CHAPTER 4

ENVIRONMENTAL MODELLING PRINCIPLES

4.1 INTRODUCTION

Air pollutants emitted from a point source such as tall stack are an important factor in assessing air quality. An atmospheric dispersion model is needed in order to calculate the spatial distribution of pollutant concentrations due to the emission source. Gaussian plume model is the basic method which is used in the U.S. for calculating ambient air pollutant concentrations due to point sources (Turner 1970, Pasquill 1971, Carpentar et al 1971). Turner (1970) presented Gaussian dispersion coefficients for moderately tall stack in open country. Carpentar et al (1971), presented Gaussian dispersion coefficients for very tall stacks in open country. Dispersion models are mathematical expressions relating emission of pollutant to its concentration at a given location. Planning of sustainable development involves some assessment or prediction and dispersion models helps in predicting the impact of a proposed activity on environment. In addition to evaluating and assessing impacts from emission sources in Environment Impact Assessment (EIA) studies dispersion models are also used:

- To estimate results of pollution control devices
- To plan the related ambient air quality monitoring programs
- To control pollution related implementation program
- To stipulate emission limits
- To fix stack heights
- To plan environmental zone/region
- To estimate assimilative capacity of air environment
- To evaluate impacts due to accidental releases
- To determine the impact of distant sources
- To plan land use pattern
- To plan traffic regulations

After discharge, the air emissions from stationary point sources are subjected to transport and diffusion process (dispersion). The following process governs the atmospheric dispersion of pollutants:

- An initial vertical rise called the plume rise (due to buoyancy and momentum of discharge)
- Diffusion by turbulence
- Transport by wind in its direction

### 4.2 GAUSSIAN PLUME MODEL

The essential elements of Gaussian plume model are shown in Figures 4.1 and 4.2 (CPCB 1998). The Concentration of pollutant at a point (x, y, z) in (µg/m³) is given by

\[
C = \frac{Q}{2\pi U\sigma_y\sigma_z} \exp\left(-\left(\frac{y^2}{2\sigma_y^2}\right)\right) \left[\exp\left(-\frac{(z - H)^2}{2\sigma_z^2}\right) + \frac{(z + H)^2}{2\sigma_z^2}\right] (4.1)
\]

where \(Q\) is the pollutant release rate (µg/s), \(U\) is the horizontal wind speed at the source level (m/s), \(\sigma_y\) and \(\sigma_z\) are the horizontal and vertical crosswind dispersion coefficients respectively, which are a function of down wind distance ‘x’ and atmospheric stability, \(y\) is the horizontal crosswind distance
from plume centerline to the receptor, \( z \) is the vertical distance from the plume centerline to the receptor (m), \( x \) is the down wind distance from the plume centerline to the receptor (m), \( H \) is the effective stack height (m) which is given as \( H = h_s + \Delta h \), where \( \Delta h \) = plume rise (m) and \( h_s \) = Physical stack height (m). The coordinate system is such that the origin (0, 0, 0) is at the source, \( x \)-axis is in the mean downwind direction, \( y \)-axis is in the horizontal crosswind direction, and \( z \)-axis is in the vertical direction. Briggs (1969, 1975) plume rise formulae for hot plumes are used for evaluating the pollutant concentrations from elevated point sources.

Briggs (1973) formulae based on downwind distance \( x \) and stability’s have been used to estimate the dispersion parameters \( \sigma_y \) and \( \sigma_z \). Considering the complexity of the study area and the number of emission sources, it was planned to calculate the pollutant concentration for three different seasons.

**Figure 4.1 Plume boundary and time averaged envelope**
4.3 ASSUMPTIONS IN GAUSSIAN PLUME MODEL

The Gaussian plume model (CPCB 1998) equation (4.1) is valid under the following assumptions:

1. It is assumed that the prevailing condition is steady state, which imply that all variables and parameters are constant in time interval considered.
2. Wind flow is considered as homogenous.
3. Atmospheric chemical reactions and gravity fall out are considered to be negligible.
4. Perfect reflection of the plume is considered at the underlying surface.
5. The turbulent diffusion in the x direction is neglected relative to advection in the transport (x) direction.
6. The plume underlying the surface is considered as flat terrain.
Despite its disadvantages arising from accepted assumptions, the Gaussian plume models, is the most commonly adopted method for calculating dispersion of pollutants from the point sources. The reasons for this may be the following:

1. More experience has been gained since first model formulation in the field of dispersion calculations.
2. Model is easy to understand and use, and efficient in computer running time
3. Model is convincing conceptually
4. Results agree with experimental data to a large extent, as evidence from past studies.

