VISUALISING POINT SOURCE POLLUTANT CONCENTRATION LEVEL DISPERSION USING THE GAUSSIAN MODEL

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ABSTRACT. *In this study, we examined the usage of the Gaussian air dispersion model to visualise point source pollutant concentration levels and implemented it in MASPLUME, a newly developed computer software which functioned as an estimation tool application for measuring the concentration level (at ground zero) of a selected pollutant dispersed from a single point source. The identified pollutants were carbon monoxide, nitrogen dioxide, and sulphur dioxide. MASPLUME was able to show a two-dimensional static air pollution dispersion and concentration level, as well as graphical data for different scenario analysis. Although MASPLUME is in its initial development stage as a comprehensive software, it would still be sufficient as a current teaching and learning aid.*

KEYWORDS. Visualisation; Gaussian Model, Air Pollution, Concentration Dispersion, Point Source

INTRODUCTION

This paper reports on the implementation of the Gaussian Dispersion Model in MASPLUME, a newly developed system used to (1) predict how specific pollutants are dispersed from a single point source, and (2) indicate their level of concentration at ground zero. The dispersion was visualised using a two-dimensional (2D) colour coded scatter plot showing the dispersion pattern and concentration level of the pollutants after ten minutes of discharge. Scenario analysis was utilised to help determine the variability of the selected parameters that impacted the concentration of specific pollutants. The problem was localised by observing air pollutants emitted from a single industrial point source (Kibble & Harrison, 2005) and noting the buoyancy of their plume concentration level at various downwind distances on the ground.

Pollutants from industrial point sources are usually emitted through chimneys which need to be sufficiently high for the contaminants to dilute before they reach the ground. This process is essential as the air quality in places near the industrial point sources might have become poor due to improper dilution. Poor air quality could lead to health implications with various researches showing evidence on the positive correlation between reduced air quality and poor health (Afroz, Hassan, & Ibrahim, 2003; Kibble & Harrison, 2005). In the context of Malaysia's air quality, industrial point sources, motor vehicles and open burning activities are the significant sources of air pollution in the country. For point source activities alone, the Environmental Quality Report (EQR) 2009 states a total of 20,298 industrial point source industries was being subjected to the Environmental Quality (Clean Air) Regulation 1978. Though this number had decreased by 6% as compared to the previous year, there was still an increase in the combined pollutant emission load for some gasses; for instance, nitrogen dioxide (NO_2) and sulphur dioxide (SO_2)

increased 30% and 3% respectively due to the addition of power and heat generation plants in the country (DOE, 2009).

If precise control of air pollutant dispersion is to be affected, simulated computer visualisation - a reliable and cost-effective method- might be the solution. Not altogether a new idea, there are already several commercial visualisation software available, each with their own distinctive features. AERMOD for instance uses a Gaussian plume model that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling. It includes surfaces and elevated source treatment on both simple and complex terrains (Air Pollution Software, 2010). Australia on the other hand has its own specially developed software named AUSPLUME which was approved by the Environment Protection Authority (EPA) Victoria in 1986. AUSPLUME predicts ground level concentration for any air pollutant or odour emitted from three different sources - point source, area source and volume source - which depend on the contour map method to visualise the concentration levels. The contour map is displayed on the screen together with an aerial view map as a coordinate background for the analysed area. Starting January 2014 however, AUSPLUME was replaced by AERMOD. (Regulatory air quality model review, 2013).

This study serves as an initial step towards an end product of a similar software specific to the diversity of Malaysia's meteorological and topographical conditions. The objective was to adopt a model able to show dispersion of pollutants, and for this purpose we investigated the Gaussian Dispersion Model proposed by Beychok (2005). The remainder of this paper presents (1) the various considerations in implementing the model, (2) the results, and (3) the limitations or aspects that need to be further improved.

METHODOLOGY

The Gaussian Model is cited as the most common model for air dispersion in many countries compared to others such as the Box Model, Lagrangian Model, Eulerian Model and Dense Gas Model (Beychok, 2005). We identified that the parameters for the applications, could be categorised as more meteorological-condition related or emission-related; the following is a list of primary aspects that we considered in determining the development of the system:

1. *Identifying air pollutant types*

Identified air pollutants for visualisation were Carbon Monoxide (CO), Nitrogen Dioxide (NO2) and Sulphur Dioxide (SO2). These gases were selected due to their toxic nature and impact on health conditions.

