ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
ENVIRONMENTAL ENGINEERING STREAM

MODELING OF AIR POLLUTANT DISPERSION AND ANALYSIS

By
ANTENEH MUHEYE

Advisor
TESHOME WORKU (Assistant professor)

A thesis submitted to the School Of Graduate Studies of Addis Ababa University in partial fulfillment of the Degree of Master of Science in Environmental Engineering

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MODELING OF AIR POLLUTANT DISPERSION AND ANALYSIS

A Thesis Submitted To The School Of Graduate Studies Of Addis Ababa University In Partial Fulfillment Of Requirement For The Degree Of Master Of Science In Chemical Engineering (With specialization in Environmental Engineering)

By

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Advisor

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ADDIS ABABA UNIVERSITY

INSTITUTE OF TECHNOLOGY

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‘Modeling of Air Pollutant Dispersion and Analysis’

By Anteneh Muheye

Approved by Board of Examiners

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any University, and that all the source of materials used for the thesis has been duly acknowledged.

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Abstract

This work has been carried out to develop a three dimensional modeling program for pollutant dispersion. The program solves partial differential equation by integrating into one mathematical equation and then various data are taken from literature s and primary sources for verification of the program.

The effects of meteorological and stack parameters on dispersion of pollutants ,like wind velocity, ambient air temperature, atmospheric stability, exit temperature, velocity ,concentration and stack height were studied and considered in the program. Several illustrations for reducing maximum ground level concentration using the program are given. The output results from the program are presented in different forms.

Different simulation runs and observations were made that clearly illustrate the utility of the program in helping decision makers about air pollution control and effects of different variables in pollution.

1. Introduction

Atmospheric dispersion modeling is the mathematical simulation of how air pollutants disperse in the ambient atmosphere. It is performed with computer programs that solve the mathematical equations and algorithms which simulate the pollutant dispersion. The dispersion models are used to estimate or to predict the downwind concentration of air pollutants or toxins emitted from sources such as industrial plants, vehicular traffic or accidental chemical releases.

Such models are important to governmental agencies tasked with protecting and managing the ambient air quality. The models are typically employed to determine whether existing or proposed new industrial facilities are or will be in compliance with the National Ambient Air Quality Standards (NAAQS) in different nations. The models also serve to assist in the design of effective control strategies to reduce emissions of harmful air pollutants [1].

Mathematical dispersion models are most useful nowadays since they provide useful information for predicting pollutant concentration and quickly provide output. Air quality mathematical models represent unique tools for:

- Establishing emission control legislation; that is, determining the maximum allowable emission rates that will meet fixed air quality standards.
- Evaluating proposed emission control techniques and strategies; that is, evaluating the impacts of future controls, in which the mathematical expression developed, as well as go a long way to control the pollution because if the concentration of pollutants at certain region is known, efforts can be geared towards preventing further dispersion from point of discharge to the areas yet to be polluted.
- Selecting locations of future sources of pollutants, in order to minimize their environmental impacts.
- Planning the control of air pollution episodes; that is, defining immediate intervention strategies (i.e., warning systems, real-time, and short-term emission reduction strategies) to avoid severe air pollution episodes in certain regions.

- Assessing responsibility for existing air pollution levels.

- Designing and optimizing AQMN (air quality monitoring network) mathematical models typically incorporate a plume rise module which calculates the height to which pollutants rise due to momentum and buoyancy, and a dispersion module which estimates how pollutants spread as a function of wind speed and atmospheric stability. Figure 1.1 show plume rise and pollution dispersion from an industrial stack [2].

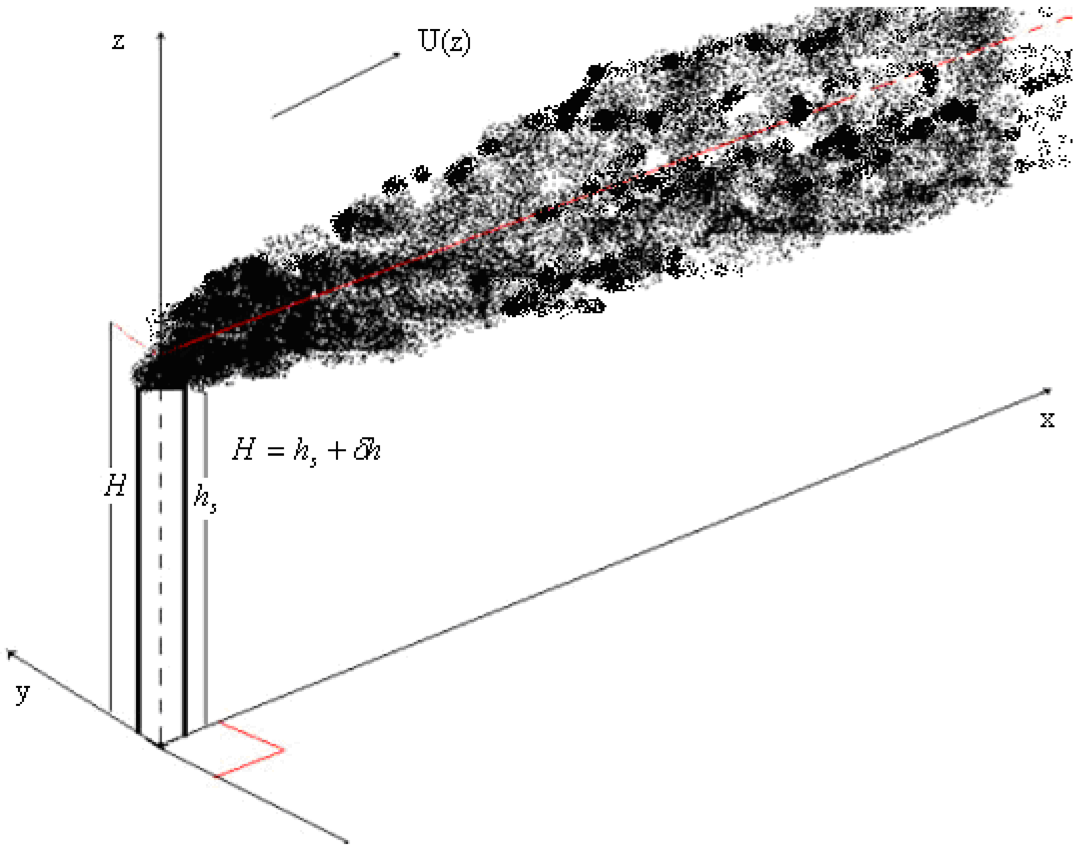


Figure 1.1. Plume rise and pollution dispersion from an industrial stack.

Standard mathematical dispersion models used for industrial dispersion modeling include the Industrial Source Complex (ISC) developed by the USEPA(United States Environmental Agency), Gaussian Models (Plume, Puff, and Fluctuating Models), EPA SCREEN model, Regression Models, Simple Diffusion Models (Box Model and Atmospheric Turbulence and Diffusion Laboratory, ATDL), Gradient Theory Models, Source-Oriented and Receptor- Oriented Models and Multiple

Cell Model. More complex models may incorporate more realistic meteorological treatments, but generally require data which is more difficult and expensive to obtain. Examples include Ausmet/Auspuff(Australian puff model), Calmet/Calpuff (California puff model), and TAPM (The Air Pollution Model). Other models may attempt to model photochemical reactions between pollutants like empirical kinetic modeling analysis (EKMA), while simpler models generally assume that pollutants are conserved.

In this thesis, a MATLAB program for pollutant dispersion from an industrial stack that determines the quality of the air was developed. After that the programme was validated using primary and secondary data in which the output result for concentration variation with distance was shown in chart and two dimensional plots.

1.1. Statement of the Problem

Air pollution is caused by emissions from point sources, area sources, mobile sources, and biogenic sources. Substantial evidence has shown that air pollution affects the health of human beings and animals, damages vegetations, soil and deteriorates materials, affects climate, reduces visibility and solar radiation, contributes to safety hazards, and generally interferes with the enjoyment of life and property [3].

About 60% of the emissions are from point sources. Major air pollutants usually considered include dust, and particulates like PM_{10} (particulate matter 10 microns or less in diameter), and $PM_{2.5}$ due to incomplete burned fuel or process byproducts, nitrogen oxides (mainly due to combination of atmospheric oxygen and nitrogen at high temperatures), sulfur dioxide (mainly due to the burning of fossil fuel containing considerable quantities of sulfur), carbon monoxide (due to incomplete burned fuel), ozone and lead [4].

Most rural areas rarely experience air quality problems, while elevated concentrations of air pollution are commonly found in many urban environments. Recently, urbanization and industrial activity has increased around Addis Ababa, resulting in air quality concerns for several regions. Air pollution results from a complex mix of, literally, thousands of sources such as industrial smoke stacks, motor vehicles, individual use of grooming products, household cleaners, and paints. Even plant and animal life can play an important role in the air pollution problem.

Because of complex nature of air pollution and absence of detailed regional plans that will identify the emission sources, methods for reducing the health impact from exposure to air pollution, availability of application of air quality models, mechanism of air pollutant emission control analysis, development of emission projections to examine possible changes in future air quality, analysis of emission trends are some of the major points that are considered for doing this thesis work.

Development of fundamentally sound emission models will estimate the air quality planning that needs continual development and refinement, so that it can be used through out the country to help and coordinate the development of emission estimates and its future effect on the ecosystem. The model will assist in implementing preservation and corrective actions over time for emissions inventories that can be developed in periodic cycles and continually to be improved to reduce its local and global effects.

1.2. Objective

1.2.1. General Objective

The general objective of the thesis was to develop a MATLAB-based modeling program for dispersion of air pollutants emitted from an industrial stack.

1.2.2. Specific Objectives

The specific objective of the thesis was to:

- develop matalab program,
- describe the geometry of the domain and its boundary conditions,
- identify sources, sink and the dispersion characteristics from the entire domain,
- select model parameter values, and
- validate the program.

2. Literature Review

2.1. Air Pollution

Air is the ocean we breathe. Air supplies us with oxygen which is essential for our bodies to live. Air is 99.9% nitrogen, oxygen, water vapor and inert gases. Human activities can release substances into the air, some of which can cause problems to humans, plants, and animals.

Air pollution is the presence of undesirable material in air, in quantities large enough to produce harmful effects. There are several main types of pollution and well-known effects of pollution which are commonly discussed. These include smog, acid rain, the greenhouse effect, and holes in the ozone layer. Each of these problems has serious implications for our health and well-being as well as for the whole environment.

One type of air pollution is the release of particles into the air from burning fuel for energy. Diesel smoke is a good example of this particulate matter. The particles are very small pieces of matter measuring about 2.5 μm. This type of pollution is sometimes referred to as black carbon pollution. The exhaust from burning fuels in automobiles, homes, and industries is a major source of pollution in the air. Some authorities believe that even the burning of wood and charcoal in fireplaces and barbeques can release significant quantities of soot into the air.

Another type of pollution is the release of noxious gases, such as sulfur dioxide, carbon monoxide, nitrogen oxides, and chemical vapors. These can take part in further chemical reactions once they are in the atmosphere, forming smog and acid rain.

Pollution also needs to be considered inside our homes, offices, and schools. Some of these pollutants can be created by indoor activities such as smoking and cooking.

Based on World Health Organization (WHO) estimates, 500,000 people die prematurely each year because of exposure to ambient concentrations of airborne particulate matter.

Air pollution is definitely not a new problem but dates back to the middle ages when the use of coal in cities such as London began to escalate. The problems of poor urban air quality even as early as the end of the 16th century are well recognized. Hundreds of years later, in 1952, a five-day temperature inversion in London trapped fog laden with pollutants created by burning of coal.

More than 4000 deaths were attributed to this deadly black fog. Similar incidents claimed 1000 lives in 1956 and 700 lives in 1962. However, during the 1980s the number of motor vehicles in urban areas steadily increased and air quality problems associated with motor vehicles became more prevalent.

In the early 1980s, the main interest was the effects of lead pollution on human health, but by the late 1980s and early 1990s, the effects of other motor vehicle pollutants became a major concern. Between September 1997 and November 1997 in Indonesia, there were 527 haze-related deaths, 298,125 cases of asthma, 58,095 cases of bronchitis, and 1,446,120 cases of acute respiratory infection reported. The most common disaster of air pollution the one that accrued because of release of hydrogen sulphide at Poza Rica, Mexico in 1950 and the other example is toxic release at Bhopal, India [5].

2.2. Air Pollution Sources and Effects

The variety of matter released into the atmosphere by natural and anthropogenic sources is so diverse that it is difficult to classify air pollutants neatly. However, usually they are divided into two categories of primary pollutants and secondary pollutants. The primary pollutants are those that are emitted directly from the sources. Typical pollutants included under this category are particulate matter such as ash, smoke, dust, fumes, mist and spray; inorganic gases such as sulphur dioxides, hydrogen sulphide, nitric oxide, ammonia, carbon dioxide, and hydrogen fluoride; olefinic and aromatic hydrocarbons; and radioactive compounds. The secondary pollutants are those that are formed in the atmosphere by chemical interactions among primary pollutants and normal atmospheric constituents.

Pollutants such as sulphur trioxides, nitrogen dioxides, PAN (peroxyacetyl nitrate), ozone, aldehydes, ketones, and various sulphate and nitrate salts are included in this category.

Of the large number of primary pollutants emitted into the atmosphere, only a few are present in sufficient concentrations to be of immediate concern. These are the five major types like particulate matters, sulphur oxides, oxides of nitrogen, carbon monoxides, and hydrocarbons. Carbon dioxides is generally not considered as an air pollutant but, because of its increased global background concentrations, its influence on global climatic patterns is of great concern.

Secondary pollutants are formed from chemical and photochemical reaction in the atmosphere. The reaction mechanisms and various steps involved in the process are influenced by many factors such as concentration of reactants, the amount of moisture present in the atmosphere, degree of photo activation, meteorological forces, and local topography.

In general the term “particulate” refers to all atmospheric substances that are not gases. They can be suspended droplets or solid particles or mixtures of the two. Particulates can be composed of inert or extremely reactive materials ranging in size from 100 μm down to 0.1 μm and less. The inert materials do not interact readily with the environment nor do they exhibit any morphological changes as a result of combustion or any other process, whereas the reactive materials could be further oxidized or may react chemically with the environment.

Particles in the size range 1 to 10 μm have measurable settling velocities but are readily stirred by air movements, whereas particles of 0.1 to 1 μm have small settling velocities. Those below 0.1 μm, a submiscropic size found in urban air, undergo random Brownian motion resulting from collisions among individual molecules. Most particulates in urban air have sizes in the range 0.1 to 10 μm.The finest and the smallest are the ones which cause significant damage to health.

The chemical composition of particulate pollutants varies over a wide range. The actual composition is very much depending upon the origin of the particulate. Particles from soils and minerals primarily contain calcium, aluminums and silicon compounds. Smoke from combustion of coal, oil, wood and solid waste contains many organic compounds.

Insecticide dusts and certain fumes released from chemical plants also contain organic compounds. Hydrocarbons themselves can coalescence into aerosols droplets that constitute one kind of particulate matter. The most harmful components of incomplete combustion are generally grouped as particulate polycyclic organic matter (or PPOM). These materials are derivatives of benz-α-pyrene, a protein carcinogen.

Of all the different types of particulates in the atmosphere, the presence of trace elements such as cadmium, lead, nickel and mercury may constitute the greatest health hazard. Many of the trace metals are toxic and are concentrated in the finest of particulate matter in a variety of combined forms such as oxides, hydroxides, sulphates, and nitrates [6].

2.3. Atmospheric Dispersion

A rapid industrialization and fast urbanization all over the world has created acute problems for mankind striving to preserve the ecological systems. Since environmental protection has become a challenging scientific task, the study of atmospheric dispersion of air pollutants from various sources has received a great deal of attention during the last few decades. The dispersion of air pollutants in the atmosphere is governed by the processes of molecular diffusion and convection and is mainly affected by various meteorological conditions such as wind, temperature inversion, foggy atmosphere etc. and removal processes such as chemical reaction, deposition rain/washout.

To answer questions like how do pollutants behave once they have been emitted, and how may we predict their concentrations in the atmosphere? Computer models that use such information as predicted emissions, smokestack heights, wind data, atmospheric temperature profiles, ambient temperature, solar insolation, and local terrain features have been developed [7].

2.4. Models

A model is a simplified abstract view of the complex reality. It represents empirical objects, phenomena, and physical processes in a logical way and attempts to formalize the principles of the empirical sciences in the same way logicians axiomatize the principles of logic use to an interpretation of reality. For the scientist, a model is also a way in which the human thought processes can be amplified. Models that are rendered in software allow scientists to leverage computational power to simulate, visualize, manipulate and gain intuition about the entity, phenomenon or process being represented.

2.4.1. Types of Models

There are four well developed types of models of a real-world system, in which each of them are described below.

1. Conceptual Models: are qualitative models that help highlight important connections in real world systems and processes. They are used as a first step in the development of more

complex models. They are also a sort of processing information how things in our surrounding environment work.

2. Physical models: are interactive demonstrations that can be easily observed and manipulated and which have characteristics similar to key features of more complex systems in the real world. These models can help bridge the gap between conceptual models and models of more complex real world systems.
3. Mathematical and Statistical Models: involve solving relevant equation(s) of a system or characterizing a system based upon its statistical parameters such as mean, mode, variance or regression coefficients. Mathematical models include analytical models and numerical Models. Statistical models are useful in helping identify patterns and underlying relationships between data sets.
4. Visualizations models: are models that can help one visualize how a system works. It can be a direct link between data and some graphic or image output or can be linked in series with some other type of model so to convert its output into a visually useful format. Examples include 1-D, 2-D, and 3-D graphics packages, map overlays, animations, image manipulation and image analysis.

The details of the atmospheric dispersion model, which is types of mathematical model having an initial known relationship between the inputs and outputs (stochastic model) is noted and expressed below [8].

2.5. Atmospheric Dispersion Modeling

A dispersion model is a mathematical description of the meteorological transport and dispersion processes, using source and meteorological parameters, for a specific period in time. The model calculations result in estimates of pollutant concentration for specific locations and times. It uses a series of equations to estimate air pollutant concentrations at given locations downwind of the emission source(s), taking into account emission rates, the source type (e.g. point, area, volume or line source), meteorological conditions, terrain effects, building wake effects and a range of other factors.

Dispersion modelling is usually the only way to assess the potential effect of an emission source which has not been constructed. Where the source exists, the benefits of modeling over ambient monitoring include the ability to estimate ground level concentrations at many hundreds of locations for the cost of a single set of measurements. In comparison, a monitoring program would have been undertaken over significant period of time (ranging from months to years depending on the frequency of sample collection) and at a number of locations to provide anywhere near the same level of information about downwind pollutant concentrations.

With modelling techniques it is also possible to investigate the relative contributions of individual sources to cumulative downwind concentrations, and to predict the effects of changes in emission rates and release parameters (stack heights, etc) on downwind concentrations.

The complexity and sophistication of a dispersion modelling study can vary widely from a simple screening exercise providing an estimate of potential worst case concentrations resulting from emissions from a single source, to a detailed study of terrain and building wake effects, plume interactions and chemical reactions within the plume itself.

The degree of complexity of a given modelling study should reflect the complexity of the emission source(s) and surrounding area and the potential for significant off-site effects.