4.4 ESSENTIAL ELEMENTS

As per CPCB (1998) guidelines the essential elements of dispersion modelling using Gaussian equation are:

- Emission inventory
- Meteorology
- Atmospheric stability
- Plume rise equations
- Dispersion coefficients
- Mixing height
- Terrain characteristics
4.4.1 Emission inventory

The following parameters should be estimated accurately and used for modelling computations

- Raw material consumption
- Fuel consumption rate and analysis
- Pollutants release rate
- Stack height and stack top diameter
- Exit gas temperature, velocity and volume

The emission rate of pollutants should be worked out using recommended norms and permissible limits. In case better pollution control equipment is envisaged, the actual emissions may also be compared with the notified standards during mathematical modelling. This approach should include likely emissions after installing the control equipment, checked against design of equipment and/or experiment with other similar projects. As the percentage of sulphur varies from time to time in different seasons of the same coal mine, it is suggested that an average percentage of 0.5% sulphur should be taken and actual percentage when sulphur is more than 0.5%, for calculating emission rate of SO$_2$ from the stack.

4.4.2 Meteorology

Generation of surface meteorological data at the project site for all representative seasons is the minimum basic requirement for EIA studies. Therefore, site specific data on wind speed and direction should be generated by following the standard procedures, preferably using continuous recording automatic instruments, taking hourly mean values over all seasons of a year,
site specific data on hourly mean values over all seasons of a year. Site specific data on hourly mean ambient temperature, humidity, cloud cover (type and height), solar insolation and barometric pressure should be collected and used in mathematical modelling.

4.4.3 Atmospheric stability

Atmospheric stability is closely related to temperature lapse rate [the rate of change of temperature with height: \((\delta t/\delta z)\)] and is an useful indicator of atmospheric turbulence. Temperature profile representing the variation of temperature with height varies widely between day and night within a layer of few hundreds of meter above ground. At any given time, temperature can increase or decrease with height at different rates in different layers.

4.4.3.1 Importance of atmospheric stability

Atmospheric stability is a simple method of classifying the turbulent conditions of the atmosphere. Turbulence is a significant factor affecting the dilution of pollutant’s emitted into the atmosphere. Atmospheric stability along with the wind speed and direction is one of the useful meteorological parameters in air pollution studies. Atmospheric stability affects both horizontal and vertical diffusion of pollutants, which in turn decides the ground level concentrations. Existing regulatory air quality dispersion models require stability categories as an input to dispersion estimates.
4.4.3.2 Causes of stability

The region in the lower troposphere within the planetary boundary layer is the region of most interest in air pollution meteorology. In this region, temperature distribution varies considerably depending upon the character of the underlying surface and upon radiation at the surface. The temperature may increase or decrease with height. Above 2 km, the temperature decreases with height in the order of 4 to 8°C per km. If the rate of decrease refers to the air environment, it is called the environmental lapse rate, whereas if it refers to a parcel of air moving with air environment, it is called the process lapse rate.

As the air parcel rises in the atmosphere, it goes through a region of decreasing pressure and expands to accommodate the decreased pressure. If the expansion takes place without loss or gain of heat to the parcel, the change is called adiabatic (i.e. the expansion takes place at the expense of its own internal energy). Similarly, a parcel of air forced downward will encounter higher pressures, will contract and become warmer. The rate of cooling with lifting or heating with descent is the dry adiabatic lapse rate (a process lapse rate) which is approximately 1°C per 100m.

The stability criterion is expressed in two forms:

1. Dry adiabatic lapse rate
2. Potential temperature gradient.
4.4.3.3 Dry adiabatic lapse rate

This is the rate at which a parcel of dry air cools due to decreasing pressure when rising vertically without any energy exchange with the surrounding air. The rate of cooling \( \frac{dt}{dz} \) is 0.0098 °C/m and is denoted by ‘Γ’. The adiabatic lapse rate provides a useful reference point in determining the stability of atmosphere.