2. *Identifying concentration levels*

Air pollutant concentration levels were determined based on the Air Quality Health Index (AQHI Canada) listed scales of 1 to 10+ indicating health risk levels associated with local air quality (Understanding Air Quality Health Index messages, 2010). We utilised the same scale to show the level of pollutant concentration: Levels 1-3 indicated Low concentration, 4-6 moderate, 7-10 high, and above 10 very high. Each of this scale was colour coded for ease of identification when visualised on the scatter plot.

3. Identifying parameters

Parameters were based on meteorological and emission conditions. Meteorological parameters included wind speed and direction, atmospheric turbulence, ambient air temperature, and mixing height. Emission parameters were determined as the physical stack height, emission velocity, stack diameter, emission gas temperature, and emission rate.

4. Applying the Gaussian Model

The graphical visualisation of the Gaussian model is shown in Figure 1 with the equation for its dispersion of a continuous point source plume as follows (Beychok, 2005):

$$C = \frac{Q}{\sigma_z \ \sigma_y \ 2\pi u}\left[e^{\frac{-y^2}{2\sigma_y^2}}\right]\left[e^{\frac{-(z-H_e)^2}{2\sigma_z^2}} + e^{\frac{-(z+H_e)^2}{2\sigma_z^2}} + M\right]$$

(1

Where,

$$M = \sum_{n=1}^{\infty}\left(e^{\frac{-(z-H_e-2nH_m)^2}{2\sigma_z^2}} + e^{\frac{-(z+H_e+2nH_m)^2}{2\sigma_z^2}} + e^{\frac{-(z+H_e-2nH_m)^2}{2\sigma_z^2}} + e^{\frac{-(z-H_e+2nH_m)^2}{2\sigma_z^2}}\right)$$

C = Concentration of pollutant emitted at any receptor located
Q = Source emission rate
u = Horizontal wind velocity along the plume centreline
y = Meter across wind from plume centreline
z = Meter above ground level
H_e = Effective stack height
σ_y = Dispersion coefficient in y direction
σ_z = Dispersion coefficient in z direction
e = Exponential function
H_m = Mixing height

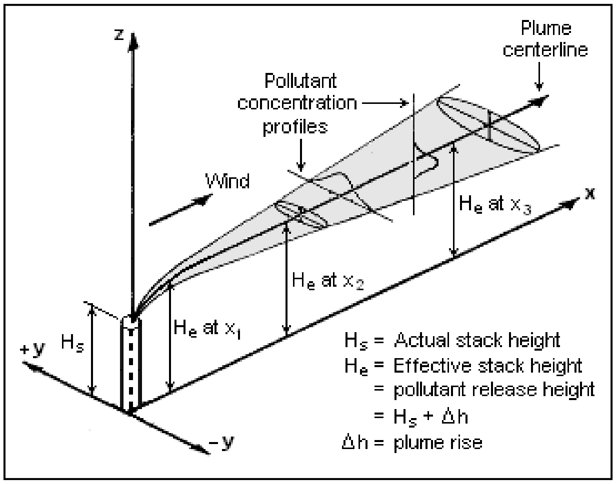


Figure 1: Graphical Visualisation of a Buoyant Gaussian Air Pollutant Dispersion Plume. Source (Beychok, 2005)

Equation (1) included the downward reflection of the plume at a stable layer and ground level which was caused by the temperature inversion. The height from the ground level to the bottom of the stable layer, the mixing height, is assumed to occur with unstable and neutral conditions, and to be undefined when the surface layer is stable (Turner, 1994).