Despite recent advances in modelling techniques, there are a number of emission sources which are not easily assessed using dispersion modelling techniques. This may be due to complex nature of the emission source (such as fugitive dust emissions from excavation activities or gases emitted from the surface of a landfill) which makes it difficult to estimate emission rates and flows. Alternatively, it may be due to the complex nature of the discharge itself, such as a complicated solvent or organic mixture which cannot be well characterized. In such instances other assessment tools would probably be more appropriate for use in determining the potential for off-site effects. In light of the above, it is recommended that before atmospheric dispersion modelling is undertaken as part of an air quality assessment, it should be consulted to ensure an appropriate technique to be used [9].

2.5.1. Types of Air Dispersion Models

There are five types of air pollution dispersion models, as well as some hybrids of the five types.

Gaussian model

The Gaussian model is perhaps the oldest (about 1936) and perhaps the most accepted computational approach to calculating the concentration of a pollutant at a certain point. Gaussian models are most often used for predicting the dispersion of continuous, buoyant air pollution plumes originating from ground-level or elevated sources. Gaussian models may also be used for predicting the dispersion of non-continuous air pollution plumes (called *puff models*).

A Gaussian model also assumes that one of the seven stability categories, together with wind speed, can be used to represent any atmospheric condition when it comes to calculate concentration.

Gaussian type models are widely used in atmospheric dispersion modelling, in particular for regulatory purposes, and are often nested within Lagrangian and Eulerian models. Gaussian models are based on a Gaussian distribution of the plume in the vertical and horizontal directions under steady state conditions. The normal distribution of the plume is modified at greater distances due to the effects of turbulent reflection from the surface of the earth and at the boundary layer when the mixing height is low. The width of the plume is determined by σ_y and σ_z, which are defined either by stability classes or travel time from the source. One severe limitation of plume models with regards to modelling particle dispersion is that since the plume models use steady state approximations they do not take into account the time required for the pollutant to travel to the receptor. Therefore, aerosol dynamics must be calculated by post-processing treatment of the results [10, 11].

In addition, regional modelling generally requires the incorporation of chemical modelling to accurately predict the formation of particles through secondary organic aerosol (SOA) formation. Even NO_x and SO_x chemistry, which is fundamental to determining particles and ozone concentrations, is often only calculated using a simple exponential decay. More advanced models can simulate some of the chemical transformations using post processing treatment of the chemistry.

Although most Gaussian models only consider diffusion and advection of the pollutants; more advance Gaussian models have recently been developed that include physical processes such as deposition and fast chemical reactions. Furthermore, the Gaussian plume equation assumes that there is no interaction between plumes, which can become significant within urban environments.

Algorithms have been developed to model the chemistry and physical processes within the plume and dispersion around buildings. The effect of wakes from buildings can be achieved by modifying the dispersion coefficients, σ_y and σ_z. However, the Gaussian equation is not able to calculate recirculation effects caused by multiple buildings or at intersections.

Some of the restrictions implicit in the Gaussian Plume models can be overcome by approximating the emission as a series of puffs over time, which allows the wind speed to be varied. In this approach each puff behaves according to the Gaussian dispersion equation and the overall contribution of the source is calculated by integration of the individual puffs with respect to time and summation of the contribution of individual puffs at the receptor position.

In order to calculate the concentration of pollutants over an urban area multiple source plumes are often used. The different equations used are determined by the nature of the source and heights of the source and receptor. Gaussian models has also great limitation because they are not designed to model the dispersion under low wind conditions or at sites close to the source, i.e. distances less than 100 m. Gaussian models have been shown to consistently over predict concentrations in low wind conditions [12,13].

Since Gaussian plume equations assume a homogeneous wind field it is not recommended that they are used for far field modelling as the meteorology is expected to change over such large distances. Caputo et al. (2003) observed that four Gaussian models calculated non-zero concentrations for the whole downwind domain and so suggested that they should be limited to distances a few tens of kilometers from the source [14].

Lagrangian model

A Lagrangian dispersion model mathematically follows pollution plume parcels (also called particles) as the parcels move in the atmosphere and they model the motion of the parcels as a random walk process. Langrangian modelling is often used to cover longer time periods, up to years.

Lagrangian models are similar to box models in that they define a region of air as a box containing an initial concentration of pollutants.

The Lagrangian model then follows the trajectory of the box as it moves downwind. The concentration is a product of a source term and a probability density function as the pollutant moves from *x* to *x'*.

Lagrangian models incorporate changes in concentration due to mean fluid velocity, turbulence of the wind components and molecular diffusion. Lagrangian models work well both for homogeneous and stationary conditions over the flat terrain and for inhomogeneous and unstable media condition for the complex terrain [14].

Box model

Box models are the simplest ones in use. As the name implies, the principle is to identify an area of the ground, usually rectangular, as the lower face of a cuboid which extends upward into the atmosphere. Box models which assume uniform mixing throughout the volume of a three dimensional box which are useful for estimating concentrations, especially for first approximations.

Box models are based on the conservation of mass. The site is treated as a box into which pollutants are emitted and undergo chemical and physical processes. It requires the input of simple meteorology and emissions and the movement of pollutants in and out of the box is allowed. The inside of the box is not defined and the air mass is treated as if it is well mixed and concentrations uniform throughout. One advantage of the box model is to include more detailed chemical reaction schemes (e.g. master chemical mechanism) and used for detail treatment of the aerosol dynamics, that are able to represent the chemistry and physics of particles within the atmosphere better. However, following inputting initial conditions; a box model simulates the formation of pollutants within the box without providing any information on the local concentrations of the pollutants. For this reason they are unsuitable to modelling the particle concentrations within a local environment, where concentrations and thus particle dynamics are highly influenced by local changes to the wind field and emissions [16].

Eulerian model

Eulerian dispersions model is similar to a Lagrangian model in that it also tracks the movement of a large number of pollution plume parcels as they move from their initial location. The most important difference between the two models is that the Eulerian model uses a fixed three-dimensional Cartesian grid.

Dense gas model

Dense gas models simulate the dispersion of dense gas plumes (i.e., pollution plumes that are heavier than air). The most common used dense gas models are: the DEGADIS model developed by Havens and Spicer. The SLAB model developed by Lawrence and the HEGADAS model developed by Shell Oil's research division. Potential air pollution impact is usually estimated through the use of air quality simulation models. A wide variety of models is available. The model requires two types of data inputs: information on the sources including pollutant emission rate, and meteorological data such as wind velocity and turbulence. The dense gas model then simulates mathematically the pollutant’s transport and dispersion, and perhaps it has chemical and physical transformations and removal processes. The model output is the air pollution concentration for a particular time period, usually at specific receptor location [16].

2.5.2. Gaussian Dispersion Model

The Gaussian formulation is one of the most commonly used frameworks for modelling local dispersion of a pollutant. It describes the transport and diffusion of a gas (or particle) from a source to a receptor according to stability class and other parameterized characteristics of the atmosphere. It can be applied to plumes from point, line and area sources. The accuracy of such models depends on stability classification schemes as well as plume rise equations.

There is a program for general plume dispersion model (GPDM) of a point source emission that was developed using Java and Visual basic tools. It has the flexibility of using five kinds of stability classification schemes, i.e., Lapse Rate, Pasquill–Gifford (PG), Turner, σ–θ and Richardson number. It also has the option of using two types of plume rise formulations – Briggs and Holland’s. The model, applicable for both rural and urban roughness conditions, uses meteorological and emission data as its input parameters, and calculates concentrations of pollutant at the center of each cell in a predefined grid area with respect to the given source location.

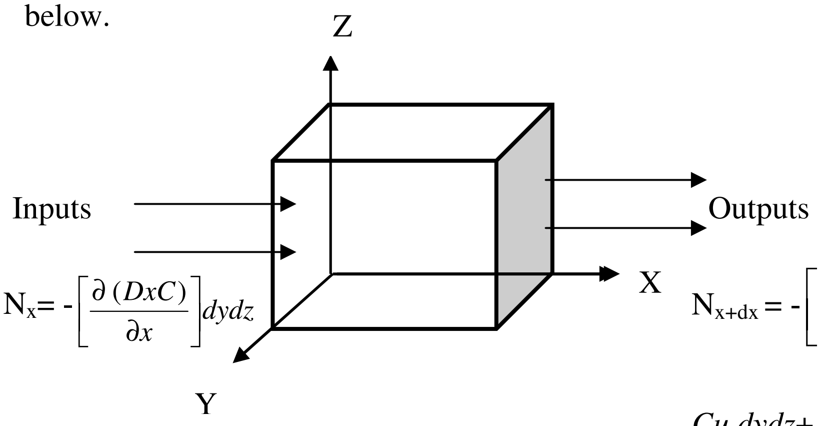
2.5.3. Theory Behind Gaussian Dispersion Model

The dispersion of air pollutants in the atmosphere is governed by the processes of molecular diffusion and convection and is mainly affected by various meteorological conditions such as wind, temperature inversion, foggy atmosphere, etc. and removal processes such as chemical reaction, deposition rain/washout.

A mass balance on the basis of a specific pollutant in control volume is taken in the modeling of basic equation:

According to the principle of conservation of mass:

Accumulation rate (mass/time) =All flow in –All flow out+ Formation rate-destruction rate; and by taking a control volume as in Figure 2.1.,it is possible to derive the basic modeling equation as below.



$$N_x = -\left[\frac{\partial\,(DxC)}{\partial x}\right]dydz$$

$$N_{x+dx} = -\left[\frac{\partial(DxC)}{\partial x}\right]dydz + \frac{\partial}{\partial x}\left[\frac{\partial(DxC)}{\partial x}dydz\right]dx$$

Diffusion Advection (by wind): $Cudydz$

$$Cu\ dydz + \frac{\partial}{\partial x}\left[Cudydz\right]dx$$

Figure 2.1. Pollutant in control volume

Two main transportation mechanisms are involved in the dispersion of air pollutants:

1. Diffusion on molecular basis in all directions (i.e.in x, y and z directions)
2. Transportation by wind in only wind direction (i.e. in x,y,z direction)

In Molecular diffusion,Fick's law is applied

$$Nx = -\left[\frac{\partial(DxC)}{\partial x}\right]A \qquad \text{(Fick's Law)} \qquad (2.1)$$

where

N_x : Mass diffusion flowrate of gas pollutant in x direction (mass/time)

D_x : Diffusivity (turbulent mixing coefficient) in x direction (area/time)

C : Concentration (mass / volume)

A : Cross-sectional area (A=dydz) in the direction of transportation (i.e. x direction)

Accumulation of pollutants $= \frac{\partial}{\partial t} C_i \, dxdydz$ (2.2)

By taking conservation of mass for each direction, similar to the x-direction

$$\frac{\partial}{\partial t} C_i \, dx\,dy\,dz = -\frac{\partial}{\partial x}\left(C_i u\,dy\,dz\right)dx - \frac{\partial}{\partial y}\left(C_i v\,dx\,dz\right)dy - \frac{\partial}{\partial z}\left(C_i w\,dx\,dy\right)dz + \frac{\partial}{\partial x}\left(\frac{\partial\left(D_x C_i\right)}{\partial x}\right)dx\,dy\,dz + \frac{\partial}{\partial y}\left(\frac{\partial\left(D_y C_i\right)}{\partial y}\right)dx\,dy\,dz + \frac{\partial}{\partial z}\left(\frac{\partial\left(D_z C_i\right)}{\partial z}\right)dx\,dy\,dz + \Phi_i\,dx\,dy\,dz \qquad (2.3)$$

where

C_i : concentration of pollutant i, μg/m^3 (i-stands for CO, NO_X,SO_X etc.)

u : mean convective velocity in x-direction (wind velocity), m/s

v : mean convective velocity in y-direction, m/s

w : mean convective velocity in z-direction, m/s

D_x : mass diffusivity in x-direction, m^2/s

D_y : mass diffusivity in y-direction, m^2/s

D_z : mass diffusivity in z-direction, m^2/s

Φ : pollutant removal or accumulation rate, μg/s

Note that: Φ can be expressed in terms of $\Phi = E_i-(K_1i+k_2i)\ C_i + Q(C_i)$

Where C_i is the concentration of the chemical species involved in the model (CO, NOx, particulate matter, SOx, etc.), E_i is the emission sources, K1i and K2i are deposition coefficients (for the dry deposition and the wet deposition, respectively) and Q (C_i) represents chemical reactions.

Dividing both sides by control volume: dxdydz

$$\frac{\partial}{\partial t} C_i = -\frac{\partial}{\partial x}(C_i u) - \frac{\partial}{\partial y}(C_i v) - \frac{\partial}{\partial z}(C_i w) + \frac{\partial}{\partial x}\left(\frac{\partial(D_x C_i)}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\partial(D_y C_i)}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{\partial(D_z C_i)}{\partial z}\right) + \Phi_i \qquad (2.4)$$

Therefore,the basic equation will be:

$$\frac{\partial C_i}{\partial t} = -u\frac{\partial C_i}{\partial x} - v\frac{\partial C_i}{\partial y} - w\frac{\partial C_i}{\partial z} + D_x\frac{\partial^2 C_i}{\partial x^2} + D_y\frac{\partial^2 C_i}{\partial y^2} + D_z\frac{\partial^2 C_i}{\partial z^2} \qquad (2.5)$$

With the continuity principle, the equation can be also given by:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (2.6)$$

Since stack emissions have some initial upward velocity and buoyancy, there is some distance downward, before the plume envelope might begin to look symmetrical about a centerline. The centerline would be somewhat above the center of the actual stack height. The highest concentration of pollutants would be along these centerlines, with lower and lower values as we get further and further away. The Gaussian plume model assumes that the pollutant concentration follows a normal distribution in both the vertical plane and horizontal direction. It also treats emissions as if they came from a virtual point source along the plume centerline, at an effective stack height H. Figure 2.2 shows Gaussian dispersion mechanism in 3-Direction .

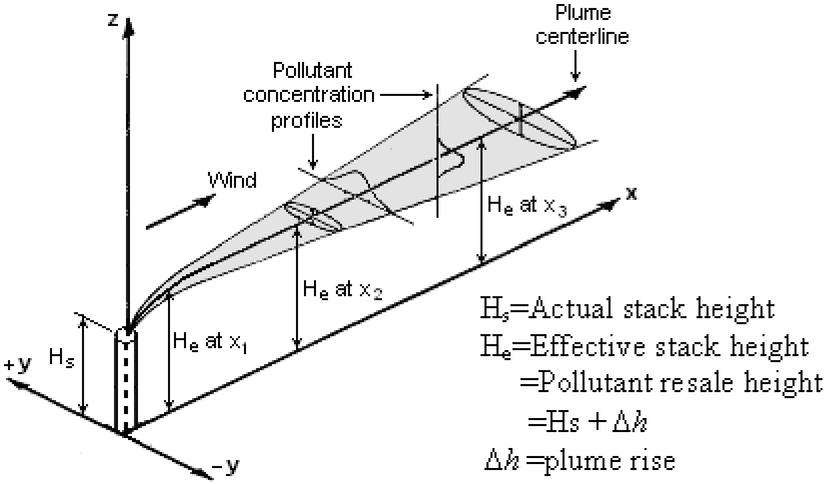


Figure 2.2. Plume dispersion coordinate system, showing Gaussian distributions in the horizontal and vertical directions

The Gaussian point source dispersion equation relates average steady-state pollutant concentrations to the source strength, wind speed, effective stack height, and atmospheric conditions.

In the analysis of the model, there are basic assumptions:

- The rate of emissions from the source is constant. In other words pollutant emission rate (Qi) from the source is constant, $\frac{\partial C_i}{\partial t} = 0$
- The wind speed is constant both in time and with elevation or wind velocity in y and z directions is zero and wind velocity in x direction is constant
- The pollutant is conservative; that is, it is not lost by decay, chemical reactions, or depositon.When it hits the ground, none is absorbed and all it's reflected.
- Advective transportation is dominant over diffusion in x direction, $u\frac{\partial C_i}{\partial x} >> D_x \frac{\partial^2 C_i}{\partial x^2}$.
- Pollutant accumulation or removal is zero or Φ=0

By taking all assumptions expressed above the equation becomes a second order differential equation:

$$\underbrace{u\frac{\partial C_i}{\partial x}}_{convection} = \underbrace{D_y \frac{\partial^2 C_i}{\partial y^2} + D_z \frac{\partial^2 C_i}{\partial z^2}}_{dispersion} \qquad (2.7)$$

Therefore the concentration can be expressed as follows, using mathematical differential equation solving method:

$$C = K x^{-1} \exp\left\{-\left[\left(\frac{y^2}{D_y}\right)+\left(\frac{z^2}{D_z}\right)\right]\frac{u}{4x}\right\} \qquad (2.8)$$

where K- is an indefinite integral constant; to find the constant K, we need to determine the integration limits depending upon the dispersion geometry. In the plume: we have

$$Q = \int\int u C dy dz \qquad (2.9)$$

Integration the above equation for ground source from y: -infinity (-∞) to +infinity (+∞); and z: 0 to +infinity (+∞):

$$Q = \int_0^{+\infty}\int_{-\infty}^{+\infty} K u x^{-1} \exp\left\{-\left[\left(\frac{y^2}{D_y}\right)+\left(\frac{z^2}{D_z}\right)\right]\frac{u}{4x}\right\} dy\, dz \qquad (2.10)$$

Which result:

$$Q = K u x^{-1} (D_y)^{1/2} (D_z)^{1/2} \left(\frac{\pi x}{u}\right)^{1/2} \left[2\left(\frac{\pi x}{u}\right)^{1/2}\right] = 2\pi K (D_x)^{1/2} (D_y)^{1/2} \qquad (2.11)$$

Where K is: $$K = \frac{Q}{2\pi (D_y)^{1/2} (D_z)^{1/2}}$$

By substituting all the above equations into equation (2.8):

$$C(x,y,z) = \frac{Q}{2\pi x (D_y)^{1/2} (D_z)^{1/2}} \exp\left\{-\left[\left(\frac{y^2}{D_y}\right)+\left(\frac{z^2}{D_z}\right)\right]\frac{u}{4x}\right\} \qquad (2.12)$$

By definition; we have the following relations between diffusion and dispersion coefficients:

$$\sigma_y^2 = \frac{2 D_y\, x}{u} \qquad \sigma_z^2 = \frac{2 D_z\, x}{u}$$

By inserting this equation in the above equation; we have Gaussian Dispersion Equation for ground level source:

$$C(x, z, y) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left\{-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right)\right\} \qquad (2.13)$$

As there is no point source elevation, there is duplication plume (lower part reflected from the ground).Therefore the equation is expressed as follows:

$$C(x, z, y, 0) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left\{-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2}\right)\right\} \qquad (2.14)$$

Similarly for elevated source of emission that are emitted from stack:

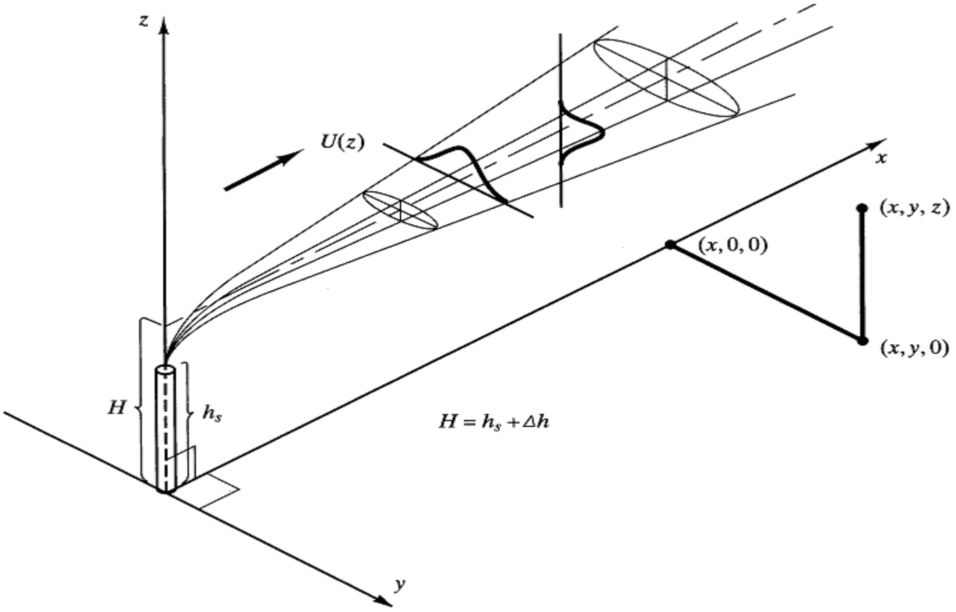


Figure 2.3. Plume dispersion coordinate system, showing Gaussian distributions in the horizontal and vertical directions (Turner, 1970).