Consider a condition in which the actual temperature profile of the atmosphere exactly follows the adiabatic lapse rate. One parcel of air from level ‘A’ moving upwards will cool at adiabatic rate and therefore will continue to have the same temperature and density as the surrounding air. The acceleration of the parcel is therefore zero. This condition is therefore termed as neutral stability, \( \frac{dt}{dz} = \Gamma \).

Next, consider a condition in which the temperature decreases with height at a super adiabatic rate that is, a rate more than adiabatic rate. Again, the parcel of air lifted from level ‘A’ to level ‘B’ will cool adiabatically, but its temperature at level ‘B’ will be higher than that of surrounding air and hence it will be comparatively lighter than the neighboring air. It will therefore experience an upward acceleration due to buoyancy. Similarly, a downward moving parcel shall experience an acceleration enhancing the downward movement. This condition is termed as unstable, \( \frac{dt}{dz} < \Gamma \).

Again consider a situation at night when a temperature inversion is present. It renders a parcel to be heavier than a parcel of air moving upwards to be heavier than the surrounding air causing it to sink back to its original position. The vertical motions are retarded. This condition is termed as stable, \( \frac{dt}{dz} > \Gamma \).
4.4.3.4 Potential temperature gradient

Potential temperature is defined as the temperature an air parcel would attain if taken adiabatically to sea level pressure. For practical purposes, sea level pressure in this context is taken as 1013 mb. If $T_a$ is the temperature of the air parcel, then from the first law of thermodynamics potential temperature $\theta$ may be obtained using the relation

$$\theta = T_a \left( \frac{1013}{p} \right)^{R^*/C_p}$$

where, $R^*$ is the gas constant of air $= 68.75 \text{ cal/kg/K} \ (or \ 287.65 \text{ J/kg/K})$ and $C_p$ is the specific heat of air at constant pressure.

In terms of ambient temperature, its profile can be approximated as:

$$\frac{d\theta}{dz} = \frac{dT_a}{dz} + \Gamma$$

where $\Gamma = 0.98^\circ\text{C}/100\text{m}$ is the reference dry adiabatic lapse rate.

Potential temperature in lower layers near sea level may be obtained using the relation

$$\theta = T + \Gamma z$$

Stability criteria expressed in terms of potential temperature profile are:

$$\frac{d\theta}{dz} < 0 \quad \text{(unstable)}$$

$$\frac{d\theta}{dz} = 0 \quad \text{(neutral)}$$

$$\frac{d\theta}{dz} > 0 \quad \text{(stable)}$$
4.4.3.5 Methods of stability determination

There are various methods to determine stability classes, but the limitation lies with the availability of data required to calculate the stability. Therefore, there is no universally accepted methodology for computing the same. The stability condition is usually computed using meteorological data.

As per the Central Pollution Board guidelines (CPCB 1998), four types of stability classes recommended for modelling studies, they are:

1. Pasquilli method
2. Turner method
3. Wind direction fluctuation method
4. Temperature profile method

A brief description of these methods is given below.

4.4.3.6 Pasquilli method

Pasquilli (1961) estimated stability of the atmosphere based on the wind speed at a height of 10 m and incoming solar radiation (during the day) or the clouds cover (during the night). The stability classification by this method is given in Table 4.1.
### Table 4.1 Stability classification by Pasquilli method

<table>
<thead>
<tr>
<th>Wind speed at 10m (m/s)</th>
<th>Day time / in coming solar radiation</th>
<th>Night time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strong</td>
<td>Moderate</td>
</tr>
<tr>
<td>&lt; 2</td>
<td>A</td>
<td>A – B</td>
</tr>
<tr>
<td>2 - 2.9</td>
<td>A – B</td>
<td>B</td>
</tr>
<tr>
<td>3 – 4.9</td>
<td>B</td>
<td>B – C</td>
</tr>
<tr>
<td>5 - 6</td>
<td>C</td>
<td>C – D</td>
</tr>
<tr>
<td>&gt; 6</td>
<td>C</td>
<td>D</td>
</tr>
</tbody>
</table>

**Note:** A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral, E = slightly stable, F = moderately stable. Strong incoming solar radiation refers to solar elevation angle more than 60°; moderate incoming solar radiation implies when sky is clear and solar elevation angle between 35° and 60°; slight incoming radiation refers to solar elevation angle less than 35°.

