TECHNICAL NOTE

ANALYSIS OF VERTICAL DISPERSION AND RELATIVE CONCENTRATION OF AN ELEVATED PLUME IN THE TROPICAL BOUNDARY LAYER USING VIDEO DIGITIZATION

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Abstract—Digital analysis of smoke plume imagery is applied to video and photographs of a smoke plume taken on 22 June 1987 at the Badrapur Power Plant in New Delhi, India. Using a medium resolution video digitizer, these photographs and video are digitized and analyzed to produce a composite averaged plume that corresponds to a sampling interval of 2 min. These estimates are then used to estimate parameters of vertical dispersion and relative centerline concentration.

Estimates of vertical dispersion are compared with Briggs' recommended values for stability class C (slightly unstable conditions). The digital technique produces values of σ_z that compare well with those estimated using Briggs' formulations. The values obtained using the digital method did not vary by more than 5 per cent from those formulated by Briggs.

Estimates of relative concentration, which are values normalized by the concentration associated with a travel distance of 100 m, are compared with relative concentrations obtained using the Gaussian diffusion equation. The digital method produces estimates of relative concentration that compare well with the Gaussian diffusion equation, the differences encountered varying by less than 10 per cent throughout the calculated travel distance.

Key word index: Plume spread, plume concentration, image analysis.

1. INTRODUCTION

Digital analysis of smoke imagery is applied to video and photographs of a plume taken on 22 June 1987 at the Badarpur Power Plant located south of New Delhi, India. Using a medium resolution video digitizer, these photographs and video are digitized and analyzed to produce a composite averaged plume which is then used to estimate parameters of vertical dispersion and relative concentration. Estimates of vertical dispersion are compared with Briggs' σ_z curves which were determined by interpolating between values obtained from Pasquill–Gifford and Tennessee Valley Authority (TVA) methods (Atmospheric Science and Power Production, 1984). The dispersion parameters derived by Pasquill and later modified by Gifford are valid for a ground level point source in rural terrain and for a sampling time of 3-min. The TVA has formulated relationships to estimate values for σ_y and σ_z based on several years of data from power plants around the Tennessee Valley. These values represent dispersion parameters estimated from buoyant, tall stack emissions in complex terrain and from sampling intervals of 2–5 min. The empirical method given by Briggs, therefore, provides a consistent estimation scheme for σ_y and σ_z that may be applied to more general situations. Estimated values of relative concentration are compared against values obtained using the Gaussian diffusion equation in which Briggs' σ_y and σ_z values are employed.

2. SITE DESCRIPTION

The Badarpur Power Plant is a 750 MW power production station located in a rural environment characterized by many open fields and small one to two storey buildings. The stack that emitted the effluent is 150 m high. The sun angle above the horizon during the filming of the plume was estimated to be 25°. While filming, the plume was located between the sun and the camera and the line of sight from the camera was approximately perpendicular to the plume; therefore, optical density values obtained from the digitized plume image represent a crosswind integration of plume density (Fig. 1). This is in contrast to the situation in which the sun is behind the camera. In this case optical density values represent pseudo-plume edge reflective densities. Here it is assumed that the video signal is proportional to the light intensity. This assumption can be confirmed using optical filters.

3. WEATHER CONDITIONS

Observations obtained from a micrometeorological tower located on the Indian Institute of Technology campus in New Delhi showed that at 0600 LST (Local Standard Time) there was a strong surface-based inversion of 0.14° C m⁻¹ (refer to Raman *et al.*, (1990) for more details on the experiment). By

0700 LST there was a moderate inversion of 0.06° C m^{-1} and by 0800 LST the ground based inversion had broken up and slight instability had set in. The wind speed at 10 m remained almost constant at about 2 m s^{-1} during this time. Filming of the Badarpur smoke plume commenced shortly after 0700 LST and continued for a 15 min period. Based on the tower information, the surface-based inversion was breaking up during this time and slightly unstable conditions were prevalent. For this analysis, Briggs' sigma values for stability category C, which corresponds to conditions of slight radiation and 2–3 m s^{-1} winds, will be used to compare with sigma z values obtained using the digitization technique. Briggs' values will also be used in the Gaussian diffusion equation for the comparison of relative concentration values.

4. ESTIMATION OF DISPERSION PARAMETERS

The video and photographs were analyzed at the Planetary Boundary Layer Laboratory of the Marine, Earth and Atmospheric Sciences Department of North Carolina State University. A series of video frames and photographs were digitized and stored in an IBM personal computer. These digitized images were then analyzed separately, in the following manner, to produce estimates of vertical plume dispersion.

