ANALYSIS OF THE FACTORS AFFECTING THE DISTRIBUTION OF CHIMNEY EMISSIONS TO THE ATMOSPHERE – SIMULATION APPROACH

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ABSTRACT

In this work, a computer program has been constructed for investigating the factors affecting the dispersion of stack emissions. These factors are wind speed, wind direction with respect to source, wind direction with respect to receptor, ambient air temperature and atmospheric stability conditions. The analysis is done via a 3-D graphical model which simulate the reality. A case study is applied for four stacks. The results indicate that the effect wind speed on total concentration, from the four stacks, is directly proportional to the increase of wind speed, while the distance of maximum concentration is inversely proportional to it. Also it is found that the total concentration is inversely proportional to the increase of wind angle direction with respect to receptor, while the distance of maximum concentration is shifted towards the source location. Total concentration is directly proportional to the increase of ambient air temperature, while the distance at which the maximum concentration occurs is almost constant. With regards to atmospheric stability conditions, the study indicates that Stability classes E and F give higher concentration than other classes while stability classes C and D give the lowest concentration.

KEYWORDS: Chimney Emissions, Graphical Model, Atmosphere

INTRODUCTION

The subject of environmental science and management is vast and interdisciplinary, ranging from highly technical matters such as the design of emission control equipment to socioeconomic matters such as the evaluation of the impacts of pollution. The goal is to prevent or reduce undesirable impacts of human activities on the environment. The criteria pollutants are carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO2), ozone (O3), particulate matter (PM), and sulfur dioxide (SO2). There are also a large number of compounds which have been determined to be hazardous which are called air toxics. Air quality modeling predicts how air pollution will affect surrounding air quality based on weather, topography, and other factors. To do this, air quality models imitate the physical and chemical processes that take place in the atmosphere. For solving any air quality problem of emission from stacks and vents, there are two basic approaches, theoretical approach and experimental approach. For each approach, there are advantages and disadvantages. Theoretical studies include analytical/numerical solutions to several appropriate equations that represent the physics of the pollutant downwind concentrations. Obviously, any air quality model must compare with real life data, to evaluate the performance of it. Experimental studies include field studies and wind tunnel studies. Field studies are likely to be most accurate of the two approaches, as they involve direct measurement of pollutant concentrations at strategically located receptors. The disadvantage of field studies is that they are expensive to conduct and typically require long lead times. One cannot place any control on mother nature for a certain condition on a given day. Wind tunnel, studies are physical simulations of actual field study experiments. Scientists have found that it is extremely expensive to simulate exact external atmospheric conditions in a typical wind tunnel study. Specifically, difficulty is faced in satisfying the conditions of similarities (i.e.
scaling requirements) and the limitation of instruments to measure turbulence, mixing height, atmospheric stability, and other parameters. In most dispersion models, determining the pollutant concentrations at ground-level receptors beneath an elevated buoyant plume of dispersing pollutant-containing gas involves two major steps: First step, the height to which the plume rises at a given downwind distance from the plume source is calculated. The calculated plume rise is added to the height of the plume's source point to obtain the so-called "effective stack height", also known as the plume centerline height or simply the emission height. Second step, the ground-level pollutant concentration beneath the plume at the given downwind distance is predicted using several dispersion equations. The air quality models can be used for the following purposes as example: Regional Planning, Supplementary Control Systems, Air Quality Prediction System, Accidental Releases...etc. The amounts and types of emissions change every year. These changes are caused by changes in the nation's economy, industrial activity, technology improvements, traffic ...etc. These curves are developed from research on dispersion over a five to fifteen minute averaging period on grassy, relatively flat terrain. Commonly used Gaussian models have a special constraint; plume direction should remain constant in any given direction for at least one hour, the minimum averaging time. Incidentally, the one-hour averaging time is much greater than the averaging period used to develop Pasquill-Gifford coefficients, which can lead to model over prediction of air concentrations.In addition to dispersion parameters, the magnitude of model predicted ground level concentrations depends upon the effective plume centerline height. Effective plume height, $H$, is the source release height, $h$, plus plume rise, $\Delta h$, due to gas momentum from mechanical air forcing, or from heated gas buoyancy figure 1.

