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ESTABLISHMENT OF A PRAGMATIC MATHEMATICAL APPROACH FOR PREDICTING PARTICULATE MATTER EMISSIONS FROM FERTILISER PLANTS 1/

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ESTABLISHMENT OF A PRAGMATIC MATHEMATICAL APPROACH FOR PREDICTING PARTICULATE MATTER EMISSIONS FROM FERTILISER PLANTS.

INTRODUCTION

In this paper the development of a method and the technique employed to predict the dispersion of particulate matter from fertiliser and other similar types of plants is described. This includes calculation of average deposition rates, maximum rise of plume from chimney stacks and average ground level concentration of particulate matter. The nature and form of the inputs employed in the analysis are described and some of the practical implications are discussed. As the method can be employed based on limited meteorological data and in cases where histroical data on ground level pollution concentrations do not exist, it is suitable for use in industrially developing countries.

1. GENERAL REMARKS

Rapidly advancing technology and the development of vast mineral resources are creating problems of serious ecological disturbances. To considerable quantities of biological waste has been added a wide variety of industrial by-products of varying degrees of toxicity and durability. Not least among the problems created by industrial effluents is that of air pollutants since they can be carried long distances and deposited over wide areas remote from the source. Pollutants in the atmosphere can affect soil and vegetation; animal and human health.

Very little research has been done on the effects of atmospheric pollution on vegetation.

However, we do know that particulate matter can form a crust on foliage and prevents photosynthesis, that reduced exchange of carbon dioxide and oxygen affects crop yeilds and the pH factor of soil can be altered and with it the quality of pasture. On the other hand, pollution can be said to have a beneficial effect in some cases in that in some areas where pollution has been eliminated, or reduced, crops have been found to suffer a sulphur deficiency.

The toxic components of atmospheric pollution can either be absorbed or remain on the surface of vegetation and these form the greatest hazard to animal and human life.

Particulate matter is always present in the atmosphere in the form of dusts, pollen or liquids, but only a very small number of such particles are intrinsically toxic. However, there are pollutants which by absorbing toxic substances, actually provide a means of conveying them into the lungs. For example sulphur oxides, in combination with particulate matter, have been found to increase resistance to pulmonary flow in animals. Therefore to be able to predict the dispersal of pollutants in the atmosphere is obviously an advantage.

Emissions from industrial stacks are dependent upon a number of variables which can be grouped under three general headings :

1. Process factors: these include

Emission Rate
Temperature of emitted material
Form of emission - dust
fumes
mist
spray
gas
Concentration of the components listed above.
Size of particles, their shape and density distribution.
Agglomerating characteristics.

2. Stack Factors: these cover those aspects which depend on the physical location and form of the source e.g. :

Height
Diameter and configuration of exit

Emission velocity

Relationship of source to surrounding structure and topography

3. Meteorological influences which include such items as :

Wind speed and direction
Temperature and humidity
Atmospheric stability
Topographical influences on these

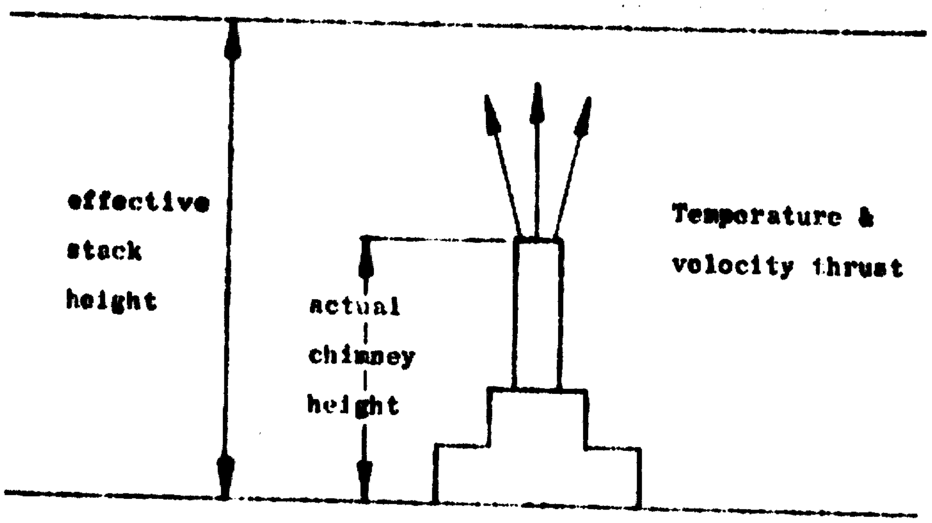
In most cases material emitted from a stack is at a higher temperature than the surrounding air and therefore less dense and the plume tends to rise initially. This tendency is an important factor in the efficient dispersal of pollutants. The pollutant is propelled to a point above the chimney know as the "effective stack height". This is generally two or three times the actual height of the chimney. (See Figure I).