$$C(x, y, z, H) = \frac{Q}{2\pi u\, \sigma_y\, \sigma_z} \exp\left(-\frac{y^2}{2\,\sigma_y^2}\right) \exp\left(-\frac{(z-H)^2}{2\,\sigma_z^2}\right) \qquad (2.15)$$

But for the ground reflection of the source the equation will be modified as:

$$C(x, y, z, H) = \frac{Q}{2\pi u\, \sigma_y\, \sigma_z} \exp\left(-\frac{y^2}{2\,\sigma_y^2}\right) \left\{\exp\left(-\frac{(z-H)^2}{2\,\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\,\sigma_z^2}\right)\right\} \qquad (2.16)$$

In general, the Gaussian dispersion model can be expressed as follows:

$$\mathrm{C(x,y,z,H)} = \frac{\mathrm{Q}}{2\pi \mathrm{u}\ \sigma_\mathrm{y}\ \sigma_\mathrm{z}} \exp\left(-\frac{\mathrm{y}^2}{2\ \sigma_\mathrm{y}^2}\right)\left\{\exp\left(-\frac{(\mathrm{z}-\mathrm{H})^2}{2\ \sigma_\mathrm{z}^2}\right)+\exp\left(-\frac{(\mathrm{z}+\mathrm{H})^2}{2\ \sigma_\mathrm{z}^2}\right)\right\} \qquad (2.17)$$

Where

$C(X, Y, Z, H)$ – position of receptor and source

$\frac{Q}{2\pi u\ \sigma_y\ \sigma_z}$ - Plume dispersion in the centerline

$\exp\left(-\frac{y^2}{2\,\sigma_y^2}\right)$ - Plume dispersion in y direction

$\exp\left(-\frac{(z-H)^2}{2\,\sigma_z^2}\right)$ - Plume dispersion in the z direction

$\exp\left(-\frac{(z+H)^2}{2\,\sigma_z^2}\right)$ -Effect of ground reflection in the z direction

In short, to use the Gaussian plume dispersion model the following basic steps should be identified:

1. Need to know proper orientations of both Source and Receptor: Source at (0,0,H) and Receptor at (x,y,z) that implies C(x,y,z;H).
2. Pollutant emission rate from source: Q (mass of pollutant/time); which is not volume flow rate of stack gas.
3. Atmospheric stability category (A, B, C. etc.).
4. Wind velocity at stack height: u.
5. Dispersion coefficients: σ_y and σ_z.
6. Effective stack height: $H = h_s + \Delta h$ implies calculation of Plume rise (Δh).
7. Finally, then use the general Gaussian dispersion model (GDM) to show C(x, y, z, H) variation (eq.2.17).So, by taking different inputs like dispersion coefficient, mass of pollutant per time, coordinates of the location of the stack height, it is possible to determine the concentration at different locations.

The above general Gaussian dispersion model equation (2.17) can be modified in to different cases based on variation of receptors and plume orientation.

For receptors at ground level=0, the above equation reduces to:

$$C(x,y,0;H) = \frac{Q}{\pi u\ \sigma_y\ \sigma_z} \exp\left(-\frac{y^2}{2\,\sigma_y^2}\right)\exp\left(-\frac{H^2}{2\,\sigma_z^2}\right) \qquad (2.18)$$

In order to make concentration estimates directly beneath the plume center line, y=0, at ground level=0, the equation further reduces:

$$C(x,0,0;H) = \frac{Q}{\Pi u \sigma_y \sigma_z}\left(\exp\frac{-H^2}{2\sigma_z{}^2}\right) \qquad (2.19)$$

To calculate concentration at the plume centerline, y=0, z=H, the general equation becomes:

$$C(x,0,H;H) = \frac{Q}{2\pi u\ \sigma_y\ \sigma_z}\left\{1+\exp\left(-\frac{H^2}{2\ \sigma_z^2}\right)\right\} \qquad (2.20)$$

To calculate concentration at the plume centerline at ground level from a ground level release, y=0, z=0, H=0, the general equation becomes:

$$C(x,0,0;0) = \frac{Q}{\Pi u \sigma_y \sigma_z} \qquad (2.21)$$

Downwind concentration under a temperature inversion

The Gaussian plume equation, as presented thus far, applies to an atmosphere where the temperature profile is a simple straight line. If, as is often the case, there is an inversion above the effective stack, then the basic Gaussian equation must be modified to account for the fact that the vertical dispersion of pollutants is limited by inversion.

If the pollutants are assumed to reflect off the inversion layer, just as they were assumed to reflect off the ground in the basic Gaussian equation, then an estimate of the concentration at any point downward would require an analysis of these multiple reflections.

The complexity can be avoided if we are willing to restrict our prediction of plume concentration to distance far enough downwind that the summation of these multiple reflections converges into a closed form solution. Beyond that distance, the air is considered to be completely mixed under the inversion, with uniform concentrations from ground level to the bottom of the inversion layer.

Turner suggests the following modified Gaussian equation to estimate concentration downwind under an inversion.

It is derived based on the assumption that the downward distance from the source is at least twice the distance to where the plume first interacts with the inversion layer.

$$C(x,y)=\frac{Q}{(2\Pi)^{1/2}u\sigma_y L}\left(\exp\frac{-y^2}{2\sigma_y{}^2}\right) \quad ; \quad for\ x \geq 2X_L \tag{2.22}$$

where

L=elevation of the bottom of the inversion layer (m)

X_L=the distance downward where the plume first encounters the inversion layer

Equation (2.22) is applicable only for distance $x \geq 2X_L$.That distance, X_L, occurs at the point where the vertical dispersion coefficient, σ_z is equal to

$$\sigma_z = 0.47(L-H) \quad \{at\ x=X_L\} \tag{2.23}$$

Once σ_z is found from equation (2.23), the distance X_L can be estimated using Eq.2.57 and Table 2.10. For $x<X_l$, the standard Gaussian plume equation can be used to estimate down ward concentrations. For distance between X_L and $2X_L$, concentrations can be estimated by interpolating between the values computed for $x= X_L$ and $x=2X_L$ [7].

2.6. Metrology and Dispersion

The main meteorological factors that affect dispersion are wind direction, wind speed and atmospheric turbulence (which is closely linked with the concept of stability).

2.6.1. Wind Direction

Wind direction is conventionally specified as the direction from which the wind is blowing, because we have been more interested in what the wind has collected before it reaches us than in where it will go afterwards. Wind direction is commonly identified with one of 16 (or sometimes 32) points of the compass (e.g. a south-westerly wind is a wind blowing from the south-west),or more scientifically as an angle in degrees clockwise from north (so the south-west wind will be blowing from between 213.75° and 236.25°). What is spoken of colloquially as the wind direction is rarely constant in either the short or long term. The average value over periods of between one and a few hours is determined by meteorology for example, the passage of a frontal system, or the diurnal cycle of sea breezes near a coast. This medium-term average value of wind direction is of fundamental importance in determining the area of ground that can be exposed to the emission from a particular source. Short-term variations (between seconds and minutes), due to turbulence, are superimposed on this medium-term average that can be seen on a flag or wind-vane. As there are short-term horizontal variations, there are also short-term variations in the vertical component of the wind that affect turbulent dispersion. The magnitudes of both horizontal and vertical variations are influenced by the atmospheric stability, which in turn depends on the balance between the adiabatic lapse rate and the environmental lapse rate. The effects of wind direction also determine the direction of transport of released pollutants. For example, west wind would cause pollution to move toward the east from the source [17, 18 &19].

2.6.2. Wind Speed

Wind speed is measured in ms^{-1} or knots (one knot is one nautical mile per hour; one nautical mile is 6080 feet, or 1.15 statute miles). Although the use of SI units is encouraged in all scientific work, some professions have stuck with earlier systems. Thus mariners, pilots and meteorologists are all comfortable with knots. Mariners also use the Beaufort scale, which relates wind speed to its effects on the sea.

Wind speed is important for atmospheric dispersion in three distinct ways. First, any emission is diluted by a factor proportional to the wind speed past the source. Second, mechanical turbulence, which increases mixing and dilution, is created by the wind. Third, a buoyant source (hot or cold) is bent over more at higher wind speeds, keeping it closer to its release height. Friction with the ground reduces the wind speed near the surface, so that the speed at the top of an industrial chimney (such as that of a power station, which might be 200 m tall) will be substantially greater than at the bottom. The change with height can be approximated by a power law such as:

$$U(z) = u_0 (z/z_0)^p \qquad (2.24)$$

Where $u(z)$ is the wind speed at height z, u_0 is the wind speed measured by an anemometer at height z_0, p is an exponent that varies with atmospheric stability. Table 2.1 gives the values of the exponent p appropriate to the Pasquill stability categories. This supports the intuitive idea that the best-mixed air (Class A) has the smallest variation of speed with height.

Table 2.1. Variation of the wind speed exponent p with stability category

Pasquill Stability class	Description	Exponent *p* for rough terrain	Exponent *p* for smooth terrain
A	Very unstable	0.15	0.07
B	Moderately unstable	0.15	0.07
C	Slightly unstable	0.2	0.1
D	Neutral	0.25	0.15
E	Slightly	0.4	0.35
F	Most Stable	0.6	0.55

2.6.3. Effect of Surface Roughness

The objects on the surface (roughness elements) over which the wind is flowing has a frictional effect upon the wind speed nearest the surface. This effect is depicted in Annex-1 for three different surfaces. The numbers given at various heights are the wind speed at that height relative to the gradient wind, in percent. The gradients wind occurs at the height above the surface where the effects on the surface are no longer felt. It can be considered as the free stream flow and is in response to the pressure and temperature gradients. Both the height and the spacing of the roughness elements on the surface will influence the frictional effect on the wind. A single parameter, the surface roughness length, Z_0, is used to signify this effect. Typical values are given in Table 2.2.

Table 2.2.Surface roughness length, Zo, for typical surface,m.

Surface type	Z_o ,value
Urban	1.0-3.0
Coniferous Forest	1.3
Deciduous Forest (summer)	1.3
Deciduous Forest (Winter)	0.5
Desert shrub land	0.3
Swamp	0.2
Cultivated land(summer)	0.2
Cultivated land(winter)	0.01
Grassland(summer)	0.1
Grassland(winter)	0.001
Water	0.0001

In surface roughness and friction velocity (u*), it is convenient to introduce a drag coefficient, C_g, based on the geostrophic wind, u_g, such that

$$u^*=C_g u_g \qquad (2.25)$$

The geostrophic drag coefficient is a function of the surface Rossby Number ($R_0 = u_g/fZ_0$) and L (Monion-Obukhov length), where f is the Coriolis parameter of the earth and Z_0 is surface roughness.

Lettau [19] suggests the following empirical relationship for a neutral atmosphere:

$$C_g = \frac{0.16}{\log_{10}(R_o) - 1.8} \tag{2.26}$$

For stable and unstable atmosphere it must be multiplied by 0.6 and 1.2, respectively.

The friction velocity can be also determined by the following equation:

$$u^* = AU_{10} \tag{2.27}$$

In which A is the function of the roughness height (z_0) and U_{10} is the wind speed measured at the height of 10 meters (i.e. $A = k/\ln(z/z_0)$, where $k = 0.4$).

2.6.4. Atmospheric Stability

2.6.4.1. Dry adiabatic lapse rate

Atmospheric pressure decreases exponentially with height. Hence, as an air parcel moves up (or down) in the atmosphere, it must expand (or compress) and cool (or warm). For a dry atmosphere (containing water vapour, but not liquid water droplets) the rate of decrease of temperature with height caused by type of displacement called dry adiabatic lapse rate (Γ, or DALR). Adiabatic simply means that the air parcel's total energy content is conserved during the displacement, not exchanged with the surrounding air.

In a neutral atmosphere, i.e. when the atmosphere is in a state in which adiabatic air parcels are in equilibrium with their surrounding during their vertical movement, the temperature profile $T(z)$ can be calculated as follows. For an air parcel of mass m moving infinitesimally in the atmosphere, the change in its internal energy dU can be obtained from the first law of thermodynamics as:

$$dU = dQ + dW \tag{2.28}$$

where dQ is the heat transferred to the air parcel from its surrounding and dW is the work done on the system.

But, $$dW = -pdV \tag{2.29}$$

Where p is the system pressure and dV is the change in its volume.

For an adiabatic system dQ =0 and dU can be also written as:

$$dU = mc_v dT \tag{2.30}$$

where C_v is the specific heat capacity of air at constant volume and dT is the temperature difference. Thus, for the adiabatic air parcel the first law of thermodynamics gives:

$$mc_v dT = -pdV \tag{2.31}$$

Replacing dV using the ideal gas law $pV = mRT/M_{air}$ we can re-write Eq. (2.31) as:

$$mc_v dT = \frac{mRT}{M_{air}} \frac{dp}{p} - \frac{mR}{M_{air}} dT \tag{2.32}$$

Re-arranging and dividing both sides by dz we get:

$$\left(mc_v + \frac{mR}{M_{air}} \right) \frac{dT}{dz} = \frac{mRT}{pM_{air}} \frac{dp}{dz} \tag{2.33}$$

Substituting $\frac{dp}{dz} = \frac{-M_{air} gp(z)}{RT(z)}$ in equation (2.33) we finally get:

$$\frac{dT}{dz} = \frac{-g}{c_v + \frac{R}{M_{air}}} \tag{2.34}$$

$$c_v + \frac{R}{M_{air}} = c_p$$

Therefore, the value of $\frac{dT}{dz}(or\Gamma)$ is fixed by physical constants, and can be calculated from:

$$\Gamma = \frac{g}{c_p} \tag{2.35}$$

where g is the acceleration due to gravity = 9.81 m s^{-2} and c_p is the specific heat of air at constant pressure = 1010 J kg^{-1} K^{-1}. Hence Γ = 9.8°C km^{-1}. This value applies to sufficient accuracy in the lower 20 km of the atmosphere. Above that height, changes in the molecular composition (which affect the molar mass) and in g (due to increasing distance from the centre of the Earth) start to affect the value. This is the reason for the steady decrease in temperature with height – up mountains [20].

2.6.4.2. Saturated adiabatic lapse rate

If the air temperature falls below the water vapour dew point while the parcel is being lifted, then the excess water vapour will start to condense. This will release latent heat of vaporization which will reduce the rate of cooling. Conversely, if a descending parcel contains liquid water droplets, then the process is reversed – the droplets evaporate as the parcel warms, extracting sensible heat from the air and reducing the rate of warming. The variation of temperature with height when there is liquid water present is known as the saturated adiabatic lapse rate (SALR), or Γ_{sat}, which is calculated as follows:

For SALR we can write Eq. (2.35) as $\Gamma_{sat} = g/c_p'$.

where c_p' is the heat capacity of a mixture of air and water vapour. If the ratio of the mass of water vapor to the mass of dry air in the air parcels (also known as saturation mixing ratio) is q_s then:

$$c_p' = (1 - q_s)c_p + q_s c_{p(\text{water vapour})} \qquad (2.36)$$

If m_w is the mass of water vapour in the air parcel and L is the latent heat of evaporation of water per gram, then the heat released for the infinitesimal motion of the air parcel is $-Ldm_w$. Therefore, the air parcel energy balance (Eq. (2.31)) can be re-written as:

$$mc_v dT = -pdV - Ldm_w \qquad (2.37)$$

Table 2.3. Variation of saturated lapse rate (^{0}C km^{-1}) with temperature and pressure

	Temperature/^{o}C				
Pressure/mb	-40	-20	0	20	40
1000	9.5	8.6	6.4	4.3	3.0
800	9.4	8.3	6.0	3.9	
600	9.3	7.9	5.4		
400	9.1	7.3			
200	8.6				

We can still apply the ideal gas law since despite the air parcel being saturated even if the thermodynamic properties of the gas phase remain the same as for air. This gives:

$$mc_v dT = \frac{mRT}{M_{air}}\frac{dp}{p} - \frac{mR}{M_{air}}dT - Ldm_w \qquad (2.38)$$

On dividing both sides by air parcel mass and substituting C_v and C_p we have:

$$C_p dT = \frac{RT}{M_{air}}\frac{dp}{p} - L\frac{dm_w}{m} \tag{2.39}$$

But m_w/m is same as q_s. So, dividing the entire expression by dz and substituting $\frac{dp}{dz} = \frac{-M_{air}gp(z)}{RT(z)}$ in Eq. (2.39) we finally get:

$$\Gamma_{sat} = \frac{dT}{dz} = \frac{-g}{c_p}\left\{\frac{1}{1+\left(\frac{L}{c_p}\right)\left(\frac{dq_s}{dT}\right)}\right\} \tag{2.40}$$

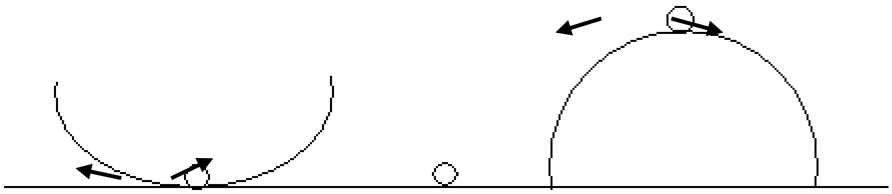
Since the saturated vapor pressure of water depends on both the temperature and pressure, the SALR is also variable (Table 2. 3.). The minimum values are found for surface pressures and the warmest temperatures. Since the air also has to be saturated, this is more likely to be in the tropics than above the Sahara. Maximum values are found where the air is very cold, because then the water vapor content is low. The average lapse rate over the Earth is about 6.5°C km^{-1}.

2.6.4.3. Atmospheric Stability and Temperature Profile

The adiabatic lapse rates describe the temperature changes expected in a parcel of air when it is displaced vertically. This is not usually the same as the vertical temperature profile of the air, as would be measured, for example, by recording the temperature transmitted by a sounding balloon as it rose through the atmosphere. This environmental lapse rate (ELR) is the vertical variation, or profile, of air temperature with height that exists at any particular time and place. It may be equal to the adiabatic lapse rate over at least part of the height range of interest (up to, say, 1 km for pollutant dispersion), but it may be substantially different.

