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Impact of Flue Gases from Brick Kilns on Rural Environment

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Abstract—*The stack emission as well as the fugitive emissions from brick kilns contribute to the air pollution and deteriorate the air quality. A general Gaussian plume dispersion model for brick kiln emissions, based on AERMOD, is developed in Excel spreadsheets. The model distinguishes between convective and stable boundary layer conditions on the basis of sign of Sensible Heat Flux. The Mixing Height is obtained by plotting the graph of height in the atmosphere and its respective potential temperature. The model, applicable for rural roughness conditions, flat terrain and for gentle wind; uses meteorological and emission data as its input parameters, and predicts ground level concentrations of pollutant and depicts the air quality in accordance with, Ambient Air Quality Index, CPCB, at receptor location with respect to the given source location. This model simulates different plume types depending upon the atmospheric stability and on the location in and above the boundary layer.*

1. INTRODUCTION

The Indian economy has been growing at a rate of 7-8% since 2001, (current scenario is 7.1% in 2017) [2]. India is the second largest brick producer. Building construction in India is estimated to grow at a rate of 6.6% per year during the period 2005 to 2030 [2]. This is resulting in a continuous increase in demand for building materials & booming brick kiln industry. India's brick sector is characterized by traditional firing technologies; environmental pollution; reliance on manual labor and low mechanization rate. Soil clay or sediments from river, rich in fine particles, are used as raw materials for brick production. The fuel used by brick kilns includes about 70% coal, 24% sawdust & remaining 6%, woods & others [3]. Assam coal, Slack coal and/or lignite which contain high level of sulfur and high ash content (25-30%) are used in most of the brick kilns [3]. Low grade carbonaceous materials such as rice husk, bagasse and wood/saw dust are also used as a part or full replacement of coal are used in certain areas. All the brick kiln operations right from digging of the earth to unloading of fired bricks from the kiln are accompanied by generation of dust. The stack emission as well as the fugitive emissions from brick kilns contributes to the air pollution. Use of thermally low efficient kilns, outdated technology such as Bull's Trench kilns and inefficient firing technologies contributes to particulate and gaseous emissions and contributes to environmental degradation. Brick kilns emission consists of mainly fine particles of coal (Black Carbon), dust particles, organic matters and gases such as SO_2, NO_x, CO, CO_2, etc. Emission of individual air pollutants from brick kilns varied significantly during a firing batch (7 days) and among different types of kilns.

The high cost and the experimental difficulties involved in monitoring/ measuring the concentrations of species at various vulnerable points of a particular area is not always feasible. Prediction of concentration pollutants resulting from a given emission and pollution levels is carried out with the help of air pollution dispersion models. These models calculate the transport and dispersion of air pollutants being emitted from vulnerable sources into the atmosphere.

2. MATERIALS AND METHODS

2.1 Study Area

The area of about 4 km radius around Uvarsad village, 23.2097° N & 72.5870° E, of District Gandhinagar in state Gujarat (India), has been taken under study for the duration of two months, June-July, 2017, for its ubiquitous and mushroom growth of brick kilns (approximately 68 brick kilns just within a diameter of 8 km) (fig 1). In a brazen violation of environmental laws and in the absence of regulatory guidance, all of the operational Fixed Chimney Bull's Trench Kiln in this area has been threatening the environment and posing a threat to public health. The estimated amount of coal consumed by each brick kiln (functional only for seven months) varies between 17 and 20 tons per season of a year.

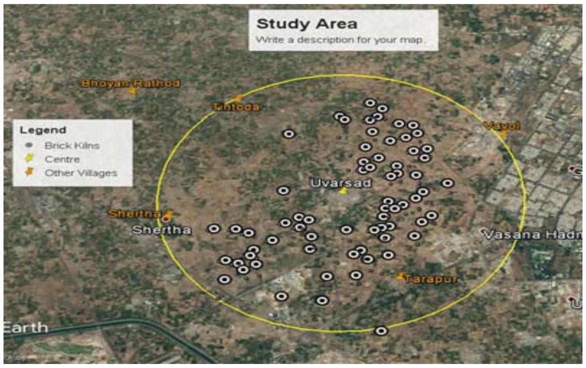

Fig. 1: Brick Kilns in the study area

2.2 Method

Out of all the Refined Air Quality models recommended by U.S. Environmental Protection Agency [5], AERMOD (Gaussian Model) is selected for prediction of ground level concentrations of pollutants emitting from brick kilns. A general Gaussian plume dispersion mathematical model for brick kiln emissions, based on AERMOD, is developed in Excel spreadsheets.