![Figure 1: Depicts a Typical Gaussian Plume](image)

Plume movement and behavior are influenced by local meteorology, building downwash and terrain. Meteorology is the most important factor. Meteorological parameters used in dispersion models include wind direction, wind speed, ambient temperature and atmosphere stability class. As mentioned previously, wind speed and atmosphere stability parameters help in determining the modeled shape of a plume. Plume behavior can also be affected by interaction with mountainous or complex terrain. Special models exist to address plume movement in valleys, around mountains, over water, and near shorelines. Other models address short-term impacts for chemicals in different physical states. Complicated processes occurring in nature could be described using mathematical models. When a pollution source emits a pollutant gases into the atmosphere at an initial concentration (mass per unit volume of air), the pollutant gases do not remain at that initial concentration. Wind and other atmospheric parameters disperse the emissions downwind into less concentration. Air dispersion models are computer tools that use mathematical equations to describe the dispersion process. Knowing the initial pollutant gases release characteristics, one can use a dispersion model to predict pollutant gases concentrations in the atmosphere at selected downwind receptor locations. In the present work a Gaussian model which commonly used for regulatory purposes is considered. Most of the techniques used in this model are based on assumptions and methods common to Gaussian dispersion models. These assumptions, properties of exit conditions and stack mouth location, are constants. Therefore, wind velocity profile, ambient temperature and turbulence do not vary with along the downwind path.
These assumptions are valid only for large industrial plants with stacks above 100 m, Anfossi, D. et al (1992)[1]. The present model uses a Gaussian plume model that incorporates source related factors and meteorological factors to estimate pollutant concentration from continuous sources. It is assumed that the pollutant does not undergo any chemical reactions, and that no other removal processes, such as wet or dry deposition, act on the plume during its transport from the source. The Gaussian model equations and the interactions of the source-related and meteorological factors are based on Turner, (1970) [Ошибка! Закладка не определена.]. The following assumptions are used in the present model, multiple buoyant or passive industrial emissions, rural areas, flat terrain, continuous and constant emission rate, constant wind speed in time and elevation, the ground reflected all the pollutants hit it, the concentration of pollutants has a normal distribution, the emissions disperse in the three directions, dispersion in direction X is a function of the wind speed, dispersion in cross wind direction (Y) and vertical wind direction (Z) takes the form of normal Gaussian curve and is described by the Gaussians plume equation, the maximum concentration occurs at the center of the plume. All inputs requirements are given from the plant or the source and have to include the following:

**Source Data**

- Q  Emission rate the quantity of gases, [g/s]
- h  Physical stack height, [m]
- ve Stack gas exit velocity, [m/s]
- d  Stack top inside diameter, [m]
- Ts  Stack exit gas temperature, [K]
- n  Number of sources, (number of stacks).
- rs  Distance of each source to the origin in meters.
- Θs  Location angle of the source to the X direction.

**Meteorological Data**

- Ta  Ambient air temperature, [K]
- Θ  
- w  Angle of the wind direction to X direction.
- u  Wind velocity, [m/s]
- A to F  Stability class form.

**Receptor Data**

- rr  Distance from the receptor to origin,[m]
- zr  Receptor height from the earth level.
- Θr  Receptor angle with X direction.

The point where the concentration calculated is called receptor. According to the above mentioned parameters, the model creates a grid of receptors. Any receptor is defined by Rr, Θr and Zr (Cylindrical Coordinate). Also emission rate, stack height, stack exit inside diameter, stack exit temperature and stack exit velocity are required as inputs data. According
to the grid of receptors some sources may be located in front of the receptor or behind it depending on receptor range, \(R_r\), and wind direction. To save time and effort, the model adjusted to eliminate the sources which lie on the same or in front of the line passing through the receptor and perpendicular to the wind direction. The plume effective height \(H\) for each source is calculated according to Briggs formula, [Ошибка! Закладка не определена.].

\[
F_b = g v_s d_s^2 \Delta T / 4 T_s
\]

\[
\Delta h = F_b / u
\]

\[
H = h + \Delta h
\]

where:

\(F_b\) Briggs buoyancy flux

\(\Delta h\) plume rise

\(H\) effective height

The plume dispersion is calculated depending on lateral dispersion and vertical dispersion coefficient \(\sigma_y, \sigma_z\). These coefficients are calculated according to Boubel, R. W., [Ошибка! Закладка не определена.], equations as follows:

**Lateral Dispersion \(\sigma_y\)**

\[
\sigma_y = \alpha \frac{X}{\sqrt{1 + 0.0001x}}
\]