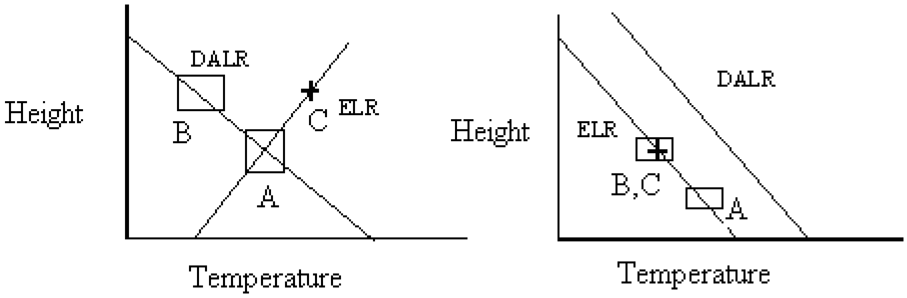
The local balance between the two lapse rates gives an insight into the concept known as stability. First, consider the different physical situations shown in Figure 2.4. In Figure 2.4(a), a marble is at rest in a bowl. Any small displacement of the marble results in a restoring force – a force that moves the marble back towards its initial position. Such a system is said to be stable. In Figure 2.4 (b), the marble is on a flat surface. No force in any direction is generated by a displacement and the system is described as neutral.

Finally, in Figure 2.4 (c), the marble is poised on the top of the upturned bowl. Now any displacement results in a force away from the initial position, and the system is unstable.

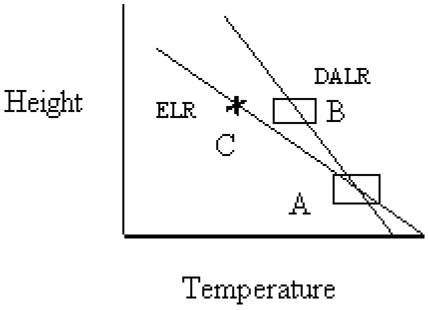


a). Stable b) Neutral c) Unstable

Figure 2.4. Stable, neutral and unstable systems.



a).Stable b).Neutral



c). Unstable

Figure 2.5. (a). Stable ;(b). neutral; and (c).unstable environmental lapse rates (ELRs).

These ideas can be applied to air parcels in the atmosphere. Consider, for example, the different situations shown in Figure 2.5(a to c). In each Figure, the prevailing ELR is shown, and the DALR is given for comparison. A parcel of air that starts at A in Figure 2.5(a) and moves upward will cool at the DALR, reaching a lower temperature at B. However, the air around the parcel at the same height will be at C on the ELR. The parcel has become cooler and denser than its surroundings and will tend to sink back towards its starting height. If its initial displacement is downward, it will become warmer and less dense than its surroundings and tend to rise back up.

The ELR is therefore stable, because small disturbances are damped out. In Figure 2.5 (b), a rising parcel will again cool at the DALR. Since this is equal to the ELR, the parcel will be in air of the same temperature and density after displacement. The ELR is therefore neutral, because vertical motions are neither accelerated nor damped. Examination of vertical displacements for Figure 2.5(c) shows that they are accelerated, and that such an ELR is unstable.

If we look at the forces acting on a parcel displaced upwards in a stable atmosphere, an equation of motion can be written for which the solution is an oscillation about the starting height. That is, the parcel experiences a restoring force that accelerates it back towards its original position. Since by then it is moving, it overshoots downwards, and a restoring force accelerates it upwards again, and so on. The frequency of this oscillation, which is called the buoyancy frequency, corresponds to a natural period of a few minutes in the lower atmosphere.

In practice, real temperature profiles in the atmosphere often consist of a mixture of different ELRs, so that vertical dispersion will be different at different heights. Consider the ELR shown in Figure 2.6. Between A and B, strong solar heating of the ground has warmed the lowest layers of air; the middle layer BC is close to DALR, while the layer CD is showing an increase of temperature with height (this is known as an inversion of the temperature profile).

This profile will be very unstable (strong dispersion) in AB, close to neutral in BC and very stable (poor dispersion) in CD. When a persistent anti-cyclonic high pressure region is present, there is often an area in the centre where high-level air is sinking.

The sinking raises the pressure and hence the temperature, generating an elevated inversion which may act as a lid to vertical plume dispersion and increase ground-level pollutant concentrations. Since the pressure gradients and hence wind speeds are low under these meteorological conditions, a serious pollutant episode may result.

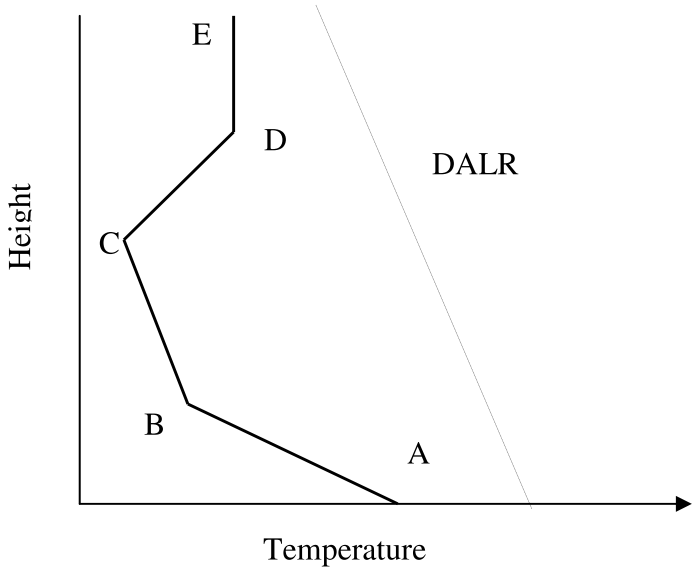


Figure 2.6. An atmospheric temperature profile involving a range of stabilities.

We saw in section 2.6.4.2 that the lapse rate for saturated air is lower than for dry air. Hence the same air mass may be stable or unstable, depending on whether it is saturated or not. As an unsaturated air parcel starts to rise, it will cool at the dry lapse rate of 9.8°C km^{-1}. If the ELR is, say 8°C km^{-1}, then the movement is stable. But if the upward movement cools the air enough to cause condensation of water vapour, then the lapse rate will fall to the saturated value of, say 7°C km^{-1}, and the displacement is now unstable. This is called conditional instability. The condition is not rare since the average global lapse rate of 6.5°C falls between the dry adiabatic rate and the average moist lapse rate of 6°C, conditional instability is the norm. Furthermore, a humidity gradient can change the stability. This is most often seen in the warm atmosphere near the surface above the tropical ocean. The sea surface evaporates water into the atmosphere. Hence, the density is reduced (because the molar mass of water is 18 compared with an average of 29 for the nitrogen, oxygen and argon), so the air density decreases and instability is promoted [20].

2.6.4.4. Potential Temperature

The DALR shows a steady reduction of temperature with height, and it is not obvious at first glance whether a particular rate of reduction is greater than or less than the DALR. This divergence is important for the assessment of atmospheric stability and pollutant dispersion, as we have seen. We can define the potential temperature of an air parcel at any pressure (i.e. height) as the temperature that it would have if the parcel were moved adiabatically to a standard or reference pressure. This reference pressure is normally taken to be 100 kPa, which is very close to the standard global average atmospheric pressure at sea level of 101.325 kPa. The potential temperature, then, is the temperature that the parcel would have if it was moved down to sea level adiabatically. If an air parcel is in equilibrium with its surroundings at temperature T and pressure p, then θ□ can be calculated by integrating Eq. (2.32) from initial conditions (T, p) to the final state (θ, p_0). This yield:

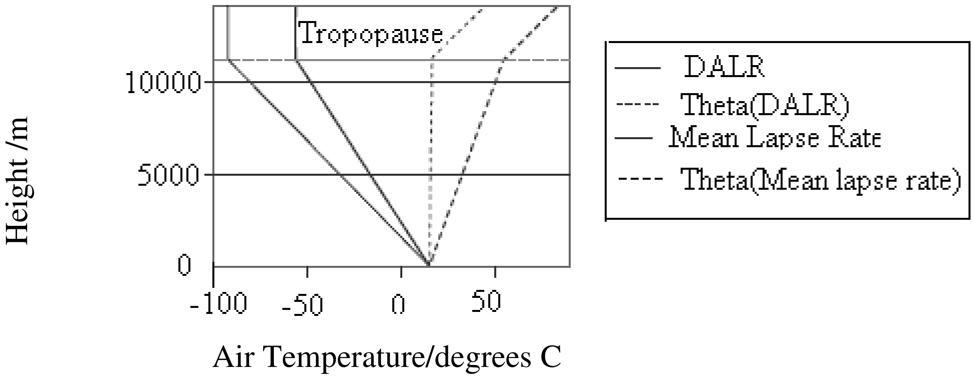


Figure 2.7. Actual and potential tempartuer profiles

$$\theta = T\left(\frac{p_0}{p}\right)^{\frac{R}{c_p M_w}} \qquad (2.41)$$

By definition, θ is constant for an air parcel that is moved upwards adiabatically from sea level.

An actual temperature profile such as that in Figure 2.7 is transformed into a potential temperature profile, where layers having neutral stability are vertical; in stable atmospheres θ increases with height, while in unstable atmosphere it decreases with height. This can be explained mathematically by differentiating Eq. (2.41) with respect to z, which yields:

$$\frac{1}{\theta}\frac{d\theta}{dz}=\frac{1}{T}\frac{dT}{dz}-\frac{Rdp}{c_p M_{air} p}\frac{dp}{dz} \tag{2.42}$$

Substituting $\frac{dp}{dz}=\frac{-M_{air}\,gp(z)}{RT(z)}$ and then $g/C_P=\Gamma$ we get:

$$\frac{1}{\theta}\frac{d\theta}{dz}=\frac{1}{T}\left(\frac{dT}{dz}+\Gamma\right) \tag{2.43}$$

But in a neutral atmosphere $dT/dZ = -\Gamma$ so, $d\theta/dz=0$ from Eq. (2.43). Thus, in a neutral atmosphere $\theta=T_0$ (i.e. constant).

2.6.4.5. Pasquill Stability Classes

The general effect of environmental variables on stability can be summarised as follows:

- On cloud-free days, solar radiation will warm the ground during the day, making the lowest air layers unstable.
- On cloud-free nights, net upwards long wave thermal radiation cools the ground, making the lowest air layers stable, and creating a ground-level inversion.
- As wind speed rises, vigorous vertical exchange tends to generate a neutral ELR equal to the DALR.
- As cloud cover increases, daytime heating and night time cooling of the ground are both reduced, again making the ELR closer to the DALR.
- A persistent high pressure region has a downward air movement at the centre, which often creates an elevated inversion and traps pollutants near the ground. This is known as ‘anti-cyclonic gloom’.

The influence of solar radiation and wind speed on stability led Pasquill to identify stability classes on a scale from A (very unstable) to G (very stable), and to relate them to the meteorology in the simple way shown in Table 2. 4.

Table 2.4. Dependence of stability on meteorological parameters

Surface wind speed ,ms^{-1}	Day time sun(flux density in Wm^{-2})			Nighttime(cloud amount in oktas)		
	strong(>590)	Moderate (300-590)	weak(<290)	8	4-7	0-3
<2	A	A-B	B	D	G	G
2-3	A-B	B	C	D	E	F
3-5	B	B-C	C	D	D	E
5-6	C	C-D	D	D	D	D
>6	C	D	D	D	D	D

First, look at the stability classes during the daytime. When the sun is strong and the wind is light, we would expect maximum ground heating, raising the temperature of the lowest layers of air and creating unstable conditions. With less sunshine, this effect is reduced and the instability is less marked. As the wind speed increases, vertical mechanical mixing starts to override the buoyancy effects and frequent exchanges of air parcels at DALR generate a neutral ELR (class D). At night, net radiation losses and ground cooling are most marked under clear skies. As the ground cools, the lowest air layers become stable (class G). The cloudier or the windier it becomes, the more probable class D becomes again.

2.6.4.6. Other Stability Estimators

The Pasquill scheme described in section 2.6.2 is semi-quantitative, in that it ascribes categories to ranges of the driving variables wind speed and solar radiation, but does not involve a formula with explicit values. There are two more quantitative parameters in common use– the Richardson Number and the Monin–Obukhov length.

The Richardson number

The Richardson number R_i is calculated from gradients of temperature and wind speed:

$$Ri=\frac{\frac{g}{T}\frac{\partial T}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2} \qquad (2.44)$$

where *T* is the absolute temperature.

The Richardson number is dimensionless. We can see by inspection that if temperature increases strongly with height, which is the stable condition that was discussed in section 2.6.4.3, then R_i will tend to be large and positive. If T decreases with height at the adiabatic lapse rate, R_i will be negative. If there is a large gradient of wind speed with height, R_i will be small.

Table 2.5. Stability as a function of Richardson number,R_i

$R_i < -1$	Free convection
$-1 < R_i < -0.01$	Unstable mixed convection
$-0.01 < R_i < +0.01$	Forced convection
$+0.01 < R_i < +0.1$	Damped forced convection
$R_i > 0.1$	Increasingly stable

The Richardson number is mainly used by meteorologists to describe events in the free atmosphere, rather than by air pollution scientists discussing dispersion closer to the ground.

The Monin–Obukhov Length

The Monin–Obukhov Length, *L* is a function of heat and momentum fluxes:

$$L=-\frac{\rho C_P T U^{*3}}{kgC} \qquad (2.45)$$

where, u* is the friction velocity is the absolute temperature (air temperature), k is Karman's constant (k=0.4), g is the gravitational constant, C_p is the specific heat of air and C is the vertical sensible heat flux (the net heat that enters the atmosphere). C value for a neutral atmosphere is 0, for a stable atmosphere is -42 and for an unstable atmosphere is 175 [21].

L is negative since it is inversely proportional to *T*. The formula for *L* recognises the two contrasting processes that drive atmospheric turbulence and dispersion.

Mechanical turbulence is generated by wind blowing over surface roughness elements. It is therefore strongest at the surface, and reduces upward depending on the stability. Convective turbulence is generated by heat flux from the surface, and will increase upwards in unstable conditions but be damped out in stable conditions (Table 2.5). The result has units of meters, and represents the scale of the turbulence. Since *C* may be positive (up) or negative (down), *L* may be positive or negative. When conditions are unstable or convective, *L* is negative, and the magnitude indicates the height above which convective turbulence outweighs mechanical turbulence.

Table 2.6.Stability as a function of *L* and h

Stability	Range of h/L
Stable	$h/L \geq 1$
Netural	$-0.3 \leq h/L < 1$
Convective(unstable)	$h/L < -0.3$

When conditions are stable,*L* is positive, and indicates the height above which vertical turbulence is inhibited by stable stratification. In practice, values range between infinity (in neutral conditions when *C* is zero) and –100 m. Atmospheric stability is related to the ratio *h*/*L*, where *h* is the depth of the boundary layer. *L* is increasingly being used in dispersion models as a more sophisticated estimator of turbulence than the Pasquill category.

For practical use in the lowest few hundred metres of the atmosphere, we can write:

$$L = \left(\frac{\rho c_p T}{kg} \right) \frac{u^{*3}}{c} = const. \frac{u^{*3}}{c} \qquad (2.46)$$

Note that although this expression does not look like a length at first sight, the dimensions do confirm that it is, i.e. (kg m^{-3})(J kg^{-1} K^{-1})(K)(m s^{-1})3/(m s^{-2})(W m^{-2}) has dimensions of length and units of metres.

The values of ρ, c_p, T, k and g are then taken as constant,

$\rho = 1.2$ kg m^{-3}

$C_p = 1010$ J kg^{-1} K^{-1}

$T = 288$K (15°C)

$k = 0.41$

$g = 9.81$ m s^{-2} , then the equation will be:

$$L = 8.7 \times 104\, u_*^3/C \qquad (2.47)$$

Other stability estimators have been used, such as the standard deviation of the fluctuations in the horizontal wind direction and the ratio of the wind speeds at two heights. Comparisons of the predictions made by different estimators from the same data set have shown that the Monin–Obukhov length method correlates best with the Pasquill classes.

Boundary layer height

The Monin-Obukhov formulation can also be used to estimate the height of the boundary layer in stable-to-neutral conditions, from:

$$\frac{h}{L}=\frac{03.u_{*}/\left|f\right|L}{1+1.9h/L} \qquad (2.48)$$

Table 2. 7. Relationship between stability estimators

winds u/ms^{-1}	Pasquill category	Boundary layer height h/m	Monin-Obukhov Length/m	h/L
1	A	1300	-2	-650
2	B	900	-10	-90
5	C	850	-100	-8.5
5	D	800	∞	0
3	E	400	100	4
2	F	100	20	5
1	G	100	5	20

The situation in unstable conditions is more complex, because the boundary layer grows from and initial value of zero when the surface heat flux becomes positive, at a rate governed by the surface heat flux, the temperature jump across the top of the layer, and the friction velocity (Table 2.7.)

2.6.4.7. Plume rise

The difference between the actual height h and the effective height H is called the plume rise Δh. When the air contaminants are emitted from a stack, they rise above the stack before drifting a significant distance downwind. The effective stack height H is not only the physical stack's height h_s but include also the plume rise (Figure 1.1).

$$H = h_s + \delta h \qquad (2.49)$$

Plume rise is caused by a combination of factors; the most important ones are buoyancy, momentum of the exhaust gases and stability of the atmosphere itself. Buoyancy results when exhaust gases are hotter than the ambient air, or when the molecular weight of the exhaust is lower than that of air (or a combination of both factors).Momentum is caused by the mass and velocity of the gases as they leave the stack.

Hence the effective plume height is likely to be different (usually, greater) than the physical height of the chimney. The dispersion equation shows that concentration is a function of the square of the release height, and hence much research has been done into the dependence of plume rise on other factors.

In principle it is possible to solve the conservation equations for mass, momentum, enthalpy and amount of emitted material, and hence predict the trajectory of the plume and the rate of entrainment into the surrounding air. A simplified, more empirical method has often been used which is less mathematically and computationally intensive, although increased computing power is making full solution more practical.

Unfortunately, a number of techniques have been proposed in the literature for dealing with plume rise, and they tend to yield very different results but Brigg's equation and Holland's equation are the widely used for the prediction of plume rise.

The general Brigg's and Holland's equations are given by Eq. (2.50) and (2.51), respectively.

$$\delta h = \frac{4CF\frac{1}{3}}{u} \quad , F = \frac{v_s g D^2 (T_s - T_a)}{4T_a}, \quad C = 1.58 - 41.4\frac{\Delta\theta}{\Delta z} \tag{2.50}$$

$$\delta h = \frac{v_s D}{u}\left(1.5 + 2.68 \times 10 - 3PD\frac{(T_s - T_a)}{T_s}\right) \tag{2.51}$$

where v_s is stack exit velocity (m/s), D is stack diameter (m), u is wind velocity (m/s) measured or calculated at the height, h_s, P is pressure (mbar), T_s is stack gas temperature (K), T_a is atmospheric temperature (K) and $\frac{\Delta\theta}{\Delta\theta_z}$ is the potential temperature difference(K /m).

Although plume rise depends on both momentum and buoyancy, we will assume that the exhaust gases have molecular weight close enough to that of air (taken to be 28.9 g/mol) that we can neglect the buoyancy due to density differences.

