes into account hourly variations in meteorological variables and employs latest air quality modeling technique, this can be used for more precise estimation of stack height.

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