\(\alpha=0.22\) stability class A

\(\alpha=0.16\) stability class B

\(\alpha=0.11\) stability class C

\(\alpha=0.08\) stability class D

\(\alpha=0.06\) stability class E
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\( \alpha = 0.04 \)  

**stability class F**

**Vertical Dispersion \( \sigma_z \)**

\[
\sigma_z = 0.2x \quad \text{Stability class A} \tag{5}
\]

\[
\sigma_z = 0.12x \quad \text{Stability class B} \tag{6}
\]

\[
\sigma_z = 0.08 \frac{x}{\sqrt{1 + 0.0002x}} \quad \text{Stability class C} \tag{7}
\]

\[
\sigma_z = 0.06 \frac{x}{\sqrt{1 + 0.0015x}} \quad \text{Stability class D} \tag{8}
\]

\[
\sigma_z = 0.03 \frac{x}{\sqrt{1 + 0.0003x}} \quad \text{Stability class E} \tag{9}
\]

\[
\sigma_z = 0.016 \frac{x}{\sqrt{1 + 0.0003x}} \quad \text{Stability class F} \tag{10}
\]

Where \( x \) is measured from the source. Using the results of \( \sigma_y \) and \( \sigma_z \), together with equation (11), the Gaussian hood shape plotted in the 3D dimensions for each source, which represent the emission prorogation in the wind direction and around the plume center line, can be plotted, figure (3.6).

\[
f(x) = \frac{Q}{2\pi \sigma_y \sigma_z} e^{-\frac{-(y-\mu)^2}{2\sigma_y^2} + \frac{-(z-\mu)^2}{2\sigma_z^2}} \tag{11}
\]

Where:

\( f(x) \)  

density function

\( \mu \)  

mean value in distribution direction.

A horizontal plane, with height equals to the receptor height is drawn and cuts the 3-D Gauss hood, figure 3.
Figure 3: Gauss Hood and Cutting Plane at Receptor Height
The result of this cutting gives a 2D Gauss distribution shape around the main axis, which is wind direction. For several sources $s_1$, $s_2$, and $s_3$ as shown in figure 4, the drawn lines which passes through the sources and parallel to the wind direction, the length of lines that intersect with the base and the Gauss curve line, are the concentration value of the sources at the receptor. The summation of these lengths gives the total concentration of all sources at the receptor.

CASE STUDY
Assume the following case to study the effect of the factors mentioned above on the dispersion of stacks emission in the air. The results are shown in figure 5.

- Number of stacks: 4 inline
- Distance between stacks: 75 [m]
- Distance from organ to 1st stack: 75 [m]

Stack Specifications
- Physical height: 123 [m]
- Top inner diameter: 4.6 [m]
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- Emission rate \(350000 \text{ [g/s]}\)
- Emission exit temperature \(125 \text{ [°C]}\)
- Emission exit velocity \(20 \text{ [m/s]}\)

**Receptor Specifications**

- Height of all receptors is fifteen meters.
- Range is 50,000 meters from the origin with a 500 meters step.
- All receptors lie on same line.

**EFFECT OF WIND SPEED**

Effect of wind speed on emission dispersion is studied. Four values for wind speed are taken, 1, 3, 5 and 7 [m/s]. All other data are kept constant. These data are:

- Stack specification (given in the introduction)
- Wind direction with respect to X axis = 0
- Ambient air temperature = 20 [°C]
- Stability class = D
- Receptor specification (given in the introduction)
Figure 6 shows that at a wind speed of 1 [m/s], the total concentration is almost zero for a distance up to 5500 m after which concentration gradually decreases to a value of 64988 µg/m³ at 50,000 m. It shows that at a wind speed of 3 [m/s], the total concentration is almost zero for a distance up to 1500 m after which concentration is rapidly increased to reach its maximum value of “68857 [µg/m³]” at 36500 meters then decreases to a value of 64988 [µg/m³] at 50,000 m. Also, it can be shown that the variation of total concentration versus distance at a wind speed of 5 [m/s]. The figure indicates that the total concentration is almost zero for a distance up to 1000 m after which concentration is rapidly increased to reach its maximum value of “160446 [µg/m³]” at 8500 meters then decreases to a value of 25294 [µg/m³] at 50,000 m. It is shown also that at a wind speed of 7 [m/s], the total concentration is almost zero for a distance up to 750 m after which concentration is rapidly increased to reach its maximum value of “224740 [µg/m³]” at 4000 meters then gradually decreases to a value of 18378.33 [µg/m³] at 50,000 m.