The meterological conditions affect the shape of the plume rising from a chimney. Plumes can thus take on a number of forms. Particulate matter concentrations in the air are also affected and have themselves an effect upon meterological conditions. For example particulate matter serves as nuclei around which moisture can condense and a noticeable reduction in London fog has been effected by the introduction of smokeless fuel.

In this article particulate matter is defined as any dispersed matter, solid or liquid, in which the single aggregates are larger than single small molecules, approx. 0.0002μ, but smaller than 500μ.

Generally speaking the point of maximum ground level concentration of large particulate matter is relatively close to the stack.

Figure 1. Effective Stack Height



As the particulate size reduces so does the effect of gravitational settling velocity. When diameters become as small as 20μ or less, the particles move essentially in the same manner as the gas in which they are suspended.

The location of the maximum concentration, at ground level, of a gaseous pollutant is generally found to be in the region of twenty effective stack heights from source. As we have stated, the "fall-out" of large particles will be relatively close to the stack and closer to source than the equivalent point for gaseous omission. For example a 300 foot chimney emitting hot dust-laden flue gases and producing a plume with an effective stack height of say 1000 feet would probably have the point of maximum ground level concentration and maximum rate of deposition of the particulate matter about 4 miles from the stack as against 6½ to 7 miles for the emitted gases (assuming a wind velocity of 10 meters/hour).

From the foregoing it can already be appreciated that dispersion of particulate matter in the atmosphere is a fairly complex phenomena.

II. MATHEMATICAL MODEL FOR ESTIMATING GROUND LEVEL CONCENTRATIONS OF STACK EMISSIONS

Most methods for estimating ground level concentrations of of stack emissions involve two steps :-

1) the "effective stack height" is calculated ;
2) the stack is replaced by a point source at the effective stack height and the diffusion of material from this equivalent source in analysed.

This method gives an approximate value which is considered satisfactory so long as the down-wind distances being considered are at least five times the effective stack height.

The pressure of the atmosphere, and with it generally the temperature, decreases with altitude. Under most atmospheric conditions there is an upper limit to plume rise which is dependent on the rate of temperature change with height. If the rate of decrease in atmospheric temperature with height is less than 5.5°F per 1000 feet in dry air (the adiabatic lapse rate) - a stack plume emitted into the atmosphere will reach a calculable maximum height. As the value of the rate of decrease of atmospheric temperature reduces so the maximum height of the plume rise will reduce. Inverse conditions under which atmospheric temperature increases with height, result in the lowest values of maximum plume rise. (See Figure II).

In the winter in temperate climes, and in tropical areas in overcast weather conditions when the rays of the sun are not sufficiently intense to heat the surface of the ground the temperature inversion can last for several days. This condition has characterised most of the disasters caused by industrial airborne pollution.

Rates of decrease in atmospheric temperature with height greater than the adiabatic lapse rate are unstable and very seldom occur except in the lower few feet of the atmosphere. However, a plume emitted into such an atmosphere would continue to rise indefinitely.