#### 4.4.3.7 Turner method

Turner (1964) improved on pasquilli method by making it more objective and involving meteorological parameters such as cloud cover, cloud height, and solar angle that are known for most locations. Turner related the parameters with net radiation index (NR) and the details are given below.

**For day or night:** If cloud amount = 8 and cloud height < 2000m, NR = 0.

**For night time** (defined as period from 1hr before sunset to 1hr after sunrise)

1. if cloud amount ≤ 3 and cloud height = any value, NR = -2
2. if cloud amount ≥ 3 and cloud height = any value, NR = -1
Net radiation index values for daytime are given in Table 4.2.

### Table 4.2 Net radiation index value for day time

<table>
<thead>
<tr>
<th>Solar angle (α)</th>
<th>Net radiation index (NR)</th>
<th>Cloud amount &gt; 4 And cloud height &lt; 2000 m</th>
<th>Cloud amount &gt; 4 And cloud height &gt; 2000 m and &lt; 5000 m</th>
<th>Cloud amount &gt; 4 And cloud height at any value</th>
</tr>
</thead>
<tbody>
<tr>
<td>60° &lt; α</td>
<td></td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>35° &lt; α ≤ 60°</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>15° &lt; α ≤ 35°</td>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>α ≤ 15°</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Turner specified the Pasquilli classes according to the net radiation index (NR) and wind speed and it is given in Table 4.3.

### Table 4.3 Stability classification by Turner method

<table>
<thead>
<tr>
<th>Wind speed/in knot</th>
<th>Net radiation index (NR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>0 - 1</td>
<td>A</td>
</tr>
<tr>
<td>2 - 3</td>
<td>A</td>
</tr>
<tr>
<td>4 - 5</td>
<td>A</td>
</tr>
<tr>
<td>6</td>
<td>B</td>
</tr>
<tr>
<td>7</td>
<td>B</td>
</tr>
<tr>
<td>8 - 9</td>
<td>B</td>
</tr>
<tr>
<td>10</td>
<td>C</td>
</tr>
<tr>
<td>11</td>
<td>C</td>
</tr>
<tr>
<td>&gt;12</td>
<td>C</td>
</tr>
</tbody>
</table>

Note:  A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral, E = slightly stable, F = moderately stable, G = highly stable.
4.4.3.8 Wind direction fluctuation method

Stability classification can also be based on the range of fluctuation of the horizontal wind direction trace. Slade (1968) proposed correspondence between standard deviation of horizontal wind fluctuation ($\sigma_\theta$) and Pasquilli stability classification. The wind direction fluctuation in each hour is divided into either 10, 15, or 20 minutes intervals depending upon the degree variation of wind direction and the stability classification can be calculated from the Table 4.4.

Table 4.4 Stability classification based on Wind direction fluctuation method

<table>
<thead>
<tr>
<th>Wind fluctuation ($\sigma_\theta$) in degrees</th>
<th>Stability class</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 22.5</td>
<td>A</td>
</tr>
<tr>
<td>22.4 to 17.5</td>
<td>B</td>
</tr>
<tr>
<td>17.4 to 12.5</td>
<td>C</td>
</tr>
<tr>
<td>12.4 to 7.5</td>
<td>D</td>
</tr>
<tr>
<td>7.4 to 3.5</td>
<td>E</td>
</tr>
<tr>
<td>&lt; 3.5</td>
<td>F</td>
</tr>
</tbody>
</table>

Note:  
A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral,  
E = slightly stable, F = moderately stable.