This figure shows that the total concentration is directly proportional to the increase of wind speed, while the distance where maximum concentration occurred is inversely proportional to it. The analysis indicates that the effective plume height, H, is inversely proportional to the increase of wind speed. Thus, the effect of wind speed works in two opposite directions; increasing wind speed will decrease plume rise, thus increase ground level concentrations. Also, increasing wind speed will increase mixing, thus the distance where maximum concentrations occurs is decreased. These results agree with the conclusion given by Irwin (1979).

EFFECT OF WIND DIRECTION

Effect of wind direction with respect to the sources on emission dispersion is studied. Four wind directions with respect to X, Θ_w = axis 0, 1, 3 and 5 degrees. In this case all receptors are lied at a line passing through the origin and in the wind direction. All other data are kept constant. These data are:

- Stack specification (given in the introduction)
- Wind speed = 3 [m/s]
- Ambient air temperature = 20 [°C]
- Stability class = D
- Receptor specification (as given in the introduction)

Figure 7 shows the outline of receptor and wind direction with respect to the sources.

![Figure 7: The Outline of Receptor and Wind Direction with Respect to the Sources](image-url)
Figures 8 show that the variation of total concentration with distance is the same for all studied wind directions. The total concentration is almost zero for a distance up to 1500m after which concentration is rapidly increased to reach its maximum value of "160446 [µg/m3]" at 8500 meters then gradually decreases to a value of 39796 [µg/m3] at 50,000m.

There is no effect of the change of wind direction with respect to source on total concentration if the receptors are laid in the same direction of the wind. Effect of wind direction with respect to receptor on emission dispersion is studied. Four wind direction angles with X axis 0, 1, 3 and 5 degrees are taken. All other data are kept constant.

These data are:
- Stack specification (given in the introduction)
- All receptors lie on the X axis
- Wind speed = 3 [m/s]
- Ambient air temperature = 20 [°C]
- Stability class = D
- Receptor specification (as given in the introduction)

It can be concluded that the total concentration is inversely proportional to the increase of wind angle direction with respect to receptor, while the distance of maximum concentration is almost constant.

![Figure 8: Effect of Wind Direction with Respect to Receptor on Concentration](image)

**EFFECT OF AMBIENT AIR TEMPERATURE ON CONCENTRATION**

Effect of ambient air temperature on emission dispersion is studied. Five values for ambient temperature are taken, 5, 10, 20, 30 and 45 [°C]. All other data are kept constant. These data are:
- Stack specification (given in the introduction)
- Wind direction with respect to X axis = 0
- Wind speed = 3 [m/s]
- Stability class = D
- Receptor specification (as given in the introduction)
Figure 9: Effect of Ambient Air Temperature on Total Concentration

Figure 9 figure shows that the total concentration is directly proportional to the increase of ambient air temperature, while the distance of maximum concentration is almost constant.

The effective plume height, $H$, is inversely proportional to the increase of ambient air temperature. This is due to the decrease of the buoyancy flux, $F_b$, as defined before.

EFFECT OF STABILITY CLASS ON CONCENTRATION

Effect of Stability classes on emission dispersion is studied. All stability classes from A to F are taken. All other data are kept constant, these data are:

- Stack specification (given in the introduction)
- Wind speed = 3 \text{ [m/s]}
- Wind direction with respect to X axis = 0
- Ambient air temperature = 20 \text{ [°C]}
- Receptor specification (as given in the introduction)

Figure 10: Effect of Stability Class on Total Concentration

CONCLUSIONS

In the present work a computer program has been constructed for investigating the factors affecting the dispersion
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of stacks outlets. Total concentration is directly proportional to the increase of wind speed, while the distance where maximum concentration occurs is inversely proportional to wind speed.

There is no effect of wind direction with respect to source on total concentration if the receptors lie in the same direction of the wind at a line passing through the origin.

Total concentration is inversely proportional to the increase of angle of wind direction with respect to receptor, while the distance of maximum concentrations is shifted towards the source location.

Total concentration is directly proportional to the increase of ambient air temperature, while the distance at which the maximum concentration occurs is almost constant. Stability classes E and F give higher concentration than other classes while stability classes C and D give the lowest concentration.

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