In this study the mathematical model developed by Bosanquet, Carey and Halton* has been used for both steps of the two-step analysis. Their formula for the maximum height H attained by a plume in a stable atmosphere is of the general form :

$$\begin{aligned} H = H_s &+ \text{function } (u, M, d_g, v.) \\ &+ \text{function } (u, M, D_g, T_g, T_a, v, G, g) \end{aligned}$$

where H_s = actual stack height
u = exit velocity of stack gases
M = gas emission rate (weight per unit time)
d_g = density of gas at temperature T_a

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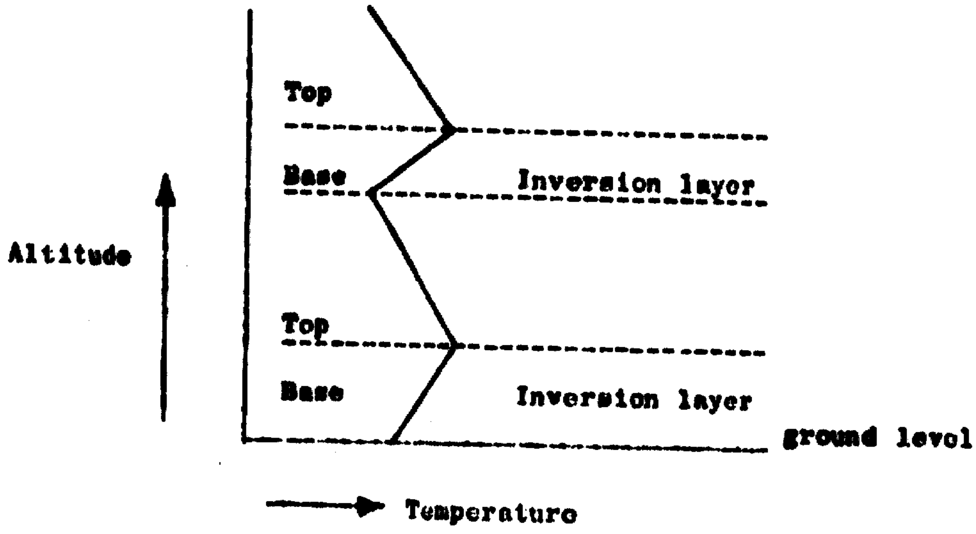
* C.H. Bosanquet, W.F.Carey, and E.M. Halton, Proc. Inst. Mech. Engrs. 162 355 (1950)

Figure II. Surface and Height Altitude Temperature Inversion



Tg = temperature of gas at stack

Ta = air temperature at maximum height of plume

v = wind velocity

G = related to rate of change of atmospheric temperature with height

g = acceleration due to gravity.

The second term in the equation gives the rise caused by the velocity of the stack gases and the final term gives the rise caused by the buoyancy of the stack gases.

This equation has received wide use for plume analysis and gives results which compare favourably with those actually observed.

Dust particles and liquid droplets in a stack gas plume are subject to atmospheric eddies which act to maintain them in a state of suspension and gravitational forces which act in opposition and favour deposition. The gravitational forces are characterised by the free settling velocity of a particle which is a function of its shape, size and density. This velocity increases approximately in proportion with the square of diameter of the particle and the difference between the density of the particle and that of the air. For particles with diameters less than 20 microns these velocities are very low and the particles move essentially as if they were gas molecules.

Assuming a "uniform" pattern of atmospheric turbulence Bosanquet, Carey and Halton developed an equation for the average deposition rate D of dust particles at a given point down-wind of the stack which is of the form :

D = Sum for all particle sizes (function (W, f, H, v, b, x)

where D = Deposition rate (weight per unit area per unit time)

W = Emission rate of particles of given size

f = Settling velocity of the particles of given size

H = effective stack height

v = Wind velocity

b = Fraction of time during which wind is in the direction under consideration

x = Distance down-wind of stack

This equation has also been widely applied but the agreement with actual results is not as good as is the equation for plume rise. It is considered that predications for rate of dust deposition will be within a factor of 2 of actual values, but this is not a serious deficiency insofar as an assessment of the order of magnitude of these values is more important than a precise estimate when evaluating possible impact on the environment. Precise estimates for given meteorological conditions have limited value as these conditions are subject to fairly wide variations, even in a period as short as 24 hours.

The same equations allow estimates to be made of average ground-level concentrations i.e. the product of the concentration very close to the ground and settling velocity for a given size particle being equal to the deposition rate for that sized particle.