It is relatively straightforward to develop a relationship between the buoyancy force on a parcel of exhaust gas and its temperature, exit temperature, exit velocity, and stack diameter. From such analysis, the following buoyancy flux parameter emerges.

$$F = gr^2 v_s\left(1 - \frac{T_a}{T_s}\right) \tag{2.52}$$

where F=buoyancy flux parameters, m^4/s^3

g=gravitational acceleration, 9.8 m/s^2

r=inside radius of the stack,m

v_s=stack gas exit velocity,m/s

T_s=stack gas temperature, K

T_a=ambient temperature, K

For neutral or unstable conditions in the atmosphere (stability categories A-D), the following equation can be used to estimate plume rise:

$$\Delta h = \frac{1.6F^{1/3}{x_f}^{2/3}}{u} \qquad (2.53)$$

where Δh =plume rise,m

u=wind speed at stack heigt,m/s

x_f=distance downward to point of final plume rise,m

Use $x_f = 120F^{0.4}$ if $F \geq 55 m^4/s^3$

Use $x_f = 50F^{0.4}$ if $F < 55 m^4/s^3$

For stable, windy conditions (stability categories E and F), use the following

$$\Delta h = 2.4\left(\frac{F}{uS}\right)^{1/3} \qquad (2.54)$$

where S is a stability parameter with units of s^{-2} given by

$$S = \frac{g}{T_a}\left(\frac{dT_a}{dz} + \Gamma\right) \qquad (2.55)$$

Recall that Γ is the adiabatic lapse rate, +0.01 ^{0}C/m.The derivative $\frac{dT_a}{dz}$ represents the actual rate of change of ambient temperature with altitude (note that a positive value means temperature is increasing with altitude [7].

2.6.4.8. Plume behavior and atmospheric lapse rate

The atmospheric temperature profiles affect the dispersion of pollutants from a smoke stack, as shown in Figure 2.8 below. Each diagram shows a temperature profile in the atmosphere, together with the expected plume behavior.

If a stack were to emit pollutants into a neutrally stable atmosphere (a, Pasquill C to D), we might expect the plume to be relatively symmetrical which disperse the plume fairly equally in both the vertical and horizontal planes. This is referred to as coning.

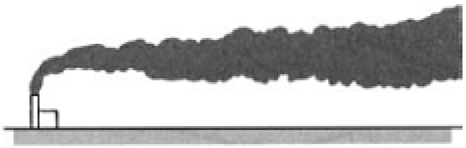
The most unstable conditions (b, Pasquill A) can result intermittently very high concentrations of poorly diluted plume close to the stack and rapid vertical air movement, both up and down, producing a looping plume.

A strong inversion of the profile (stable atmosphere), (c, Pasquill E to F) prevents the plume from mixing vertically or greatly restricts the dispersion of plume in the vertical direction; although it can still spread. The result is called a fanning plume.

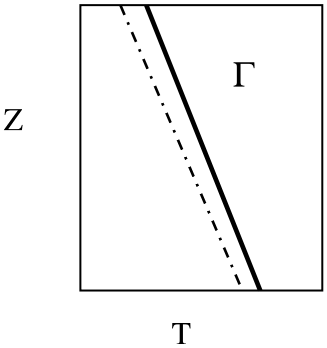
Emissions realsed from a smokestack that is under an inversion layer head (d) downward much more easily than upward. The resulting fumigation can lead to greatly elevated ground-level concentrations. In practice, complex environmental lapse rate (ELR) structures interact with stack and plume heights to create a much more variable picture.

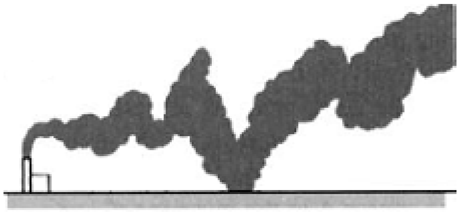
When the stack is above an inversion layer, as shown in figure 2.8 (e) below, mixing in the upward direction is uninhibited, but downward motion is greatly restricted by the inversion's stable air. Such lofting plumes are helpful in terms of exposure to people at ground level because it prevented from mixing down to the ground and makes ground-level concentrations kept low. Thus, a common approach to air pollution control is to build taller and taller stacks to emit pollutants above inversions.

An unfortunate consequence of this approach for pollutants that released from tall stack are then able to travel distances, so that effects such as an acid deposition can be felt hundreds of miles from sources.

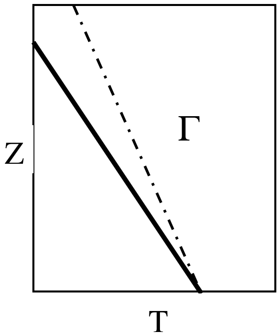


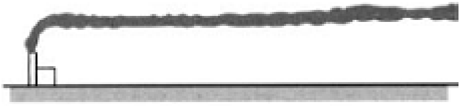
a).Coning



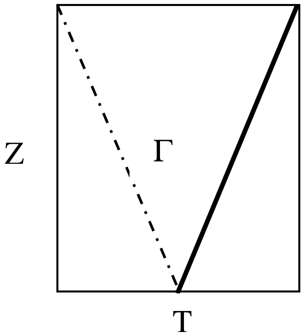


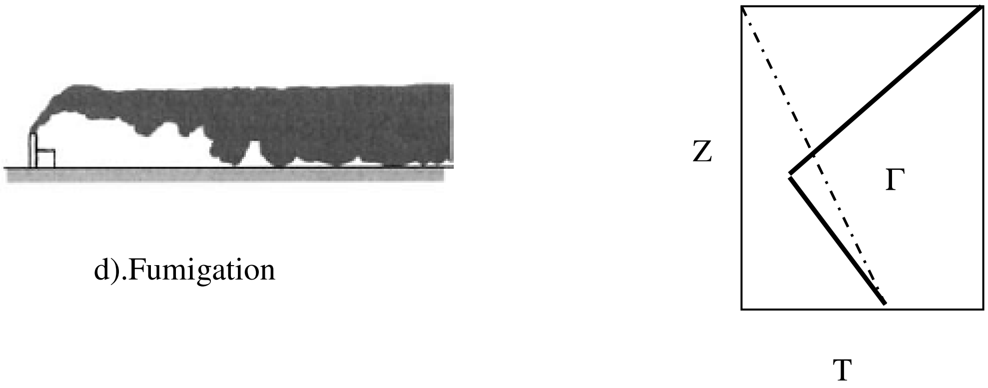
b).Looping



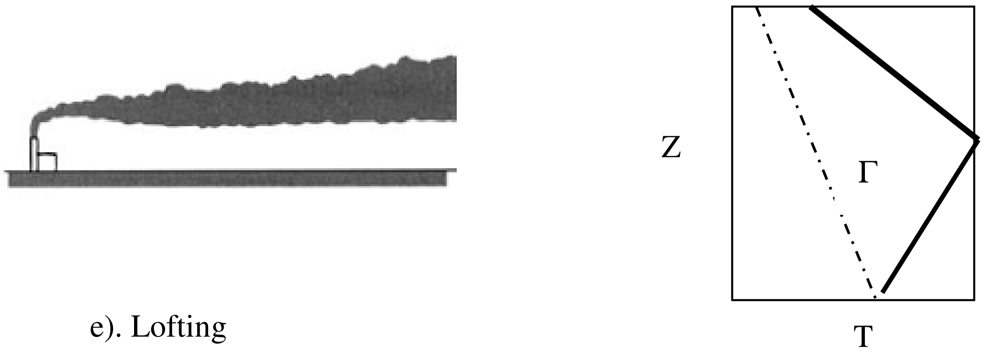


c).Fanning





d).Fumigation



e). Lofting

Figure 2.8. Effect of lapse rate on plume dispersion [23].

Note: All the above figures are effect of atmospheric lapse rates and stack heights on plume behavior. The dashen line is the dry adiabatic lapse rate for reference.

2.6.4.9. Estimates of σ_y, σ_z

The two dispersion coefficients, σ_y, σ_z, are the standard deviations of the horizontal and vertical Gaussian distributions, respectively (about 68% percent of the area under a Gaussian curve is within $\pm 1\sigma$ of the mean value). Smaller values for a dispersion coefficient mean the Gaussian curve is narrower, with a higher peak, while larger values mean the opposite. The further downward we go from the source, the larger these coefficients become. This causes the Gaussian curves to spread further and further. Not only are these coefficients a function of downward distance, they also depending a complex way, on atmospheric stability.

Expressions for σ_y and σ_z have been derived in terms of the distance travelled by the plume downwind from the source under different Pasquill stability classes. They are available both as graphs and as empirical equations that are valid in the range $100 \text{ m} < x < 10 \text{ km}$. As the graph form it is indicated in Annex 2 that shows the variations of standard deviation with distance from the source for the different Pasquill stability categories. Note that the x scale runs from 100 m to 100 km – this dispersion methodology is designed for medium physical scales, neither small enough to be influenced by individual topographic features nor large enough to be controlled by synoptic wind flows. Note also that σ_z, the vertical standard deviation, is much more influenced by stability than σ_y, horizontal standard deviation, owing to the influence of buoyancy forces. Table 2.8 gives corresponding equations for variation of σ_y and σ_z for open-country and urban conditions. The main difference is that the greater surface roughness in built-up areas generates greater turbulence.

Table 2.8.Equations for the variation of σ_y and σ_z with stability class

Pasquill category	σ_y(meter)	σ_z (meter)
Open-country		
A	$0.22x(1.0+0.0001x)^{-0.5}$	$0.20x$
B	$0.16x(1.0+0.0001x)^{-0.5}$	$0.12x$
C	$0.11x(1.0+0.0001x)^{-0.5}$	$0.08x(1.0+0.0002x)^{-0.5}$
D	$0.08x(1.0+0.0001x)^{-0.5}$	$0.06x(1.0+0.0015x)^{-0.5}$
E	$0.06x(1.0+0.0001x)^{-0.5}$	$0.03x(1.0+0.0003x)^{-1}$
F	$0.04x(1.0+0.0001x)^{-0.5}$	$0.016x(1.0+0.0003x)^{-1}$
Urban		
A-B	$0.32x(1.0+0.0004x)^{-0.5}$	$0.024x(1.0+0.001x)^{0.5}$
C	$0.22x(1.0+0.0004x)^{-0.5}$	$0.20x$
D	$0.16x(1.0+0.0004x)^{-0.5}$	$0.14x(1.0+0.0003x)^{-0.5}$
E-F	$0.11x(1.0+0.0004x)^{-0.5}$	$0.08x(1.0+0.0015x)^{-0.5}$

There is also most common procedures for estimating the dispersion coefficient introduced by Pasquill (1961),modified by Gifford(1961),and adopted by the U.S. Public Health Service(Turner,1970).The parameter A to F in annex 3 represent stability classification based on qualitative descriptions of prevailing environment conditions. Table 2.9 describes these parameters. For example, a clear summer day, with the sun higher than 60^0 above the horizon and wind speed less than 2 m/s (at elevation of 10 m) ,creates a very unstable atmosphere with stability classification A. The opposite classification F, which is labeled stable, and corresponds to a clear night (less than 3/8 of the sky covered by clouds), with winds less than 3m/s. It should be noted that the stability classifications used in table 1 to estimate wind speeds at elevations rather than the standard 10-m anemometer height, are the same for A-F classifications used here.

Table 2. 9. Atmospheric stability classifications

Surface wind speed (m/s)[a]	Day solar insolation			Night cloudness[e]	
	Strong	Moderate [c]	Slight [d]	Cloudy(≥4/8)	Clear(≤3/8)
<2	A	A-B[f]	B	E	F
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

[a] *Surface wind speed is measured at 10m above the ground*

[b] *Correspond to clear summer day with sun higher than* 60^{o} *above the horizon*

[c] *Corresponds to summer day with a few broken clouds ,or clear day with sun* $35\text{-}60^{o}$ *above the horizon.*

[d] *Corresponds to a fall afternoon, or a cloudy summer day, or clear summer day with the summer day with the sun* $15\text{-}35^{o}$ *above the horizon.*

[e] *cloudiness in defined as the fraction of sky covered by clouds*

[f] *For A-B,B-C,or C-D conditions ,average the values obtained for each. Note:A,very unstable;B,moderately unstable;C,slightly unstable; D,neutral ; E,slightly stable; F,stable.Regardless of wind speed, class D should be assumed for overcast conditions ,day or night.*

Source: Turner (1970)

It is easier to use a computer to work with main Gaussian dispersion model equation, in which case the graphical presentation of dispersion coefficients in Annex-2 is inconvenient. A reasonable fit to those graphs can be obtained using the following equations (Martin, 1976):

$$\sigma_y = ax^{0.894} \tag{2.56}$$

and

$$\sigma_z = Cx^d + f \tag{2.57}$$

Where the constants a, c, d, and f are given in Table 2.10 for each stability classification. The downward distance x must be expressed in kilometers to yield σ_y and σ_z in meters.

For convenience, a few values for the dispersion coefficients calculated using the above equations are listed in Table 2.11.As plume goes away from source, dispersion increases in both y and z directions; as x increases σ_y and σ_z icrease depending upon stability. So the downward distance X must be expressed in kilometers to yield σ_y and σ_z in meters.

Table 2. 10. Values of the constants, a, c, d, and f for use in Equations (2.56) and (2.57).

Stability	x≤1km				x≥1km		
	a	c	d	f	c	d	f
A	213	440.8	1.941	9.27	459.7	2.094	-9.6
B	156	106.6	1.149	3.3	108.2	1.098	2
C	104	61	0.911	0	61	0.911	0
D	68	33.2	0.725	-1.7	44.5	0.516	-13
E	50.5	22.8	0.678	-1.3	55.4	0.305	-34
F	34	14.35	0.74	-0.35	62.6	0.18	-48.6

Table 2.11. Dispersion coefficients (m) for selected distances downwind (km), computed with Equation (2.48) and (2.49) .

	σ_y(m)						σ_z(m)					
x(km)	A	B	C	D	E	F	A	B	C	C	E	F
0.1	27	19	13	8	6	4	14	11	7	5	4	2
0.2	50	36	23	15	11	8	29	20	14	8	6	4
0.4	94	67	44	29	21	14	72	40	26	15	11	7
0.7	155	112	74	48	36	24	215	73	43	24	17	11
1	215	155	105	68	51	34	355	110	61	32	21	14
2	390	295	200	130	96	64	1950	230	115	50	34	22
4		550	370	245	180	120		500	220	77	49	31
7		880	610	400	300	200		780	360	109	66	39
10		1190	840	550	420	275		1350	510	135	79	46
20		2150	1540	1000	760	500		2900	950	205	110	60

3. Material and Methods

3.1. Methods

The computational model to the solution of the modeling of air pollutant dispersion involves the following six major tasks:

Data Preparation. Data should be collected and analyzed to understand the physical processes of study, determine initial and boundary conditions, estimate model parameters, and calibrate the model. The following data are commonly required by models.

Study domain

The study domain usually covers the area to be analyzed during dispersion modeling. Its distance to be covered in the x and y-directions will be used to determine the concentration at different distances in the x-direction.

Historical data

Historical measurement data of emission rate (g/s), stack height (m), stack inside diameter (m), stack exit velocity (m/s) or stack gas exit flow rate(m^3/s), stack gas exit temperature (K) ,ambient air temperature (K) etc., should be collected and analyzed for better understanding of the study problem and calibration of the numerical model.

Estimation of Model Parameters. Model parameters can be classified as numerical and physical. Numerical parameters, such as concentration, dispersion coefficients, wind velocity, result from numerical differential solving methods. They should be determined by considering the accuracy of the study problem required to be used. Physical parameters can be subdivided into two groups. One group represents the physical properties of stack height (m), stack inside diameter (m), stack exit velocity (m/s) or stack gas exit flow rate (m^3/s), stack gas exit temperature (k). These physical properties can be measured. The other group results from the conceptualization of physical processes and that represents characteristics like friction velocity, surface roughness, density of air, specific heat capacity of air, atmospheric pressure and boundary layer.

These physical parameters are often calibrated using measured data or determined using empirical formulas.

Design the model. The conceptual model will then be set into a suitable form of equation in spatially bases for further mathematical simplication and considerations during the modeling.

Model Calibration. The computational model should be calibrated using the available data measured in the study to reach to insure that the aforementioned parameters are estimated correctly, that the empirical formulas are chosen appropriately, and that the observed physical processes are generally well reproduced by the model. The calibrated model can then be applied to predict the physical processes in various scenarios.

Interpretation of Simulation Results. Because dispersion models are highly empirical and the model development and application processes are not infallible, engineering judgment should be used in the interpretation of simulation results. Consulting with model developers, senior scientists, and local engineers who are familiar with the dispersion modeling can enhance confidence in the end results. In addition, efficiently grouping important results using attractive graphs and tables permits an easy understanding and communication among model developers, users, and report readers.

Analysis of Uncertainties. Sources of uncertainties include model conceptualization, boundary conditions, model parameters, and data. Uncertainties may be reduced by using a more adequate model, selecting appropriate boundary conditions, calibrating model parameters carefully, and collecting more reliable data.

The general procedure for developing a computational model consists, essentially, of the following steps:

1. Conceptualize the complicated physical phenomena of study, with the necessary simplifications and assumptions that express our understanding of the nature of the system and its behavior (e.g., dimensionality; steady, quasi-steady, or unsteady; pollutants; solution domain; initial and boundary conditions etc);
2. Describe the physical phenomena of study using a set of algebraic and differential equations that are subject to the conservation laws of mass and momentum;
3. Divide the study domain into different distance variation corresponding to be used in numerical equations;
4. Solve the differential equations by using differential equation solving methods like integration to find expressive equation for evaluating the concentration of pollutants at different distances;

5. Code the established solution procedures using computer languages, and package the model with matlab M-file editor or using graphical user interface (GUI) for pre- and post-processing ,and
6. Verification of matlab based developed program using different data's.

3.2. Materials

The different materials that will be used and utilized in the study work are:

1. Resources

Literature review and secondary data on metrology, emission factors was gathered from different books,journals,articles and archive of different institutions, published and unpublished documents. Field survey, unstructured interview, professional observations are some methods used for gathering primary data.

2. Metrological data:
    - Monthly average temperature
    - Wind speed
    - Atmospheric pressure
    - Specific heat capacity of air
    - Density of air
3. Softwares:
    - MATLAB for solving the model
    - MS Office (Excel, Word and access) for write-up and data processing.
    - Screenview for checking some parameters.