Wind

Different obstructions have different effects on wind speed where some inaccuracy is normal in wind speeds recorded at ground meteorology stations. These stations record ambient atmospheric characteristics, usually at the 10 m level, and typically with lower wind speeds than those affecting the plume (Liptak, 1974). The power law equation is hence introduced to convert the wind speed data at anemometer height to the wind speed velocity at stack height as shown in the following:

$$u = u_1 \left(\frac{H_s}{z_1}\right)^p \tag{2}$$

Where

u_1 = wind speed
H_s = Physical Stack Height
z_1 = Vertical height of wind station
p = Exponent varies with type of ambient weather condition

Hot Plume and Plume Rise

The hot plume emitted from a physical stack height (H_s) does not instantly move in a horizontal x-direction. Instead, it will rise until it has expanded and cooled sufficiently to be in a volumetric and thermal equilibrium with the surrounding atmosphere (Liptak, 1974). The height at which the plume reaches this equilibrium is subjected to effective stack height (H_e) as shown in the following equation:

$$H_e = H_s + \Delta h \tag{3}$$

The significant rise from the stack is referred to as 'plume rise' (Δh), the increase in height induced by the momentum and buoyancy effects of the plume (Liptak, 1974). The calculation of the plume rise for the Gaussian dispersion model will usually consider more this buoyancy factor; Briggs (1970) indicates hot plume buoyancy as the dominant factor compared to momentum forces. The Briggs equation is therefore utilised to determine the buoyancy factor which falls into six stability classes - extremely unstable, moderately unstable, slightly unstable, neutral, slightly stable, and moderately stable (Pasquill, 1961).

$$F = g v_s \left(\frac{d}{2}\right)^2 \left(\frac{\Delta T}{T_s}\right) \tag{4}$$

Where

F = Buoyancy factor
g = Gravitational constant
v_s = Stack gas exit velocity
d = Diameter of stack
T_s = Stack gas temperature
T_a = Ambient temperature
$\boldsymbol{\Delta T}$ = Difference between T_s and T_a

The plume rise has a critical role in reducing the concentration of the plume around ground level. The appropriate type of equation to calculate the plume rise that depends on the buoyancy factor and atmospheric stability is introduced by Briggs (1970). This conditional process is shown in Figure 2.

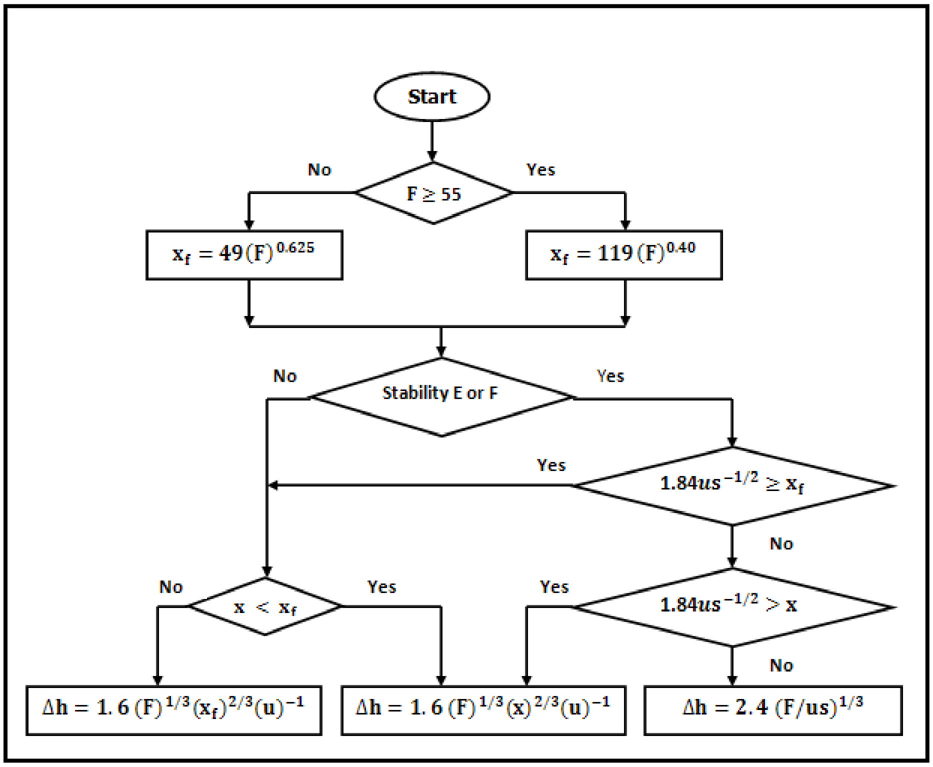


Figure 2: Logic diagram for Briggs' Equation to calculate rise of a buoyant plume.
Source (Beychok, 2005)