On this basis the following equations have been established, suitable as input for the computer determination of particulate matter emissions for chimney stacks :

A. EQUATION FOR MAXIMUM RISE OF PLUME IN STABLE ATMOSPHERE

$$H = Hs + \frac{4.77}{1+0.43\ v/u}\left(\frac{\sqrt{Qu}}{v}\right) + 6.37\ \frac{g\ Q\ \Delta}{v^3\ \ T_1}\ (\log_e J^2 + \frac{2}{J} - 2)$$

$$\text{where } J = \frac{v^2}{\sqrt{Qu}}\left((0.43\sqrt{\frac{T_1}{gG}} - 0.28\ \frac{u}{g}\ \ \frac{T_1}{\Delta}\right) + 1$$

H = height of plume, (feet)

H_s = Height of stack, (feet)

Q = gas emission rate measured at temperature T, (cu.ft/sec)

T_1 = temperature at which density of stack gases is equal to that of the atmosphere (degrees centigrade abs.)

Δ = temperature difference between actual stack gas temperature and T_1 (degrees centrigrade).

u = stack gas emission velocity (ft/sec)

v = wind velocity (ft/sec)

G = gradient of potential atmospheric temperature (deg C/ft)

g = acceleration due to gravity (32 ft/sec per sec)

B. EQUATION FOR AVERAGE DEPOSITION RATE

$$D = \sum_i di = \sum_i 2.75 \times 10^6 \; \frac{Wib \left(\frac{20H}{x}\right)^{\frac{20fi}{v+2}}}{H^2 \, \Gamma\left(\frac{20\,fi}{v}\right)} \, . \, e^{\frac{-20H}{x}}$$

D = average deposition rate (tons/sq mile/annum)

W_i = rate of dust emissions of particles of given size (ft/sec)

f_i = settling velocity of particles of given size (ft/sec)

b = fraction of time during which wind is in direction under consideration

di = deposition rate of particles of given size (tons/sq mile/annum)

H = height of plume i.e. effective stack height (ft)

x = distance down-wind of stack (feet)

$\sum_i$ = implies summation over all particle sizes

C. EQUATION FOR AVERAGE GROUND LEVEL CONCENTRATION

$$C = 4.08 \times 10^{-2} \sum_i di/fi$$

C = average ground level concentration in microgrammes per cubic metre

fi = settling velocity of particles of given size ft/sec

It must be emphasised that this mathematical model for dispersion of particulate emissions does not take account of such factors as topography, rainfall and mists which do alter the dispersion pattern. It the moment only through detailed meteorological analysis, and wind tunnel modelling can such factors be taken into account.

III. APPLICATION OF THE MATHEMATICAL MODEL

To allow maximum flexibility in evaluating the effects of the different parameters, the mathematical model can by programmed into a computer. During the analysis of the data the dispersion pattern can be analysed by considering any suitable sectors e.g. 45 degree sectors based on specified sources of emissions.

For each sector a value can be calculated for the fraction of time the wind blows into that sector, the figure used being calculated from historical data e.g. four-hourly meteorological readings over several years.