4. Result and discussion

The model equation developed for predicting air pollutant dispersion is given by:

$$C(x,y,z,H)=\frac{Q}{2\pi u\,\sigma_y\,\sigma_z}\exp\left(-\frac{y^2}{2\,\sigma_y^2}\right)\left\{\exp\left(-\frac{(z-H)^2}{2\,\sigma_z^2}\right)+\exp\left(-\frac{(z+H)^2}{2\,\sigma_z^2}\right)\right\}$$

To simplify the computational effort for the above equation, a matlab code is developed below. In this case a number of different assumptions are taken to calculate the concentration of the pollutant with distance for many types of pollutants from any emission sources. The code below is the general programme, which is user friendly that can be upgraded and edited.

```
%Purpose: To calculate the concentration of pollutant with distance when the
%pollutants are dispersed
%Date: July 2010; Programmer: Anteneh Muheye
%=================================================================
%h=stack height
%D=stack diameter
%vs=stack exit velocity
%Ts=stack exit temperature
%Ta=ambient or atmospeheric temperature
%Q-mass of pollutant per time ;not volume flowrate of stackgas
%emission factors
%uo=windspeed measured by anemomete
%z1=height of anemometer to inplace mostly @10meter
%p=atmospheric stability exponent for different terrain type
% u=wind speed at the stack height
%Blh=boundary layer height
%Ta=ambient or atmospeheric temperature
%L=Monion-Obukhov length used to calculate atmospheric stability
%cp=specific heat capacity of air
%k=karman's constant
%c=vertical sensible heat flux()
```

```
%g=acceleration due to gravity(m/s^2)
%d=density of the air
%vf=friction velocity ,but written as u* in literature
%stabcrit-stability criteria
%1= stabcrit for stable
%2= stabcrit for neutral
%3=stabcrit for unstable
%dh=plumerise
%zo=surface roughness length
%C=concentration
clc
clear all
format short
%emssion factor
%==============
disp('Enter emission rate of pollutant ,(g/s)');
disp('==========================================')
Q=input('Q=');
disp('Enter the stack height,(m)');
disp('==========================================')
h=input('h=');
disp('Enter the stack diameter,(m)');
disp('==========================================')
D=input('D=');
disp('Enter  stack exit velocity ,(m/s)');
disp('==========================================')
vs=input('vs=');
disp('Enter the stack exit temperature,(k)');
disp('=================================')
Ts=input('Ts=');
%stability estimator
%====================
```

```
disp('Enter the  boundary layer height,(m)');
disp('==============================')
Blh=input('Blh=');
disp('Enter the specific heat capacity of air,(J/kg.K)');
disp('====================================')
cp=input('cp=');
disp('Enter the density of the air,(kg/m^3)');
disp('===================================')
d=input('d=');
disp('Enter the friction velocity,m^2/s');
disp('===================================')
vf=input('vf=');
g=9.81 ;
k=0.40;
disp('Enter ambient or atmospheric temperaure,(k)');
disp('=====================================')
Ta=input('Ta=');
%dispersion coefficient calculation
%==============================================
% disp('Enter the sensible heat flux value as 0(number approach to zero),-42 or 175');
disp('Enter the sensible heat flux value in the range beteween -100 upto 200');
disp('=========================================================')
c=input('c=');
L=-((d.*cp.*Ta.*(vf.^3))./(k.*g.*c));
Blh/L;
stabcrit=Blh/L;
if(stabcrit>=1)
%     stablcrit=1;
fprintf('The stability_criteria=stable\n');
disp(' ***********************************')
elseif(stabcrit<-0.3)
%      stabcrit=3;
```

```
fprintf('The stability_criteria=unstable\n')
disp(' ***********************************')
else(-0.3<=stabcrit & stabcrit/L<1)
%   stabcrit=2;
fprintf('The stability_criteria=neutral\n')
disp(' *************************************')
end
disp('Enter the surface roughness length,\n (m)');
disp('============================================')
zo=input('zo=');
if zo<1
surface_type=4;
fprintf('The surface_type=opencountry(rural)\n');
%   disp('The surface type is opencountry(rural)');
disp(' ********************************************')

else (1<=zo & zo<=3)

surface_type=5;
fprintf('The surface_type=urban\n');
%    disp('The surface type is urban');
disp(' ********************************')

end
%meterology factors
%=====================
disp('Enter the windspeed @10meter anemometer,(m)');
disp('===========================================')
uo=input('uo=');
disp('Enter the value of p for different stability and surface type identified before')
disp('The value of p for unstable condition of rough terrain=0.15')
disp('The value of p for neutral condition of rough terrain=0.20')
disp('The value of p for stable condition of rough terrain=0.60')
disp('The value of p for unstable condition of smooth terrain=0.07')
```

```
disp('The value of p for neutral condition of smooth terrain=0.15')
disp('The value of p for stable condition of smooth terrain=0.55')
disp('Enter the exponent that varies with atmospheric stability');
disp('===============================================================')
p=input('p=');
z1=10;
u=uo*((h/z1)^p ) ;
fprintf('The value of u is = %f\n ',u)

%plumerise calculation using Hollands's equation
%==================================================
disp('Enter the atmospheric pressure,(mbar)');
disp('==========================================')
p=input('p=');

x1=(vs*D)/u;
x2=(Ts-Ta)/Ta;
dh=x1*(1.5 +(0.00268*p*D*x2))
fprintf('The value of dh is= %f\n',dh)
disp(' ********************************')
H=h+dh;
disp('Enter receptors positions or coordinates for y,z(m)');
disp('===========================================================')
y=input('y=');
z=input('z=');

sigmay=[];
sigmaz=[];
C=[];
Xfinal=[];
%    sigmayCur=0;
%    sigmazCur=0;
%    CCur=0;
%Cur -stands for current
```

```
for x=100:100:10000

Xfinal=[Xfinal,x];
if(zo<1 & Blh/L<-0.3)

sigmayCur=(0.22.*x.*((1+(0.0001.*x)).^-0.5));
%        sigmay=[sigmay,sigmayCur]
sigmazCur=0.20.*x;
%         sigmaz=[sigmaz,sigmazCur]
CCur=((Q/(2.*pi.*u.*sigmayCur.*sigmazCur)).*exp((-y.^2)./(2*(sigmayCur.^2)))).*(exp((-(z-H).^2)./(2*(sigmazCur.^2)))+ exp((-(z+H).^2)./(2*(sigmazCur.^2))))
%  C=[C,CCur]
elseif(zo<1 & (-0.3<=Blh/L & Blh/L<1))

sigmayCur=(0.08.*x.*((1+(0.0001.*x)).^-0.5));
sigmazCur=(0.06.*x.*((1+(0.0015.*x)).^-0.5));
CCur=((Q./(2.*pi.*u.*sigmayCur.*sigmazCur)).*exp((-y.^2)./(2.*(sigmayCur.^2)))).*(exp((-(z-H).^2)./(2.*(sigmazCur.^2)))+ exp((-(z+H).^2)./(2.*(sigmazCur.^2)))) ;
elseif(zo<1& Blh/L>=1)

sigmayCur=(0.04.*x.*((1+(0.0001.*x)).^-0.5));
sigmazCur=(0.016.*x.*((1+(0.0003.*x)).^-1));
CCur=((Q./(2.*pi.*u.*sigmayCur.*sigmazCur)).*exp((-y.^2)./(2.*(sigmayCur.^2)))).*(exp((-(z-H).^2)./(2.*(sigmazCur.^2)))+ exp((-(z+H).^2)./(2.*(sigmazCur.^2))));
elseif((1<=zo & zo <=3) & Blh/L<-0.3)

sigmayCur=(0.32.*x.*((1+(0.0004.*x)).^-0.5));
sigmazCur=(0.024.*x.*((1+(0.001.*x)).^0.5));
CCur=((Q./(2.*pi.*u.*sigmayCur.*sigmazCur)).*exp((-y.^2)./(2.*(sigmayCur.^2)))).*(exp((-(z-H).^2)./(2.*(sigmazCur.^2)))+ exp((-(z+H).^2)./(2.*(sigmazCur.^2))));
elseif((1<=zo & zo <=3) & (-0.3<=Blh/L & Blh/L<1))

sigmayCur=(0.16.*x.*((1+(0.0004.*x)).^-0.5));
sigmazCur=(0.14.*x.*((1+(0.0003.*x)).^-0.5));
CCur=((Q./(2.*pi.*u.*sigmayCur.*sigmazCur)).*exp((-y.^2)./(2.*(sigmayCur.^2)))).*(exp((-(z-H).^2)./(2.*(sigmazCur.^2)))+ exp((-(z+H).^2)./(2.*(sigmazCur.^2))));
```

```
elseif((1<=zo & zo<=3) & Blh/L>=1)

sigmayCur=(0.11.*x.*((1+(0.0004.*x)).^-0.5));
%        sigmay=[sigmay,sigmayCur];
%      sigamzCur=(0.08.*x.*((1+(0.0015.*x)).^-0.5));
sigmazCur=(0.08.*x.*((1+(0.0015.*x)).^-0.5));
%      sigmaz=[sigmaz,sigmazCur];
CCur=((Q./(2.*pi.*u.*sigmayCur.*sigmazCur)).*exp((-y.^2)./(2.*(sigmayCur.^2)))).*(exp((-(z-
H).^2)./(2.*(sigmazCur.^2)))+ exp((-(z+H).^2)./(2.*(sigmazCur.^2))));
end
sigmay=[sigmay,sigmayCur];
sigmaz=[sigmaz,sigmazCur];
C=[C;CCur];
end
sigmay
sigmaz
C;
%Concentration of pollutants should be in microgram per metercube
Concentration=C.*(10.^6)
Xfinal;
% hold on;
%Receptor =2*ones(length(C),length(Xfinal));

plot(Xfinal,Concentration,'Color','red','LineWidth',2)
%mesh(Xfinal,C,2)
%surf(Xfinal,C,Receptor)
xlabel('Distance(m)')
ylabel('Concentration( {\mu}g/m^3 )')
title('Concentration vs Distance')
grid on;
```

In the analysis of the dispersion modeling the following conditions are taken into consideration:

- A rectangular dimension of having 2x500x20 is taken, in which a variation of dimensions in x-direction is considered in the program.
- The boundary conditions like at x=0,C(0,j,k)=0;at y=0, $\frac{\partial c}{\partial y} = 0$;at z=0, , $\frac{\partial c}{\partial z} = 0$;and at z=mixing height, , $\frac{\partial c}{\partial z} = 0$;are taken into consideration.
- There are no sources and sinks in the model.

To validate this programme, a number of secondary and primary data are taken from different literatures, experts and practical documents for case of CRBC (China road and bridge company) asphalt mixer plant in which values for different model parameters are given in the next page.

The average temperature of Addis Ababa is taken as one model parameter (Annex 3).

Data:

Table 4.1. Data input to validate the model programme [2, 7,6,22 &24].

Emission rate of pollutant (g/s)	20
Stack height (m)	15
Stack diameter (m)	0.7
Stack exit velocity (m/s)	10
Stack exit temperature (^{0}K)	313
Boundary layer height (m)	360
Specific heat capacity of air (kJ/kg.K)	1010
Density of air (kg/m^3)	1.2
Friction velocity (m/s)	0.26
Ambient temperature (^{0}K)	289.0
Surface roughness (m)	2.0
Wind speed at 10 meter anemometer (m/s)	5.0
Atmospheric pressure (mbar)	786.60
Receptors position in y-direction (m)	20.0
Receptors position in z-direction (m)	2.0

In the validation of the program using the above data, effects of metrological parameters such as stability, wind velocity, air temperature, atmospheric pressure and other parameters like effect of exit temperature, exit velocity, stack height and exit concentration is discussed below. To show the variation of concentration with distance all the above data are used as an input.

Effect of atmospheric stability: Programme results for neutral, stable and unstable atmospheric condition is shown below:

Table 4.2. Output result for neutral atmospheric condition.

Distance (m)	Sigmay (m)	Sigmaz (m)	Concentration (µg/m3)
100	15.689	13.795	1123.2
200	30.792	27.196	930.3
300	45.356	40.229	532.9
400	59.422	52.915	334.7
500	73.030	65.275	229.1
600	86.211	77.328	167.2
700	98.995	89.091	128
800	111.410	100.580	101.6
900	123.479	111.810	82.9
1000	135.225	122.790	69.3
1100	146.667	133.530	58.9
1200	157.823	144.060	50.9
1300	168.710	154.370	44.5
1400	179.344	164.480	39.3
1500	189.737	174.400	35.1
1600	199.902	184.130	31.6
1700	209.853	193.680	28.6
1800	219.598	203.070	26.1
1900	229.149	212.290	24
2000	238.514	221.360	22.1
2100	247.703	230.280	20.5
2200	256.722	239.050	19
2300	265.581	247.690	17.8
2400	274.286	256.200	16.6
2500	282.843	264.580	15.6
2600	291.258	272.830	14.7
2700	299.538	280.970	13.9
2800	307.688	288.990	13.2
2900	315.712	296.900	12.5
3000	323.616	304.700	11.9
3100	331.404	312.400	11.3
3200	339.080	320.000	10.8

3300	346.649	327.500	10.3
3400	354.114	334.910	9.9
3500	361.478	342.230	9.5
3600	368.746	349.460	9.1
3700	375.92	356.610	8.7
3800	383.004	363.670	8.4
3900	390.000	370.650	8.1
4000	396.911	377.550	7.8
4100	403.740	384.380	7.5
4200	410.489	391.130	7.3
4300	417.161	397.810	7.1
4400	423.758	404.420	6.8
4500	430.282	410.970	6.6
4600	436.736	417.440	6.4
4700	443.120	423.860	6.2
4800	449.438	430.200	6.1
4900	455.691	436.490	5.9
5000	461.880	442.720	5.7
5100	468.008	448.890	5.6
5200	474.076	455.000	5.4
5300	480.086	461.060	5.3
5400	486.038	467.060	5.2
5500	491.935	473.010	5.0
5600	497.778	478.90	4.9
5700	503.568	484.750	4.8
5800	509.306	490.550	4.7
5900	514.994	496.300	4.6
6000	520.633	502.000	4.5
6100	526.224	507.650	4.4
6200	531.768	513.260	4.3
6300	537.266	518.820	4.2
6400	542.719	524.340	4.1
6500	548.128	529.820	4.0
6600	553.494	535.260	4.0
6700	558.819	540.650	3.9
6800	564.102	546.010	3.8
6900	569.345	551.330	3.7
7000	574.548	556.600	3.7

7100	579.713	561.840	3.6
7200	584.839	567.040	3.5
7300	589.929	572.210	3.5
7400	594.982	577.340	3.4
7500	600.000	582.440	3.4
7600	604.983	587.500	3.3
7700	609.931	592.520	3.2
7800	614.846	597.520	3.2
7900	619.727	602.480	3.1
8000	624.576	607.410	3.1
8100	629.393	612.300	3.0
8200	634.179	617.170	3.0
8300	638.934	622.000	3.0
8400	643.659	626.810	2.9
8500	648.355	631.590	2.9
8600	653.021	636.330	2.8
8700	657.658	641.050	2.8
8800	662.268	645.740	2.7
8900	666.849	650.410	2.7
9000	671.404	655.040	2.7
9100	675.931	659.650	2.6
9200	680.432	664.240	2.6
9300	684.908	668.790	2.6
9400	689.357	673.320	2.5
9500	693.782	677.830	2.5
9600	698.182	682.310	2.5
9700	702.557	686.770	2.4
9800	706.909	691.200	2.4
9900	711.237	695.610	2.4
10000	715.542	700.000	2.3

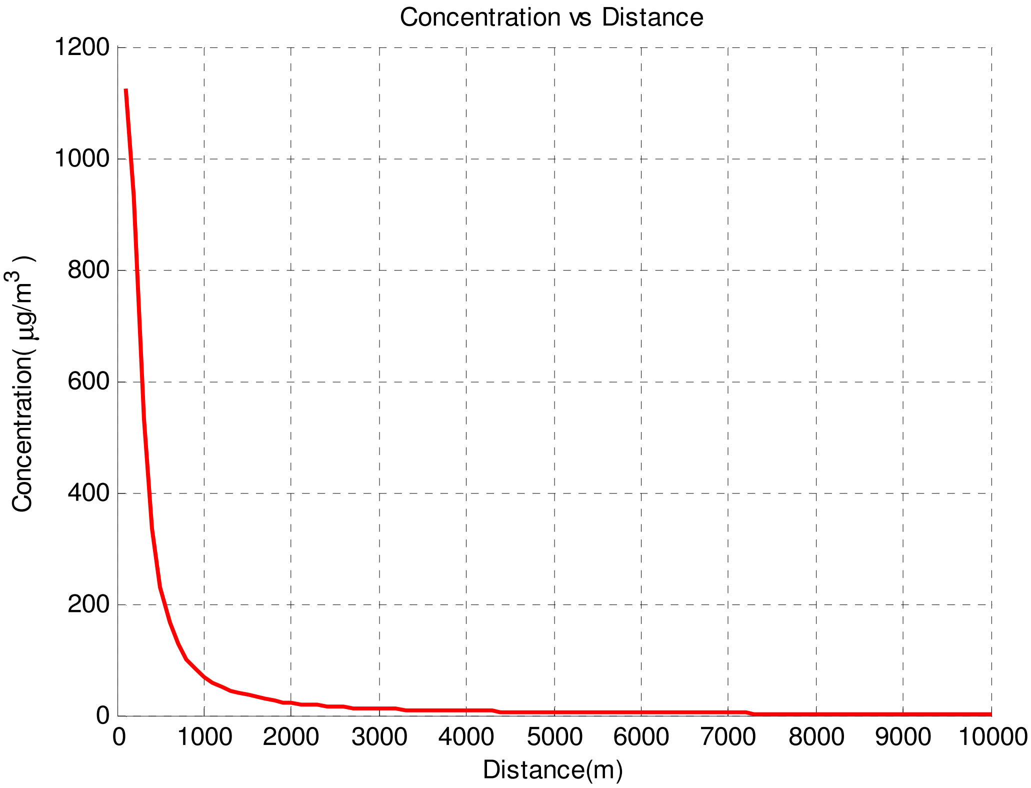


Figure 4.1. Effect of atmospheric stability (neutral) on particle matter concentration with distance variation.

Table 4.3. Programme results for stable atmospheric condition.

Distance (m)	Sigmay (m)	Sigmaz (m)	Concentration (µg/m^3)
100	10.786	7.460	202.9
200	21.170	14.033	1056.6
300	31.182	19.931	916.0
400	40.853	25.298	686.4
500	50.208	30.237	519.9
600	59.270	34.823	406.3
700	68.059	39.112	327.2
800	76.594	43.149	270.4
900	84.892	46.968	228.3
1000	92.967	50.596	196.1
1100	100.833	54.058	171

1200	108.503	57.371	151
1300	115.988	60.551	134.7
1400	123.299	63.612	121.3
1500	130.444	66.564	110.0
1600	137.433	69.418	100.5
1700	144.273	72.181	92.4
1800	150.974	74.862	85.4
1900	157.540	77.466	79.2
2000	163.978	80.000	73.9
2100	170.296	82.468	69.1
2200	176.497	84.875	64.9
2300	182.587	87.224	61.1
2400	188.571	89.521	57.8
2500	194.454	91.766	54.7
2600	200.240	93.965	51.9
2700	205.932	96.119	49.4
2800	211.535	98.231	47.1
2900	217.052	100.302	45.0
3000	222.486	102.336	43.1
3100	227.840	104.334	41.3
3200	233.118	106.298	39.6
3300	238.321	108.229	38.1
3400	243.453	110.130	36.7
3500	248.516	112.000	35.3
3600	253.513	113.842	34.1
3700	258.445	115.6568	32.9
3800	263.315	117.4454	31.9
3900	268.125	119.2091	30.8
4000	272.876	120.949	29.9
4100	277.571	122.665	29.0
4200	282.211	124.359	28.1

4300	286.798	126.032	27.3
4400	291.334	127.684	26.5
4500	295.819	129.316	25.8
4600	300.256	130.929	25.1
4700	304.645	132.523	24.5
4800	308.989	134.099	23.9
4900	313.287	135.657	23.3
5000	317.543	137.199	22.7
5100	321.756	138.724	22.2
5200	325.927	140.234	21.6
5300	330.059	141.728	21.2
5400	334.151	143.207	20.7
5500	338.205	144.671	20.2
5600	342.222	146.122	19.8
5700	346.203	147.558	19.4
5800	350.148	148.981	19.0
5900	354.059	150.392	18.6
6000	357.935	151.789	18.2
6100	361.779	153.175	17.9
6200	365.590	154.548	17.5
6300	369.370	155.909	17.2
6400	373.119	157.260	16.9
6500	376.838	158.599	16.6
6600	380.527	159.927	16.3
6700	384.188	161.244	16.0
6800	387.820	162.551	15.7
6900	391.424	163.848	15.5
7000	395.002	165.135	15.2
7100	398.552	166.412	15.0
7200	402.077	167.680	14.7
7300	405.576	168.939	14.5