Where

x = Downwind distance from plume source
x_f = Downwind distance from plume source to maximum point plume rise
s = Stability parameter

Physical Stack Height

Physical stack height is also considered in the calculation of the effective stack height in the event of a stack-tip downwash which occurs when the ambient wind speed is high relative to the exit velocity of the plume causing some or the entire plume pulled into the wake directly downwind of the stack (Liptak, 1974). The corrected physical stack height is introduced as shown in Equation (5).

$$h_c = H_s + 2d\left[\frac{v_s}{u} - 1.5\right] \tag{5}$$

Where

h_c = Corrected Physical Stack Height
v_s = Emission velocity

Dispersion Coefficient

The dispersion coefficient is defined as the standard deviation for a function of the Gaussian distribution related to the conditional stability class and the downwind distance from where the plume disperses from the point source to nearby areas. The estimation results of the range in between the two dispersion coefficients and the downwind distance are interpreted by Turner (1994).

Stability Class

In the Gaussian Model calculation, both mechanical and buoyant turbulence that affect the estimation of atmospheric stability are also considered. The stability class of the atmospheric turbulence is therefore developed into six stability classes (Pasquill, 1961) determined by three types of factors that include surface wind speed approximately at 10 meters, insolation, and cloudiness.

5. Identifying visualisation techniques

The plume dispersion was visualised in a two-dimensional (2D) graph plotted using OpenGL. The concentration level was colour coded based on the concentration level identified earlier. The application interfaces were designed and developed using Visual Basic 6.0.

6. Setting assumptions

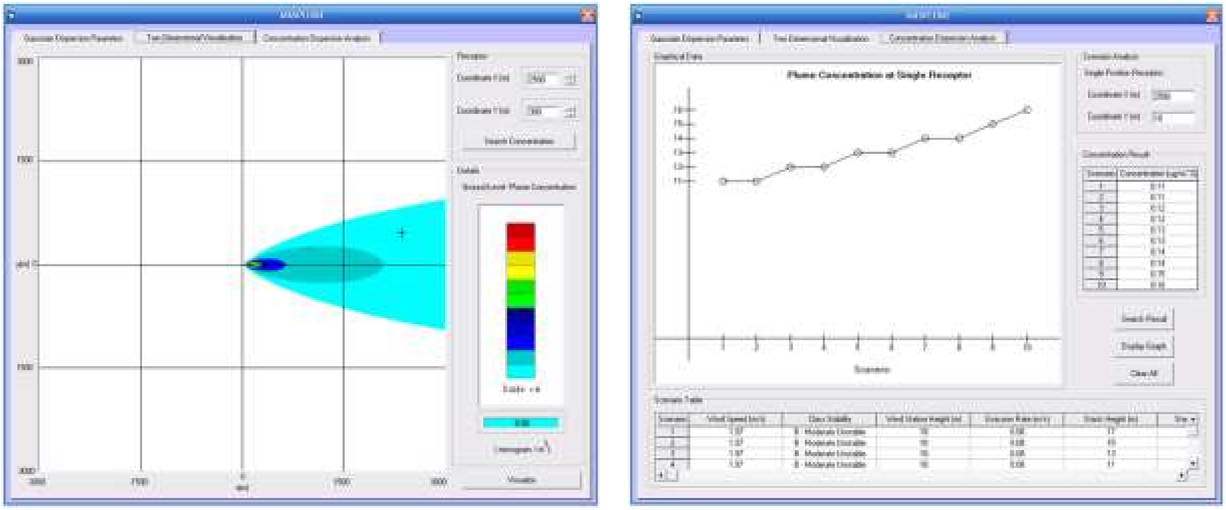
The following were the assumptions or criterion that we set for the application:

- MASPLUME was a Gaussian steady state system;
- Diffusion in the x-direction was ignored;
- Plume was reflected on the ground rather than deposited (rules of conservation of matter);
- Calculations were only valid for wind speeds greater or equal to 1 meter per second;
- Wind direction was a single wind direction;
- Dispersion was only dispersed to the positive direction of x coordinate;
- Dispersion prediction only showed the last 10 minutes of occurrence; and
- Dispersion was limited to 3000 meters, with a variance of 10 meters from 1 receptor to another.