2.3 Assumptions

The study area is assumed to be rural (Land Use Procedure) and flat terrain. Roughness length is chosen to be 0.4m as the study area falls under the category of villages [6]. The meteorological conditions are considered uniform spatially for the study period. There are few periods of calm or light winds. The average value of wind speed during the study period is 3.32 m/s (gentle breeze). Reference heights for wind speed and temperature is chosen to be 10m.

3. METEOROLOGICAL PARAMETERS

Meteorology is fundamental as it helps in determining the diluting effect of atmosphere. The critical solar elevation angle φ_{crit} , corresponding to the transition point between the Convective Boundary Layer (CBL) and Stable Boundary Layer (SBL) can be determined from

$$sin\varphi_{crit} = \frac{1}{990}\left[\frac{-c_1T^6+\sigma_{SB}T^4-c_2n}{(1-r\{\varphi\})(1-0.75n^{3.4})}+30\right] \quad (1)$$

To properly characterize the Planetary Boundary Layer (PBL), a good estimate of sensible heat flux (H) is required, which in turn, depends upon net radiation (R_n) and Bowen Ratio (B_o). For the CBL, Sensible Heat Flux can be calculated by the equation,

$$H = \frac{0.9R_n}{1+\frac{1}{B_0}} \quad (2)$$

Solar radiation depends on latitude, time of year, time of day, and orientation of the land surface with respect to the Sun. From Holtslag and van Ulden (1983),

$$R_n = \frac{(1+r\{\emptyset\})R+c_1T_{ref}^6-\sigma_{SB}T_{ref}^4+c_2n}{1+c_3} \quad (3)$$

where c_1=5.31x$10^{-13}$$Wm^{-2}K^{-6}$, c_2=60Wm^{-2}, c_3=0.12, Boltzman Constant σ_{SB}=5.67x$10^{-8}$$Wm^{-2}K^{-4}$.
From Kasten and Czeplak (1980), Solar Radiation,

$$R = R_o(1-0.75n^{3.4}) \quad (4)$$

where n is fractional cloud cover and clear sky insolation,

$$R_o = 990(sin\varphi)-30 \quad (5)$$

where φ is solar elevation angle. The Albedo is the fraction of reflected shortwave radiation and is calculated as

$$r\{\varphi\}=r'+(1-r')exp(a\varphi+b) \quad (6)$$

where a=-0.1, b=-0.5$(1-r')^2$, r'=r{φ=90°} and r'=0.19698 (from table 1).

Table 1: Bowen Ratio and Noon-time albedo Calculation Uvarsad, Gandhinagar [4]

Land use Code	Area Division	Area (km^2)	Percentage of area (%)	Area Fraction (w_i)	Noon-time Albedo	Area Fraction*noon-time Albedo	Bowen Ratio (x_i)	Bowen Ratio*ln(Area Fraction) W_i*ln(x_i)/
22	Physical Infrastructure	4	8	0.08	0.18	0.0144	1.5	0.032
11	Surface water source	0.2	0.4	0.004	0.1	0.0004	0.1	-0.0092
82	Green Area	15	29.84	0.2984	0.2	0.05968	0.5	-0.206
21	Brick Kilns	0.68	1.35	0.0135	0.16	0.00216	0.8	-0.003
21	Roads	0.7	1.4	0.014	0.16	0.00224	0.8	-0.003
31	Barren, Uncultivated land	29.68	59.05	0.5905	0.2	0.1181	1.5	0.24
Aggregate		50.26				0.19698		0.0508

$$B_o = e^{(\Sigma w_i ln x_i / \Sigma w_i)} \quad (7)$$

The value calculated of Bowen ratio for present study is 1.05209. The calculated value of Noon-time albedo for the study area is 0.19698. The albedo is a ratio which lies in the range of 0 to 1 [4]. The value of noon-time albedo is used to calculate the hourly albedo values. Solar elevation angles are calculated using equations from Astronomical Algorithms, by Jean Meeus.