7400	409.050	170.188	14.3
7500	412.500	171.429	14.0
7600	415.926	172.660	13.8
7700	419.328	173.884	13.6
7800	422.706	175.099	13.4
7900	426.062	176.305	13.2
8000	429.396	177.504	13.0
8100	432.708	178.695	12.8
8200	435.998	179.878	12.7
8300	439.267	181.054	12.5
8400	442.516	182.221	12.3
8500	445.744	183.382	12.1
8600	448.952	184.536	12.0
8700	452.140	185.683	11.8
8800	455.308	186.822	11.7
8900	458.459	187.955	11.5
9000	461.590	189.081	11.4
9100	464.703	190.201	11.2
9200	467.797	191.314	11.1
9300	470.874	192.421	11.0
9400	473.933	193.522	10.8
9500	476.975	194.616	10.7
9600	480.000	195.705	10.6
9700	483.008	196.787	10.5
9800	485.999	197.864	10.3
9900	488.975	198.935	10.2
10000	491.935	200.000	10.1

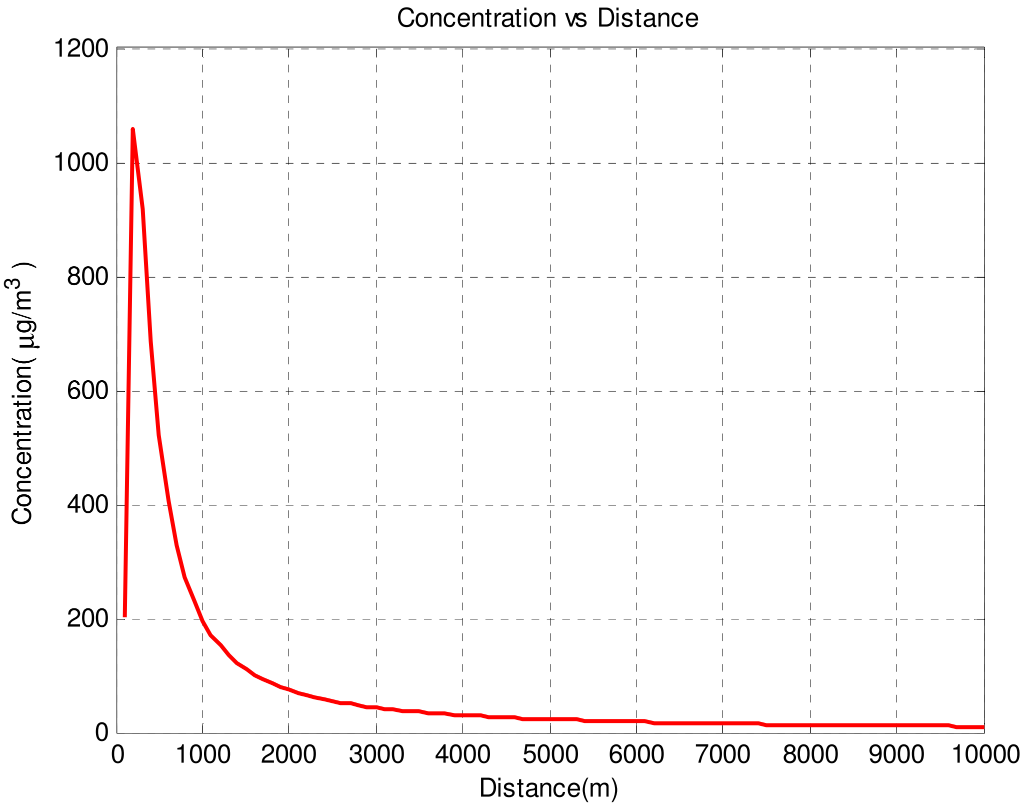


Figure 4.2. Effect of atmospheric stability (stable) on particle matter concentration with distance variation

Table 4.4. Output result of unstable atmospheric condition.

Distance (m)	Sigmay (m)	Sigmaz (m)	Concentration (µg/m^3)
100	31.4	2.517	0.001
200	61.6	5.258	30.166
300	90.7	8.209	195.280
400	118.8	11.359	285.863
500	146.1	14.697	281.085
600	172.4	18.215	243.240
700	198.0	21.905	202.061
800	222.8	25.760	166.347
900	247.0	29.774	137.411

1000	270.4	33.941	114.439
1100	293.3	38.257	96.242
1200	315.6	42.717	81.747
1300	337.4	47.317	70.101
1400	358.7	52.053	60.651
1500	379.5	56.921	52.907
1600	399.8	61.918	46.499
1700	419.7	67.041	41.148
1800	439.2	72.287	36.641
1900	458.3	77.654	32.814
2000	477.0	83.138	29.541
2100	495.4	88.738	26.722
2200	513.4	94.452	24.279
2300	531.2	100.276	22.148
2400	548.6	106.209	20.281
2500	565.7	112.250	18.635
2600	582.5	118.396	17.179
2700	599.1	124.645	15.883
2800	615.4	130.997	14.727
2900	631.4	137.449	13.690
3000	647.2	144.000	12.757
3100	662.8	150.649	11.915
3200	678.2	157.393	11.153
3300	693.3	164.233	10.460
3400	708.2	171.166	9.829
3500	723.0	178.191	9.253
3600	737.5	185.307	8.726
3700	751.8	192.514	8.242
3800	766.0	199.809	7.796
3900	780.0	207.192	7.386
4000	793.8	214.663	7.006

4100	807.5	222.219	6.655
4200	821.0	229.859	6.329
4300	834.3	237.584	6.027
4400	847.5	245.392	5.745
4500	860.6	253.283	5.483
4600	873.5	261.251	5.238
4700	886.2	269.303	5.008
4800	898.9	277.438	4.794
4900	911.4	285.649	4.593
5000	923.8	293.939	4.404
5100	936.0	302.306	4.226
5200	948.2	310.750	4.059
5300	960.2	319.270	3.902
5400	972.1	327.865	3.753
5500	983.9	336.535	3.613
5600	995.6	345.280	3.480
5700	1007.1	354.098	3.355
5800	1018.6	362.989	3.236
5900	1030.0	371.953	3.123
6000	1041.3	380.988	3.017
6100	1052.4	390.095	2.915
6200	1063.5	399.272	2.818
6300	1074.5	408.520	2.727
6400	1085.4	417.837	2.639
6500	1096.3	427.224	2.556
6600	1107.0	436.679	2.476
6700	1117.6	446.202	2.400
6800	1128.2	455.793	2.328
6900	1138.7	465.451	2.259
7000	1149.1	475.176	2.193
7100	1159.4	484.967	2.129

7200	1169.7	494.824	2.069
7300	1179.9	504.746	2.010
7400	1190.0	514.734	1.955
7500	1200.0	524.786	1.901
7600	1210.0	534.902	1.850
7700	1219.9	545.082	1.801
7800	1229.7	555.325	1.754
7900	1239.5	565.631	1.708
8000	1249.2	576.000	1.664
8100	1258.8	586.431	1.622
8200	1268.4	596.924	1.582
8300	1277.9	607.478	1.543
8400	1287.3	618.094	1.505
8500	1296.7	628.7702	1.469
8600	1306.0	639.507	1.434
8700	1315.3	650.304	1.400
8800	1324.5	661.161	1.368
8900	1333.7	672.078	1.331
9000	1342.8	683.052	1.306
9100	1351.9	694.086	1.276
9200	1360.9	705.179	1.248
9300	1369.8	716.329	1.221
9400	1378.7	727.538	1.194
9500	1387.6	738.804	1.168
9600	1396.4	750.128	1.143
9700	1405.1	761.509	1.120
9800	1413.8	772.946	1.096
9900	1422.5	784.440	1.073
10000	1431.1	795.999	1.0514

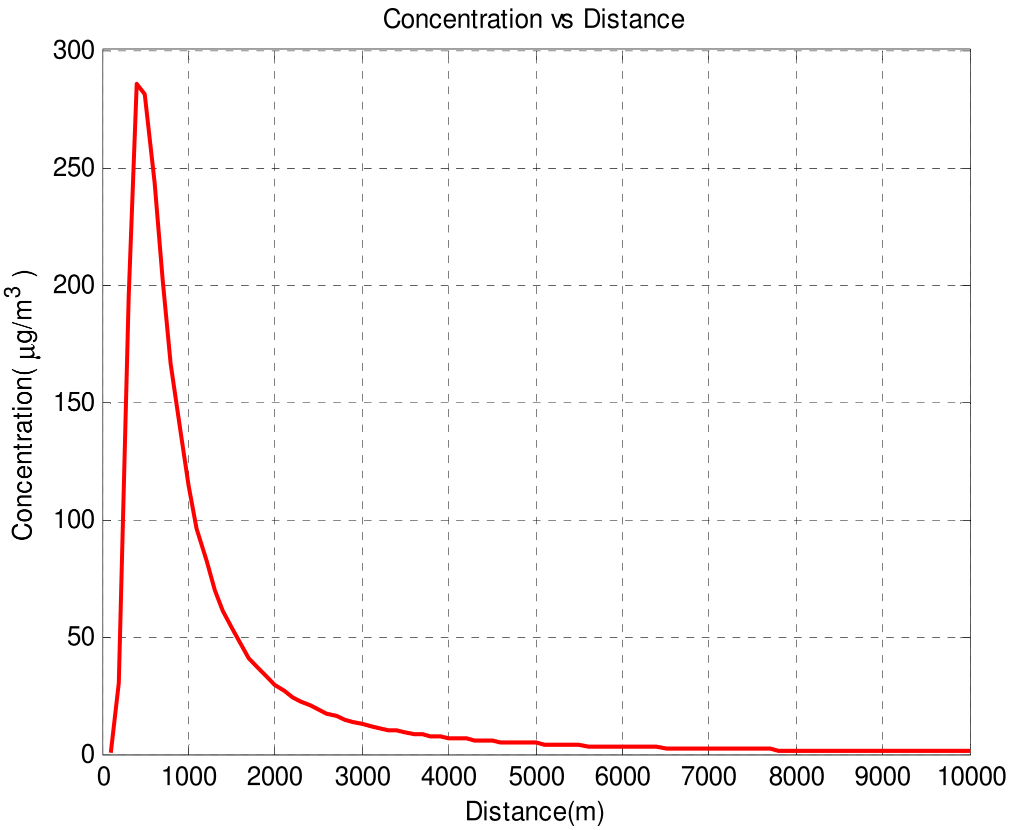


Figure 4.3. Effect of atmospheric stability (unstable) on particle matter concentration with distance variation.

As shown in the output, the dispersion coefficients increased in the y and z-directions as shown in Figures 4.1, 4.2 and 4.3. Maximum concentration occurs in neutral condition but distribution of pollutants is better for unstable conditions in which its concentration decreases with distance relative to stable condition and neutral condition.

Effect of exit velocity: Using the following matlab code, the effect of exit velocity on ground concentration is shown.

```
Format short
D=0.7;
u=11;
Q=20;
p=786.6;
Ts=313;
Ta=289;
h=10;
y=20;
z=2;
sigmay=[];
  sigmaz=[];
  C=[];
  Xfinal=[];
for vs=10:5:40;
      for x=100:500:3400;
         x1=(vs*D)/u;
         x2=(Ts-Ta)/Ta;
dh=x1*(1.5 +(0.00268*p*D*x2));
H=dh+h ;
```

```
sigmayCur=(0.16.*x.*((1+(0.0004.*x)).^-0.5));
    sigmazCur=(0.14.*x.*((1+(0.0003.*x)).^-0.5));
CCur=((Q./(2.*pi.*u.*sigmayCur.*sigmazCur)).*exp((-y.^2)./(2.*(sigmayCur.^2)))).*(exp((-(z-H).^2)./(2.*(sigmazCur.^2)))+ exp((-(z+H).^2)./(2.*(sigmazCur.^2))));
         end
   sigmay=[sigmay,sigmayCur];
  sigmaz=[sigmaz,sigmazCur];
  C=[C;CCur];
  dh
  H
end
sigmay
sigmaz
C;
Concentration=C.*(10.^6)
```

By running the above matlab code, the output data and the graph are as follows:

```
vs=[10,15,20,25,30,35,40];
C=[5.5763,5.576,5.5756,5.5753,5.5749,5.5745,5.5741];
plot(vs,C)
xlabel('Exit velocity ,m/s')
ylabel('Concentration,microgram/metercube')
```

Based on the above programme, the output is shown in Table 4.5 and Fig.4.4.

Table 4.5. Effect of exit velocity on the ground level concentration.

dh(plume rise)	H(effective height)	vs(Exit velocity)	C((μg/m^3))
1.0325	11.0325	10	5.5763
1.5488	11.5488	15	5.5760
2.0651	12.0651	20	5.5756
2.5813	12.5813	25	5.5753
3.0976	13.0976	30	5.5749
3.6139	13.6139	35	5.5745
4.1301	14.1301	40	5.5741

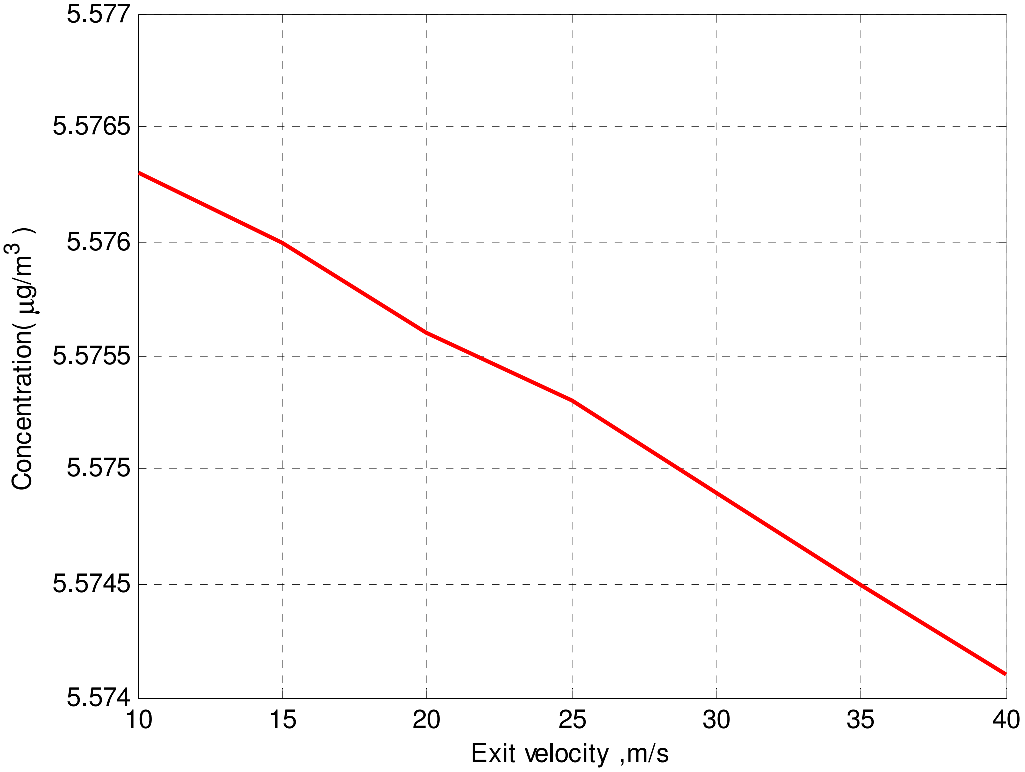


Figure 4.4. Effect of exit velocity on concentration of particulate matter concentration.

As shown in the Figure 4.4, when exit velocity increased, plume rise increased and finally ground level concentration decreased.

Effect of exit temperature: By varying the value of exit temperature from Ts=313:40:450 and taking v_s=10 m/s for the previous programme, the effect of exit temperature on ground level concentration is shown in Table 4.6.

Table 4.6. Effect of exit temperature on the ground level concentration.

Exit temperature(k)	Concentration(μg/m^3)
313	5.5763
353	5.5762
393	5.5761
433	5.5760

```
Ts=[313   353   393   433];

C=[5.57632563247159,5.57624322150054,5.57615984657732,5.57607550774519]

plot(Ts,C,'Color','red','LineWidth',2)

xlabel('Exit temperature,K')

ylabel('Concentration( {\mu}g/m^3 )')

grid on
```

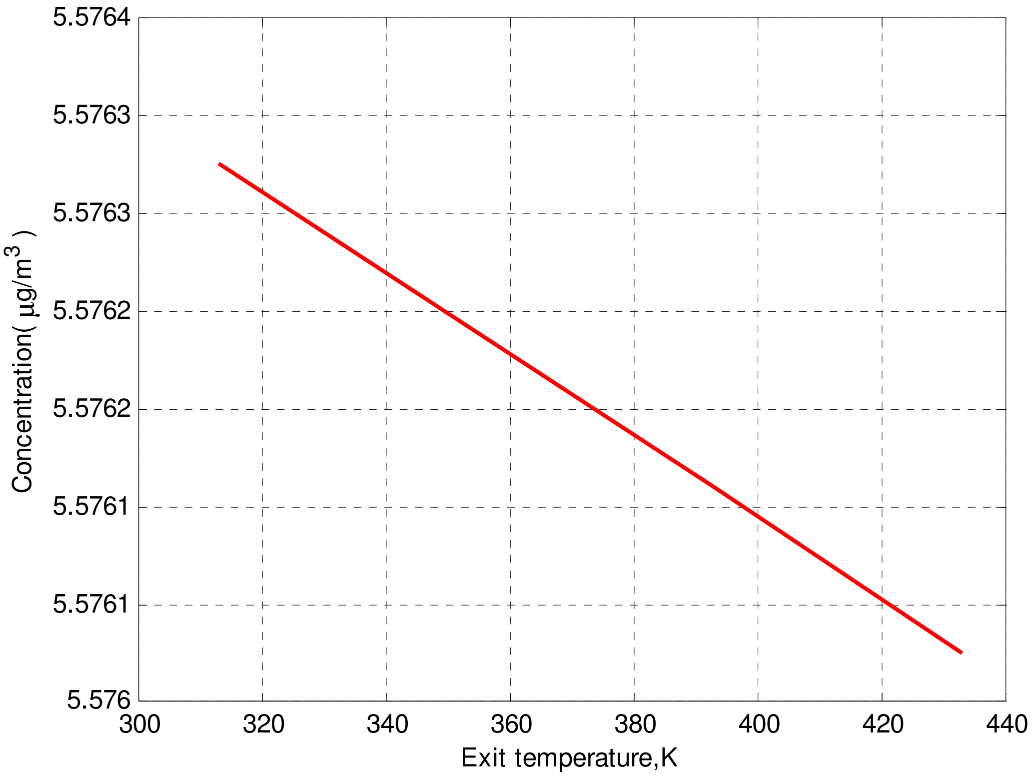


Figure.4.5. Effect of exit temperature on particulate matter concentration.

Based on Figure 4.5, when exit temperature increased, density of gases decreased and then gases go to upper layers in which ground level concentration decreased.

Effect of stack height: With similar matlab code, but varying the stack height,the output of programme is indicated in Table 4.7.

Table 4.7. Effect of stack height on the ground level concentration.