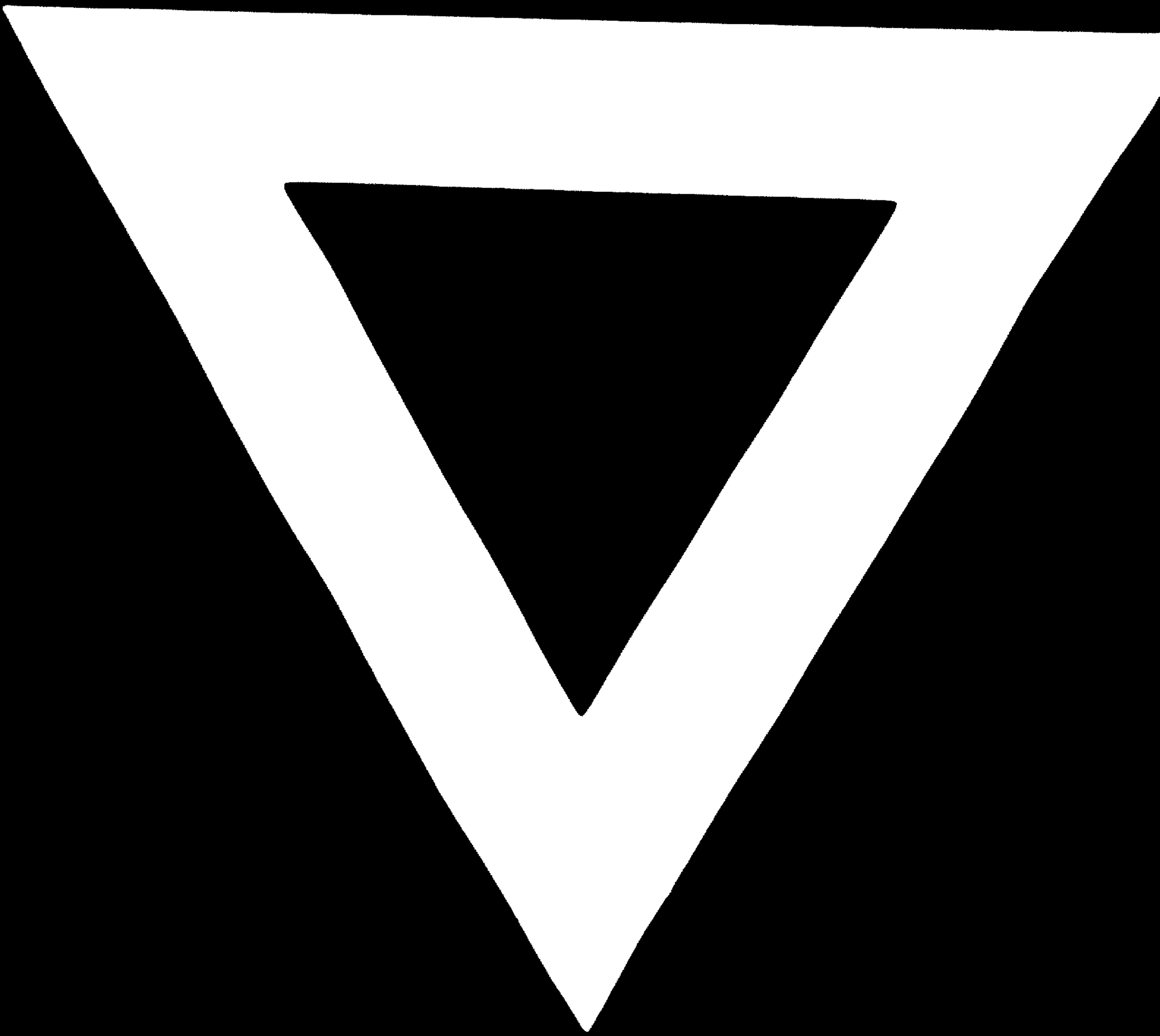
For a given stack or other source of atmospheric emissions, and its set of emission data, the distribution of average deposition rate and average ground level concentration can be computed for a series of values of wind velocity and rate of change of atmospheric temperature with height.

On the basis of these computations, concentration contour maps can be developed.

By plotting the computed values on a map of the area surrounding the source and joining the points of equal ground level concentration a series of "foot-prints"over the terrain can be obtained.

This method can be used to predict the probable ground level concentration of materials emitted from a proposed plant in the surrounding district. The predicted effects of the new plant can be added to the existing, measured ground level concentrations for the area and the probability of the total deposition approaching an unacceptable level can be determined. In addition, the effect of changing of the plant specifications e.g. the stack height, emission temperature, additional scrubbing facilities etc. can all be demonstrated in terms of probable ground level concentrations. Thus, the controlling authority for the area considered is in a position to make recommendations about the siting of a planned factory or indicate changes in the plant design that would result in improvement in deposited levels of particulate matter.

In many countries, especially in the industrially developing countries, historical data on ground level pollution is not available. Although in such countries data on meteorological conditions such as prevailing wind speed and direction may be generally limited, it usually exists for more populous areas around airports, and urban centres which are the likely site for the establishment of industrial plants. It is generally possible in such cases therefore to predict with an estimatable degree of confidence using the methods outlined above, the change in ground level concentration of particulate matter pollution which would result from establishment or expansion of fertiliser and allied industries.



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