4.4.3.9 Temperature profile method

Potential temperature gradient (lapse rate) is determined by taking temperature measurements at two or more heights. Based on the temperature gradient $d\theta/dz$, the stability classes are classified and are given in Table 4.5.
Table 4.5 Stability classification by temperature profile method

<table>
<thead>
<tr>
<th>Temperature gradient $d\theta/dz ^\circ C/100m$</th>
<th>Stability class</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -1.9</td>
<td>A</td>
</tr>
<tr>
<td>-1.9 to -1.7</td>
<td>B</td>
</tr>
<tr>
<td>-1.7 to -1.5</td>
<td>C</td>
</tr>
<tr>
<td>-1.5 to -0.5</td>
<td>D</td>
</tr>
<tr>
<td>-0.5 to 1.5</td>
<td>E</td>
</tr>
<tr>
<td>&gt; 1.5</td>
<td>F</td>
</tr>
</tbody>
</table>

Note: A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral, E = slightly stable, F = moderately stable

4.4.3.10 Extrapolation of wind speed

The wind speed measurements are normally carried out at a height of 10m. In order to use these measurements for modelling purposes, the wind speeds need to be extrapolated to the effective height of release. It is recommended that for extrapolation, an empirical power law as given by Irwin wind scaling law. As per CPCB (1998).

$$U_1 = U_2 \left(\frac{Z_1}{Z_2}\right)^n$$

(4.2)

where, $U_1$ and $U_2$ are wind speeds at heights $Z_1$ and $Z_2$ respectively, and $n$ is an exponent. The value of $n$ is a function of stability class given in Table 4.6.
Table 4.6 Values of exponent n for various stability classes

<table>
<thead>
<tr>
<th>Stability class</th>
<th>Urban conditions</th>
<th>Rural &amp; other conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>B</td>
<td>0.15</td>
<td>0.07</td>
</tr>
<tr>
<td>C</td>
<td>0.20</td>
<td>0.10</td>
</tr>
<tr>
<td>D</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>E</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>F</td>
<td>0.60</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Note: At heights above 200 m, the value of wind speed calculated at 200 m should be used. A = extremely unstable, B = moderately unstable, C = slightly unstable, D = neutral, E = slightly stable, F = moderately stable.

4.4.4 Plume rise equations

The effective stack height are determined using Briggs (1975) plume rise equations (alternatively, with modifications incorporated by Briggs in 1984).

4.4.4.1 Plume rise

Most effluents emitted through a stack have an initial momentum of discharge and initial buoyancy due to temperature excess of the effluent over the ambient air. Effluents with predominantly momentum discharge with little or no buoyancy are called jets or momentum plumes. At the other extreme are the stacks attached to thermal power plants where the effluents are discharged at temperatures of about 150°C, much higher than the ambient temperature. Such plumes are predominantly buoyant. Plumes from stacks attached to
small and medium boilers fall in between. It is customary to add the plume rise from jet component to the buoyant component to obtain the total plume rise. However, in case of predominantly buoyant plumes, the plume rise from jet component may be neglected.

The behavior of rising plumes, whether jets or buoyant, depends upon the meteorological conditions, particularly atmospheric stability and wind speed. Plumes may be classified as vertical plumes and bent over plume. Vertical plumes occur under calm conditions (wind speed less than 0.5 m/s) when the plume rises vertically until it meets a wind layer or stable layer. Bent over plumes occur for wind speed above 1 m/s with the plume trajectory taking a somewhat parabolic shape. The behavior of the bent over plume depends upon atmospheric stability, one type of behavior for stable atmosphere and another for unstable and neutral atmosphere. The different plume shapes along with temperature profile and velocity are given in Figure 4.3 (CPCB 1998).

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**Figure 4.3** Typical velocity, temperature profile, and plume shapes

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- Adiabatic lapse rate
- Environmental lapse rate
4.4.4.2 Unstable and neutral atmosphere

Since the vertical motions are accelerated, the plume continues to rise without leveling until turbulence of the entrained air dissipates the momentum and buoyancy leading to a final plume rise. The trajectory is given by “2/3 power law” which states ‘the rise is proportional to 2/3 power of the horizontal travel distance x’.

4.4.4.3 Stable atmosphere

In this case a definite final plume rise is possible and it depends upon degree of stability (potential temperature gradient).

As far as the dispersion calculations are concerned the vertical plumes are of minor interest since the high plume rise leads to negligible concentrations. It is the bent over plumes which are of significant interest.