Stack height(m)	Concentration((μg/m^3)
15	3.1688
25	3.1649
35	3.1593
45	3.1519
55	3.1427
65	3.1317
75	3.1189
85	3.1045
95	3.0883

To plot the graph of variation of concentration with stack height, the following matlab code is used:

```
C =[3.1688,3.1649,3.1593,3.1519,3.1427,3.1317,3.1189,3.1045,3.0883];

h =[15,25,35,45,55,65,75,85,95];

plot(C,h,'Color','red','LineWidth',2)

xlabel('Concentration( {\mu}g/m^3 )')

ylabel('Stack height,m')

grid on
```

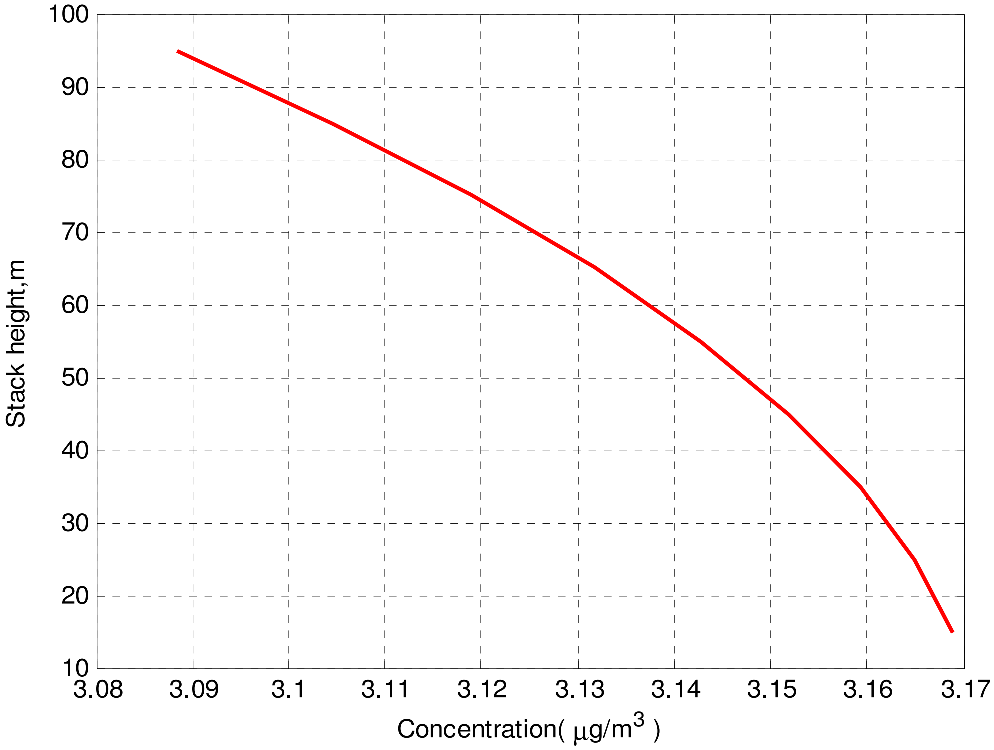


Figure 4.6.Effect of stack height on particulate matter concentration.

From the above figure, the ground level concentration decreases with increasing stack height.

Effect of wind velocity: Variation of concentration with wind velocity is shown Table 4.8 by considering the matlab code as the same as the previous one.

Table 4.8.Effect of wind velocity on the ground level concentration.

Wind velocity(m/s)	Concentration((µg/m^3))
1	34.8366
2	17.4288
3	11.6211
4	8.7164
5	6.9734
6	5.8113
7	4.9812

To plot the graph for variation of concentration with wind velocity, the following matalab code is used:

```
C=[34.8366,17.4288,11.6211,8.7164,6.9734,5.8113,4.9812]
uo=[1,2,3,4,5,6,7]
plot(uo,C,'Color','red','LineWidth',2)
xlabel('windspeed,m/s')
ylabel('Concentration( {\mu}g/m^3 )')
grid on
```

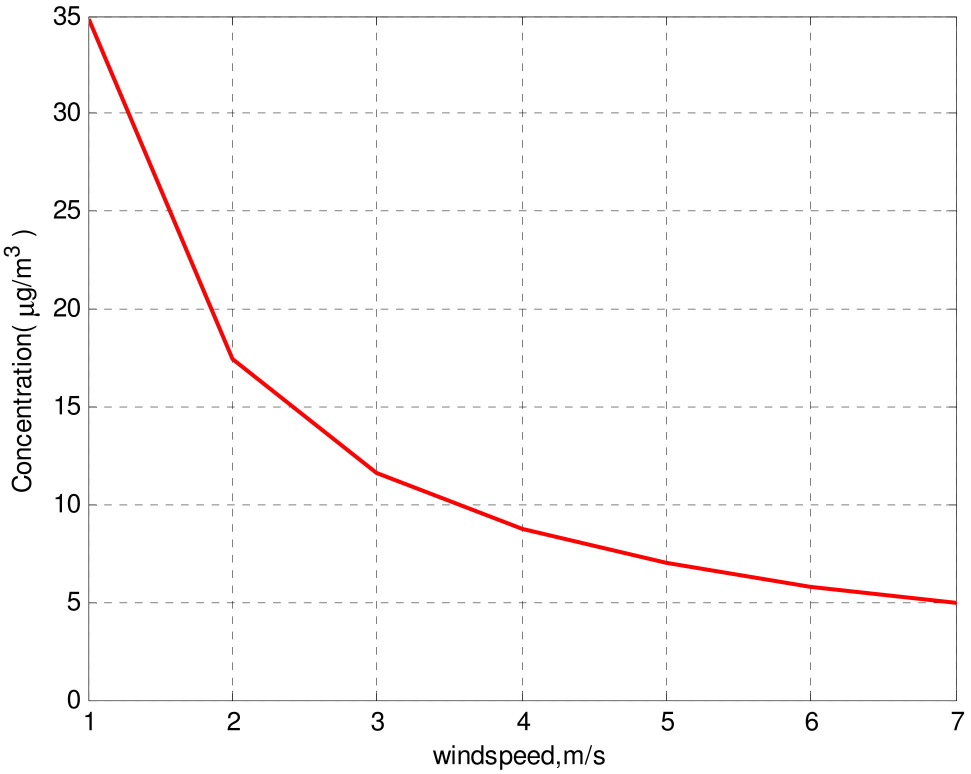


Figure 4.7. Effect of wind speed on particulate matter concentration.

As indicated in Figure 4.7, pollution dispersion decreased when wind velocity increased and pollutants went far from the stack region.

Effect of air temperature: The following matlab code is used to show the dispersion of pollutants with distance due to the effect of different air temperatures.

```
clc

clear all

format long

D=0.7;

u=11;

Q=20;

p=786.6;
```

```
% Ta=289;
h=10;
y=20;
z=2;
vs=10;
Ts=313;
zo=2;
sigmay=[];
sigmaz=[];
C=[];
Xfinal=[];
z1=10;
u=11;
for Ta=280:5:310
x1=(vs*D)/u;
x2=(Ts-Ta)/Ta;
dh=x1*(1.5 +(0.00268*p*D*x2))
% fprintf('The value of dh is= %f\n',dh);
% disp(' ********************************')
H=dh+h ;
for x=100:500:5000;
sigmayCur=(0.16.*x.*((1+(0.0004.*x)).^-0.5));
```

```
sigmazCur=(0.14.*x.*((1+(0.0003.*x)).^-0.5));

CCur=((Q./(2.*pi.*u.*sigmayCur.*sigmazCur)).*exp((-y.^2)./(2.*(sigmayCur.^2)))).*(exp((-(z-H).^2)./(2.*(sigmazCur.^2)))+ exp((-(z+H).^2)./(2.*(sigmazCur.^2))));

end

C=[C;CCur];

end

C;

%Concentration of pollutants should be in microgram per metercube

Concentration=C.*(10.^6)
```

For variation of temperature from Ta=280:5:310, concentration output is shown in Table 4.9 and graph of concentration variation with air temperature is shown in Figure 4.8.

Table 4.9.Effect of air temperature on the ground level concentration.

Air temperature(K)	Concentration (µg/m3)
280	3.169994194
285	3.169997898
290	3.170001468
295	3.170004912
300	3.170008236
305	3.170011446
310	3.170014548

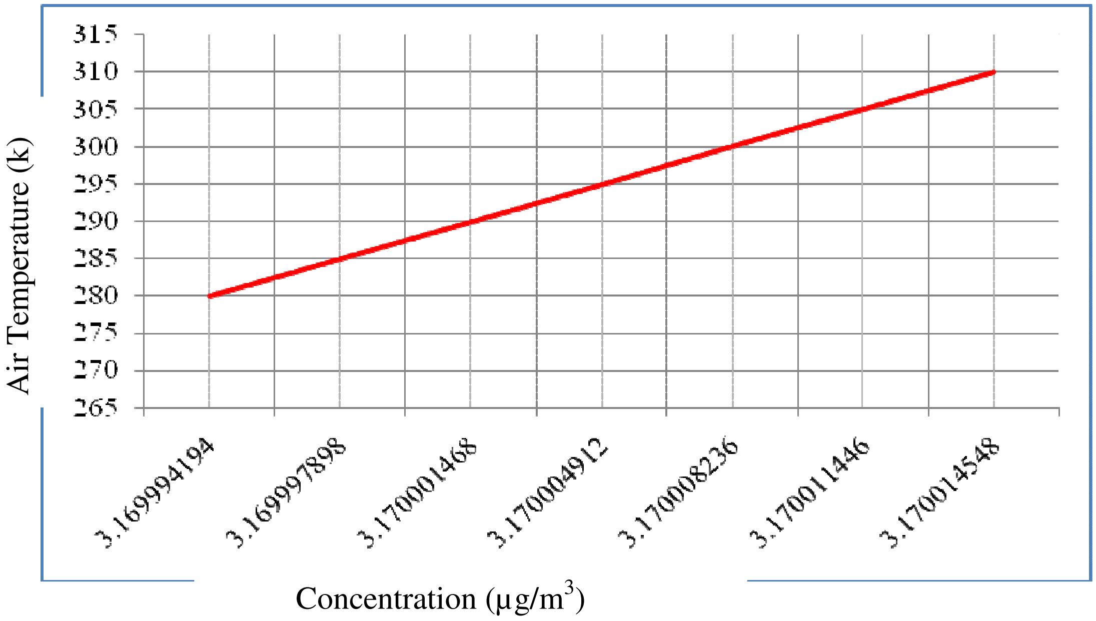


Figure 4.8. Effect of air temperature on particulate matter concentration.

The dispersion of pollutants increased with increasing temperature and then pollutants came down near the stack region. An increase in dispersion occurs, because when temperature increases, the dispersion coefficient increases. Besides this, the ground level concentration increases with increasing exit concentration.

The above simulation runs clearly illustrate the utility of the program in helping decision makers about air pollution control and the effects of different variable on pollution dispersion. For instance the following observations are made based on the simulation runs:

1. Under winter (‘Bega’) conditions, places that are far from the stack observe higher pollutant concentrations, while under summer (‘keremete’) conditions places near the stack are affected most.
2. By increasing stack heights, pollutants go up into the atmospheric layer and pollution gets dispersed over a wider region and ground level concentration decreases.
3. Increasing exit velocity and temperature for stack’s emission causes a decrease in ground level concentrations.
4. Decreasing exit concentration can be obtained by reducing the emission rates. This can be achieved, for instance, by installing control devices and/or redesigning factories by using new technologies.

In the analysis of concentration of pollutants from different stability criteria cases indicated above, the concentration are beyond the standard limited allowed by any EPA (Environmental Protection Agency). As the maximum concentration of particle matter is 1123.2 $\mu g/m^3$ from the predicted model, therefore the pollutant concentration should be reduced or controlled by proper monitoring of the industry within operating conditions that are complied with EPA standard. The mathematical expression developed can also go along way to control the pollution because if the concentration of pollutants at certain region is known, effort can be geared towards preventing further dispersion from point of discharge to the areas yet to be polluted.

5. Conclusion and Recommendation

Gaussian formulation is one of the most commonly used frameworks for modeling local dispersion of a pollutant which describes the transport and diffusion of a gas (or particles) from a source to a receptor according to stability class, wind speed and other parameterized characteristics of the atmosphere.

The variation of concentration with distance for different parameter of stability and wind speed, ambient air temperature and stack height was identified. From each parameter, there is variation of concentration and dispersion coefficient. In the analysis, the neutral stability criteria produced the maximum concentration at the ground system which is 1123.2 $\mu g/m^3$ that validates the developed model is practically visible because it provides a real picture of the model. Therefore, it is the neutral atmosphere that produces the highest peak downward concentration rather than the unstable atmosphere. The turbulence in an unstable atmosphere brings the plume to earth very quickly, resulting in high peak values near the stack in which concentration drop off quickly.

In general, the matlab programme developed validates the theoretical Gaussian dispersion model that are applied to show the variation of ground concentration with distance which leads the firms to use some air pollution devices and equipment to reduce the load on the ecosystem. Therefore, bag filter is recommended to decrease the concentration of the pollutant to 150 $\mu g/m^3$, Ethiopian particulate matter air quality standard. And it also recommended that the safe distance for human habitation from the emission source should be one (1) km away.

Effective stack height should be sufficient to provide adequate dispersion related to the wind speed to the extent to which emissions can rise into the atmosphere to decrease its effect on ground system in the absence of inversion.

In addition, it is recommended that the consideration of chemical reaction in the atmosphere and unsteady state condition as a future prospect project on pollutant dispersion modeling for further works in this area.

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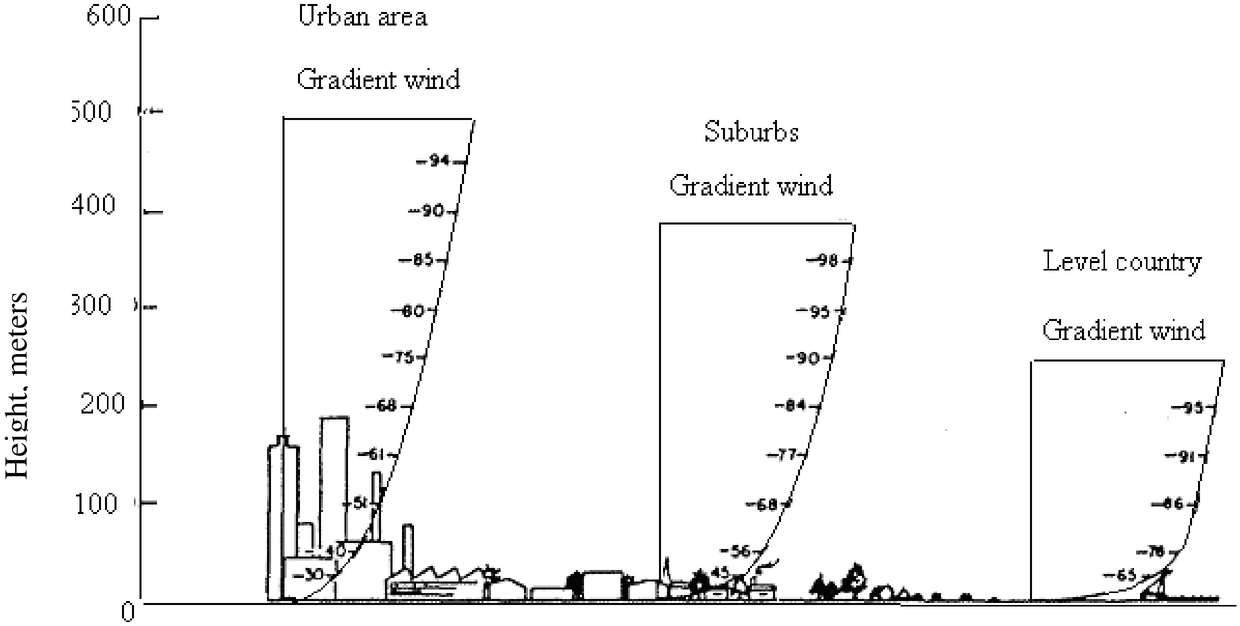
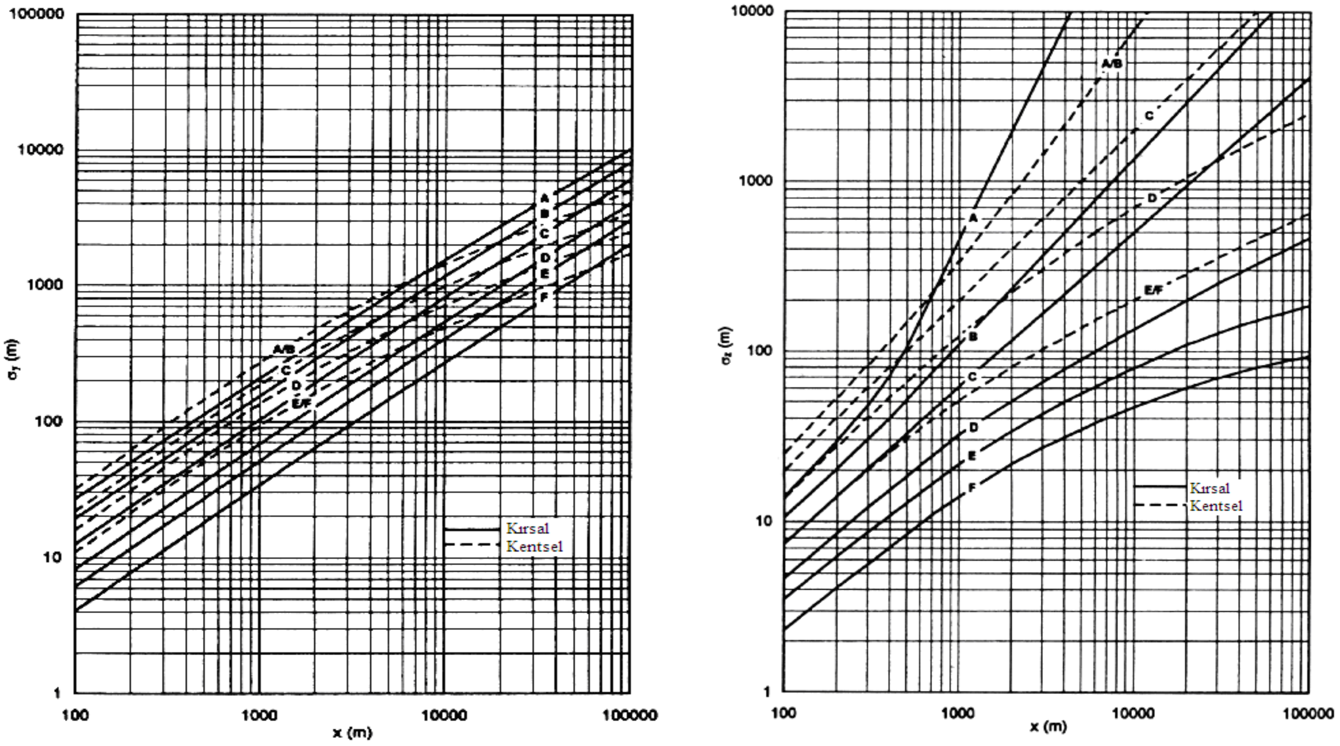
Annexes

Annex 1. Example of variation of wind with height over different size roughness elements (figures are percentages of gradient wind) (from Davenport, 1963)



Annex 2. Gaussian dispersion coefficients as a function of distance downward: a).Horizontal coefficients σ_y: b). Vertical coefficients coefficient σ_z.(Turner ,1970)



Annex 3. Average temperature of Addis Ababa of 2010/2011(2002 E.C) [21].

Months	Average Minimum Temperatures in Addis Ababa, Ethiopia (°C)	Average Maximum Temperature in Addis Ababa, Ethiopia (°C)	Addis Ababa Average Temperature (°C)
January	7	23	15
February	8	24	16
March	10	25	18
April	11	24	18
May	11	25	18
June	10	23	17
July	10	20	15
August	10	20	15
September	10	21	16
October	8	22	15
November	7	23	15
December	7	23	15
Average Temp.	9.08	22.75	16.08333

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any University, and that all the source of materials used for the thesis has been duly acknowledged.

Declared by:

Name: Anteneh Muheye

Signature: ___________________________

Date: _______________________________

Confirmed by:

Name: Ato Teshome Worku (Ass.Professor)

Signature: _____________________________

Date: _________________________________