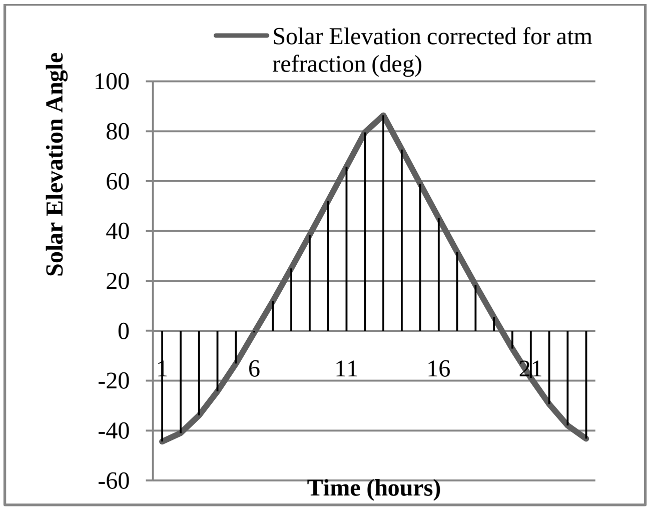

Fig. 2: Variation of Solar Elevation Angle on 10 June 2017

From the Fig. 2, it is clear that the value of solar elevation angle is increasing in beginning, is maximum at noon and decreasing thereafter.

Atmospheric Pressure at various heights are calculated with the formula,

$$P = P_o e^{\frac{-mgz}{RT}} \quad (8)$$

Temperature at various heights in atmosphere is calculated in accordance with the following table (Fig. 3).

Moist adiabatic lapse rate: vary with temperature and pressure

• TABLE 6.1

The Moist Adiabatic Rate for Different Temperatures and Pressures in °C/1000 m and °F/1000 ft

	TEMPERATURE (°C)					TEMPERATURE (°F)				
PRESSURE (MB)	−40	−20	0	20	40	−40	−5	30	65	100
1000	9.5	8.6	6.4	4.3	3.0	5.2	4.7	3.5	2.4	1.6
800	9.4	8.3	6.0	3.9		5.2	4.6	3.3	2.2	
600	9.3	7.9	5.4			5.1	4.4	3.0		
400	9.1	7.3				5.0	4.0			
200	8.6					4.7				

Fig. 3: Moist Adiabatic Lapse Rate

From Fig. 3, the lapse rate is ≈ 9.8 °C/km, but varies when air parcel becomes saturated. Wind Speed profiling is done in accordance with boundary layer conditions (CBL/SBL) based on AERMOD Description of Model Formulation.

The convective mixing height can be obtained by plotting graph between early morning potential temperature sounding (prior to sunrise) and respective heights in the atmosphere [7]. A potential temperature sounding taken on 10 June 2017 at 00:00 is shown in Fig. 4. An unstable surface layer extends to a height of about 250m above ground level. Mixed layer was observed from 250 to 1500m above ground. Above the mixed layer, the air parcel is saturated and rises above with wet adiabatic lapse rate. The mixing height on 10 June 2017 is predicted to be 1250 m (fig 4).

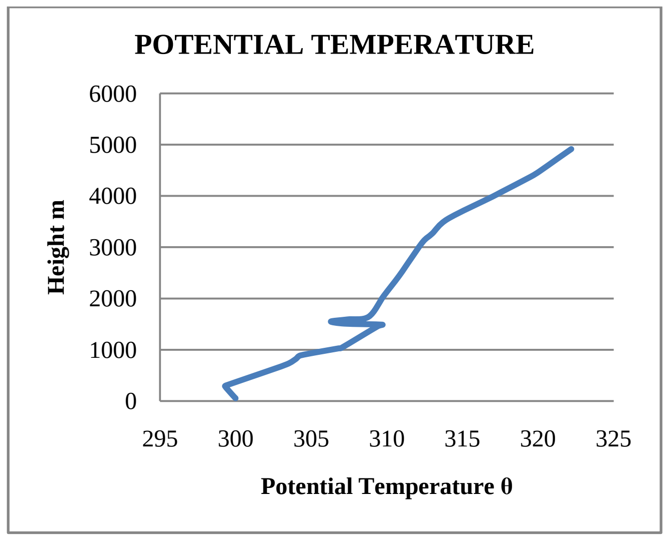

Fig. 4: Potential temperature (K) profile from, Gandhinagar on 10 June 2017 at 00:00. Height of the mixed layer derived from the profile is around 1250 m.