4.4.4.4 Briggs plume rise equations

Briggs (1969) reviewed the plume rise data and relations and initiated development of a sound theoretical basis for the study of the plume rise. The relations given by Briggs (1969) have been further improved to obtain separate relations under unstable, neutral and stable conditions (Briggs 1972, 1975, 1984).

4.4.5 Dispersion coefficients

Briggs urban and rural dispersion coefficients should be used to determine the values of horizontal and vertical dispersion coefficients, $\sigma_y$ and $\sigma_z$ and obtained from Table 4.7 (CPCB 1998).
Table 4.7 Briggs dispersion parameters for $\sigma_y$ and $\sigma_z$ (100 m < x < 10000 m)

<table>
<thead>
<tr>
<th>Stability class</th>
<th>$\sigma_y$ (m)</th>
<th>$\sigma_z$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rural conditions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>$0.22X(1+0.0001X)^{-0.5}$</td>
<td>$0.20X$</td>
</tr>
<tr>
<td>B</td>
<td>$0.16X(1+0.0001X)^{-0.5}$</td>
<td>$0.12X$</td>
</tr>
<tr>
<td>C</td>
<td>$0.11X(1+0.0001X)^{-0.5}$</td>
<td>$0.86X(1+0.0002X)^{-0.5}$</td>
</tr>
<tr>
<td>D</td>
<td>$0.08X(1+0.0001X)^{-0.5}$</td>
<td>$0.06X(1+0.0015X)^{-0.5}$</td>
</tr>
<tr>
<td>E</td>
<td>$0.06X(1+0.0001X)^{-0.5}$</td>
<td>$0.03X(1+0.0003X)^{-1}$</td>
</tr>
<tr>
<td>F</td>
<td>$0.04X(1+0.0001X)^{-0.5}$</td>
<td>$0.016X(1+0.0003X)^{-1}$</td>
</tr>
<tr>
<td><strong>Urban conditions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A – B</td>
<td>$0.32X(1+0.0004X)^{-0.5}$</td>
<td>$0.24X(1+0.001X)^{-0.5}$</td>
</tr>
<tr>
<td>C</td>
<td>$0.22X(1+0.0004X)^{-0.5}$</td>
<td>$0.20X$</td>
</tr>
<tr>
<td>D</td>
<td>$0.16X(1+0.0004X)^{-0.5}$</td>
<td>$0.14X(1+0.0003X)^{-0.5}$</td>
</tr>
<tr>
<td>E – F</td>
<td>$0.11X(1+0.0004X)^{-0.5}$</td>
<td>$0.08X(1+0.0015X)^{-0.5}$</td>
</tr>
</tbody>
</table>

4.4.6 Mixing height

The mixing height is defined as the height of the layer adjacent to the ground over which pollutants or any constituents emitted within this layer or entrusted into it become vertically dispersed by convection or mechanical turbulence within a time scale of about an hour (Beyrich 1997).

Knowledge of mixing height is very crucial in realistic adoption of plume rise and vertical dispersion parameters. In India, the IMD generators mixing height data using radio sond at 35 locations and the data are available from Institute of Tropical meteorology, Pune. The National Physical Laboratory (NPL), New Delhi has generated mixing height data using SODAR for 9 locations and the data are available on payment from NPL.
Substances emitted into the atmospheric boundary layer (ABL) are gradually dispersed horizontally and vertically through the action of turbulence, and finally become completely mixed over this layer if sufficient time is given and if there are no significant sinks. Therefore, it has become customary in air pollution meteorology to use the term “mixed layer” or “mixing layer”. Since under stable conditions complete mixing is often not reached, the term “mixing layer” seems preferable, because it emphasizes more the process than the result. Obviously, the mixing layer coincides with the ABL if the latter is defined as the turbulent domain of the atmosphere adjacent to the ground. However, other definitions of the ABL have also been used which may include the domain influence by nocturnal radioactive exchange processes.

The height of the mixing layer (the mixing height MH) is a key parameter for air pollution models. It determines the volume available for the dispersion of pollutants and is involved in many predictive and diagnostic methods and/or models to assess pollutant concentrations, and it is also an important parameter in atmospheric flow models. The MH is not measured by standard meteorological practices, and moreover, it is often a rather unspecific parameter whose definition and estimation is not straightforward.