RESULTS AND DISCUSSION

MASPLUME is categorised into (1) the pre-processor module, and (2) the post-processor module. The pre-processor module comprises functionalities to process input data of identified parameters and ensures that the required data are entered and the values valid. Proper window messages are displayed to guide users in rectifying errors as well as confirm user actions.

The post-processor module is designed to show the results of the selected pollutant concentration level dispersion (in scatter plot form) and the scenario analysis (in line graph form). The screenshots for the interfaces of both results are shown in Figure 3.



(a) Postprocessor module (Visualisation) (b) Postprocessor module (Scenario Analysis)

Figure 3 : MASPLUME Interfaces

From Figure 3(a), a sample result of a pollutant dispersion plot is shown with the point source located at the centre as the origin. The region of the pollutant concentration is coloured based on its concentration level. The top left side of the screen shows the receptor coordinate information where the user may change these coordinates. The concentration value is displayed below the concentration level table. The plot is equipped with a pointer capability which when pointed at any region of the dispersion would display the corresponding coordinates and concentration level.

In scenario analysis, a user may enter ten sets of different values with each representing different scenarios and subsequently obtain their corresponding concentration values. This feature is useful in determining the parameters that have high impact on the concentration level. For example, if a user wishes to ascertain which stack height value is sufficient, ten different values of stack height may be entered. Figure 3(b) is the result of a scenario analysis whereby the selected pollutant was SO_2, the receptor location at 2500 - *x*, 10 – *y*, and wind speed set to 1.97 m/s. The list of the stack height values and their concentration reading is presented in Table 1.

Table 1: List of stack height values and their concentration results

Scenario	Stack Height (m)	Concentration result (ug/m^3)	Scenario	Stack Height (m)	Concentration result (ug/m^3)
1	17	0.11	6	8	0.13
2	15	0.11	7	7	0.14
3	13	0.12	8	6	0.14
4	11	0.12	9	5	0.15
5	9	0.13	10	4	0.16

From the concentration results, we may conclude that the concentration of sulphur dioxide is inversely proportional to stack height; the higher the stack height, the less concentration it produces. Therefore, ascertaining which stack height is sufficient could be made based on such results.

CONCLUSION

MASPLUME was able to (1) produce a prediction for the dispersion of a selected pollutant, and (2) show its level of concentration at the ground level based on the Gaussian Model. The dispersion was visualised using a 2D static scatter plot with the level of consistency colour coded for ease of identification. A scenario analysis was added to enable users determine the parameters that had high impact on the level of concentration of a selected pollutant with the result shown using a graph line. MASPLUME is still in its initial stages with further improvements necessary. The issues and limitations in this first version of MASPLUME are discussed in the section ‘Future Work’. As of now, MASPLUME is deemed sufficient for use as a teaching and learning aid for the Environmental Science course in Universiti Malaysia Sabah.

FUTURE WORK

Since MASPLUME is still in its early stages, improvements in its development could still be incorporated. Below are several aspects that merit due attention:

1. Scatter Plot

The scatter plot produced was not based on real map coordinates. The coordinates of visualised images had distance limitation ranging from 0 to 3000 meter. Every successive receptor represented by one point on the Cartesian grid was approximately 10 meters apart. Any receptor residing between these ranges was not considered in the visualisation.

It will be more realistic if the dispersion could be animated. MASPLUME however is only capable of plotting the dispersion on a 2D scatter plot. Change of dispersion concentration with time would not be possible since the plot is static.

2. Storage Space

The scenario analysis was limited to 10 scenarios due to memory space constraints. This was a trade-off to ensure acceptable processing speed. Since there was no external storage used in the system, limiting the function to save current data for retrieval at a later stage was necessary.

3. Wind

Wind was the main factor in the dispersion calculation. The application could not be used to predict the concentration when there were other winds from different directions, or the wind speed changed rapidly from one stage to the other.

Although wind could also be affected by physical obstructions in the surroundings, the application design does not take into consideration this environmental probability or the aspects of actual contexts or real places. The existence of obstacles would need to be incorporated in the design in future phases.

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