3.1 Derived Parameters in CBL

Friction velocity is used to describe shear-related motion in moving fluids and the velocity profile near the boundary of a flow.

From Panofsky and Dutton (1984), the expression of u_* used is

$$u_* = \frac{k u_{ref}}{\ln\left(\frac{z_{ref}}{z_o}\right) - \Psi_m\left\{\frac{z_{ref}}{L}\right\} + \Psi_m\left\{\frac{z_o}{L}\right\}} \quad (9)$$

The Monin-Obukhov length is that height at which turbulence is generated more by buoyancy than by wind shear.

$$L = -\frac{\rho c_p T_{ref} u_{ref}^3}{kgH} \quad (10)$$

The convective velocity scale is roughly the updraft speed in convective thermals. It is used to characterize the convective portion of the turbulence in CBL.

$$w_* = \left(\frac{gHz_{ic}}{\rho c_p T_{ref}}\right)^{\frac{1}{3}} \quad (11)$$

Table 2: Derived Parameters in the CBL

Friction Velocity u* (ms-1)	MoninObukhov Length L (m)	Convective Velocity Scale w*(ms-1)
0.392866205	-58.14432917	1.482605331

The friction velocity, Monin-Obukhov Length and the convective velocity scale is calculated for 10 June, 2017, 16:00, as shown in table 2. The negative sign of Monin-Obukhov Length L, is predicting that it is convective boundary layer condition. The velocity scale is typically on the order of 1 ms^{-1}[1]. The calculated convective velocity scale, 1.482605331 ms^{-1} (from table 2), is approximately of the order of 1 ms^{-1}.

3.2 Derived Parameters in SBL

From Garratt (1992), Critical wind speed value,

$$u_{cr} = \left[\frac{4\beta_m z_{ref}\, g\theta_*}{T_{ref}\, C_D}\right]^{0.5} \quad (12)$$

From Hana and Chang (1983)

$$u_* = \frac{C_D u_{ref}}{2}\left[-1 + \left(1 + \left(\frac{2u_o}{C_D^{\frac{1}{2}} u_{ref}}\right)^2\right)^{\frac{1}{2}}\right] \qquad \text{for } u \geq u_{cr}$$

(13)

$$u_* = u_*\{u = u_{cr}\}\left(\frac{u}{u_{cr}}\right) \qquad \text{for } u < u_{cr}$$

Monin-Obukhov Length

$$L = \frac{T_{ref}}{kg\theta_*} \quad (14)$$

Sensible Heat Flux

$$H = -\rho c_p u_* \theta_* \quad (15)$$

Table 3: Derived Parameters in the SBL

Temperature Scale θ*	Friction Velocity u*	Monin-Obukhov Length L	Sensible Heat Flux H	Mechanical Mixing Height Zim
0.0535	0.02897	1.20264	-1907.8	243.199

The temperature scale, friction velocity, Monin-Obukhov Length, Sensible Heat Flux and Mechanical Mixing height is calculated for 10 June, 2017, 20:00, as shown in table 3. The negative sign of sensible heat flux and positive sign of Monin-Obukhov Length is specifying that it is stable boundary layer condition at 20:00. The low value of mechanical mixing height is due to nocturnal inversion, turbulence is suppressed by the strong thermal stratification. Thermally stable conditions occur in night. The product of temperature scale and friction velocity should not exceed 0.05ms^{-1}K in any condition [1]. From table3, the product of these two is 0.0015 ms^{-1}K, which is under limit.

4. CONCLUSION

According to USEPA models, a general Gaussian Plume Dispersion Mathematical Model for brick kiln emissions, based on AERMOD, and is developed in Excel spreadsheets. The parameters of Convective Boundary Layer and Stable Boundary Layer, of study area are calculated. The calculated value of friction velocity is 0.392866205, Monin-Obukhov Length is -58.14432917 and Convective velocity scale is 1.482605331. For Stable Boundary Layer, the calculated value of friction velocity is 0.02897 and Monin-Obukhov Length is 1.20264. The predicted convective mixing height on 10 June, 2017 from potential temperature profile is 1250 m. The calculated values are approximately are well within the standards as compared with various studies conducted by different researchers.

Further work is under progress which includes the wind speed profiling, calculation of Lateral and Vertical Turbulence and prediction of ground level concentrations of pollutant and the air quality in accordance with, Ambient Air Quality Index, CPCB, at receptor location with respect to the given source location.

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