The practical and theoretical problems associated with the determination of the MH, and sometimes even its definition, are reflected in the numerous definitions found in the literature (Stull 1988, Garratt 1992, Seibert et al 1998). It seems also that the MH definitions of different authors have to be seen in the context of the data available to them.

Mixing heights are seldom measured directly due to high cost involvement and such measurements do not indicate the realistic values. So the mixing heights are being worked out by utilizing Radio Sond (RS) data
(vertical distribution of temperature) together with hourly surface temperatures. Hourly surface temperatures need to be recorded continuously by thermograph or by other good sensors. India Meteorological Department has 35 of such Observatories, which take RS flights twice a day i.e. at 00 GMT and 12 GMT and 32 stations are recording surface temperatures continuously out of 35 observatories (CPCB 2003b). 00 GMT RS data and hourly surface temperature data have been used for working out hourly mixing depth based on techniques as suggested by Ludwig (1970) and Raman and Kelkar (1972). In view of the complex structure of the real atmosphere, these definitions of mixing depth will be recognized as approximations particularly applicable in climatological and air pollution studies.

4.4.7 Terrain characteristics

The area is classified as urban when more than 50% of land, inside a circle of 3 km radius, around the source consists heavy or medium industrial, commercial or residential units.

Downwash effects due to buildings and other elevated structures should be considered during mathematical modelling. Such a situation shall arise only when the tallest building or other structure in the area have a height equivalent to at least 40% of the source height and are within a distance of 5 times of the lesser of the height or maximum projected width of such tall buildings.

There can be diverse scenarios of emission and site characteristic, as well as meteorological conditions involved in dispersion. For example, the terrain may be even in which case the effective stack height may be different in different directions. If the site is near a coast then the wind characteristics of offshore wind and onshore wind (land and sea breeze) can be different due
to difference of roughness over land and sea. If the source receptor distance is large than the time taken by the plume to reach the point down wind and subsequent changes caused to wind speed/direction creates a different dispersion scenario, than expected.

There are situations when the basic relations have to be modified or correction factors applied appropriately to help the situation. Typical examples are the presence of a building wake, a capping inversion, presence of different stability layers at different heights and effect of physico-chemical processes like transformation to another species of pollutant, deposition and rain out.

Some of the points require consideration for modelling are whether the plume is able to penetrate the stable layers during plume rise. Also at coastal sites, when winds come from sea to land, the flow is aerodynamically smooth, typical of the land roughness develops. This can lead to complicated situations like fumigation.

4.5 EFFECT OF BUILDING WAKE

Releases from short stacks and other fugitive emissions get mixed in the turbulent wake created by the airflow around the building or stack structure. This effect gives rise to a volume source. Based on the studies of experimental releases from buildings and on assumption of uniform mixing of the effluent in the building wake, the normal short-term centerline concentration is given by CPCB (1998).

\[
C(x,0) = \frac{Q}{(\pi \sigma_y \sigma_z + C_w A) u} \quad (4.3)
\]
A = area of the building normal to the wind, \( C_w \) = fraction of A over which the plume is dispersed by the wake or more commonly known as building shape factor (conservatively estimated as 0.5). It would be seen that the effect of wake is to reduce the ground level concentrations in the downwind direction. The effect of wake becomes insignificant when \( C_w A \ll \sigma_y \sigma_z \). On the downwind side of an obstacle, the release gets mixed-up due to turbulence created in the wake of the building. This can be treated as the area source in this case and virtual source approach should be applied. In this approach the dimensions of the building perpendicular to the wind direction are taken as dimension of plume spread. As per CPCB (1998) if \( H_B \) is the height of the building and \( W_B \) is the width of the building then

\[
\sigma_z (\text{vir}) = \frac{H_B}{2.14} \quad \text{and} \quad \sigma_y (\text{vir}) = \frac{W_B}{2.14}
\]

The distance corresponding to these spread parameters in respective category are the virtual distances in vertical and horizontal directions. For estimating the spread parameter for downwind distances, these virtual distances should be added to the actual downwind distance and the effective distance be used.

4.6 URBAN HEAT ISLAND EFFECT

In an urban area one has lot of concrete structures apart from various industries, leading to higher temperature in the urban area as compared to the surrounding rural area. These areas are sometimes referred to as heat islands. To evaluate the transport and diffusion of pollutants in urban areas, like the effect of local wind circulation systems due to urban heat island effect should be considered. The difference in the diurnal temperature
variation in rural and urban areas causes the heat island to be most intense at night than during the day.

The differential temperature distribution produces a weak two-cell circulation during weak winds over the urban area (An upward motion of urban air and an upper level horizontal divergence to the rural area). Under fairly strong winds, the circulation system is displaced downwind to a distance which appears to be proportional to the mean wind speed and heating rate. Presence of an elevated temperature inversion over the urban area has also been indicated, which acts as a lid to vertical diffusion of pollutants in urban area. This may lead to a downward subsidence of air over urban area causing the urban pollution levels to increase during day time. A layer of pollutants over the city during daytime also inhibits solar radiation reaching and heating the area, thereby reversing the temperature difference between the urban and rural area.

4.7 COASTAL SITES

The peculiarities of a coastal site depend on two features. One is the land and sea breeze system, which dominates the local flows and other, is the significant change and the surface roughness felt by the airflow, when air enters land from sea and vice-versa. The land and sea breeze system is basically a thermal wind system caused by the density gradients due to unequal heating of air above land and water bodies. The sea breeze on the west coast has an on set time around noon and lasts up to late evening. The land breeze has an onset time late at night and last up to early morning. On east coast, the situation is more complex. Since the sea lies to the east and the tendency of the gradient flow is westerly, the thermal wind opposes the gradient flow during the sea breeze regime and sea breeze is felt only if thermal wind is stronger than the gradient wind. As far as short distance
dispersion is concerned, this aspect of sea and land breeze does not impose any problem since it is reflected in the wind records.

The change of the roughness feature along sea and land surface is more complicated. The wind coming from the sea, as soon as it crosses the shore, develops an internal boundary layer, the thickness of which depends upon the downwind distance from the shore and the potential temperature difference between the sea and land surface. The aerodynamically smooth flow from the sea is slowly converted into a rough flow due to increased surface roughness. The relation for height of the internal boundary layer (IBL) given by CPCB (1998) is

$$H_i = 8.8(x/u_\Delta \theta)^{0.5} \quad (4.5)$$

where $\Delta \theta$ is the potential temperature difference between top and bottom of the initial stable layer (at the shore). The concentration due to fumigation from CPCB (1998) is given by

$$C(x, y) = \frac{Q}{(2\pi u_\gamma \sigma_y H_i)^{0.5}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \quad (4.6)$$

where $\sigma_y$ relevant to initial layer should be used.

4.8 MULTIPLE POINT STACKS

Many industrial units have multiple identical and/or non-identical stacks and if the stacks are close to one another, the plume can merge with each other. The buoyancy of the combined plume will be higher than the
individual plume. Therefore for industrial units with more than one stack, the following calculations should be applied.

4.9 FOR IDENTICAL STACKS

The plume rise enhancement factor as suggested by Briggs should be followed. The emission rate of all stacks should be added and GLC should be computed assuming single stack located at the centroid of the group of stacks. Consider two similar plumes separated by a distance ‘s’ and have a plume rise ‘Δh’. The combined plume rise ‘H’ from two plumes will be EΔh, where E is the enhancement factor. If s = 0, then E will be $2^{1/3}$. If s is very large, then E will be 1 and plume will not merge.

Briggs equation for calculation of enhancement factor ‘E’

$$E = \left\{ \frac{(n+s)}{(1+A)} \right\}^{1/3} \quad (4.7)$$

where,  
- n - number of stacks  
- s - inter stack distance  
- A - dimensions factor obtained from $A = 6\{((n-1) s) / (n^{1/3} \Delta h)\}^{3/2}$  
- Δh - plume rise

For identical stacks, if the plume do not merge (when E = 1), then GLC at downwind distance ‘x’ due to a single source should be computed. To obtain aggregate impact at ‘x’, GLC’s due to multiple sources should be computed and added algebraically.

4.10 FOR NON-IDENTICAL STACKS

The emission rate from individual stack should be taken for computation of GLC.