Through interactive software the digitized image is first displayed on a monitor and using a cursor the x and y coordinates and the optical density of that position are displayed (Fig. 2). Using this feature, objects of known height, such as the smoke stack in this study, can be used to obtain a scaling factor which gives absolute units to each picture element (pixel). The number of pixels which comprise the stack is determined and knowing the stack height, a scaling factor is obtained by dividing the stack height by the number of pixels. In this study the average pixel dimension was found to be 1.9 by 1.9 m. Vertical slices of the plume image are then taken at several selected downwind distances. Starting at the stack exit, the pixel coordinates in the x (horizontal) direction are calculated for several downwind distances and then used to obtain vertical slices through the plume (Fig. 3). Figure 4 is a plot of optical density vs vertical position. Plume edges are easily detected from these plots by sharp increases in optical density from normal background values. Multiplying the number of pixels, which fall between the two plume edges, by the scaling factor yields a plume depth. This process continues for each vertical slice and for each digitized image.

When all of the video frames and photographs have been analyzed the plume depths are recalled and averaged to obtain mean plume depths. Calculated mean plume depths are estimated to represent an averaging time of 2 min. Dividing the averaged plume depth by 2 yields the plume half depth which is assumed proportional to 2.15 σ_z, based on Gaussian diffusion theory (where concentration at the plume edge is one-tenth of the centerline value) (Pasquill and Smith, 1983). The half depth of the plume is then divided by 2.15 to obtain a σ_z value for that slice. The σ_z values are then fitted to a third degree polynomial equation in order to obtain values for any downwind distance and to predict σ_z values beyond the 0.5 km maximum observed plume distance.

σ_z values obtained from the plume analysis and forecasted σ_z values obtained using the polynomial equation are plotted against travel distance and compared with Briggs' σ_z values in Fig. 5. A reasonably good agreement is found between the computed and the theoretical σ_z values for the prevailing weather conditions (stability category C). The overall trend of the curve is an encouraging indication that this technique, of measuring vertical dispersion, can be applied to field studies with the confidence that the data obtained from the analysis are of high quality and are comparable to those derived from conventional methods.

5. ESTIMATION OF RELATIVE CONCENTRATION

Estimates of relative concentration are calculated using optical density information obtained during the vertical slicing of the plume. Optical density values for the digitizer used in this study range from 0 to 255, black to white, respectively, and represent the amount of light entering the camera at a particular pixel point. These optical density values are proportional to the amount of light penetrating the plume and represent crosswind integrated values of plume density. Average plume centerline optical density values are found and stored for each slice. Similar to calculating averaged plume depths, averaged centerline optical density values are obtained for each designated distance downwind.

The averaged optical density found at 100 m downwind from the stack is assumed to be 100% of the concentration of the effluent being emitted from the stack. As the plume disperses downwind the centerline optical densities decrease. This decrease with downwind distance should be proportional to the decrease of effluent concentration. By dividing the averaged centerline optical density of each averaged slice by the value obtained at 100 m downwind, relative concentration values are obtained.

Figure 6 is a plot of relative concentration vs downwind distance. Curve A was calculated by integrating the Gaussian diffusion equation (Equation 1) from $-2.15\,\sigma_y$ to $+2.15\,\sigma_y$. To be consistent with previous analysis the values of σ_y and σ_z used in the equation were obtained from Briggs' recommended values for stability class C. Equations 2 and 3 represent Briggs' formulations for the calculations of σ_y and σ_z respectively. Briggs' values are not valid for distances shorter than 100 m, therefore calculated concentrations using the Gaussian diffusion model are based on values that assume that the concentration at 100 m downwind represents 100 per cent of the effluent being emitted form the stack. Curve B was calculated using the centerline optical densities of the digitized plume. Relative concentration values obtained from the digitized images show good agreement with the Gaussian diffusion equation given below for concentration $C(x, y, z)$.

$$C(x, y, z) = \int_{-2.15\sigma_y}^{2.15\sigma_y} \frac{Q}{2\pi\sigma_y\sigma_z\bar{U}} \exp\left[-\frac{(y-y_0)^2}{2\sigma_y^2} - \frac{(z-h)^2}{2\sigma_z^2} \right] \tag{1}$$

$$\sigma_y = 0.11x(1 + 0.0001x)^{-0.5} \tag{2}$$

$$\sigma_z = 0.08x(1 + 0.0002x)^{-0.5}. \tag{3}$$

At shorter distances the values obtained by the digital method overestimate the plume concentration, as determined by the Gaussian diffusion equation, but by < 10 per cent. A 350 m the two curves cross and the digital method begins to underestimate the plume concentration. However, over th calculated distances the digital method remains within 10 pe cent of the values obtained using the Gaussian diffusio equation. This indicates that the digital technique of calculat ing relative concentration, given appropriate conditions, is valid method for calculating relative concentration for a elevated point source.

6. CONCLUSIONS

The digital technique for analyzing smoke plume imager is a reasonably accurate and economic method for estimai ing, directly, plume dispersion close to the stack (up to abou 5 km). Using this technique estimates of dispersion have bee made from photographs and video that agree well wit Briggs' suggested values, at least for stability class C.
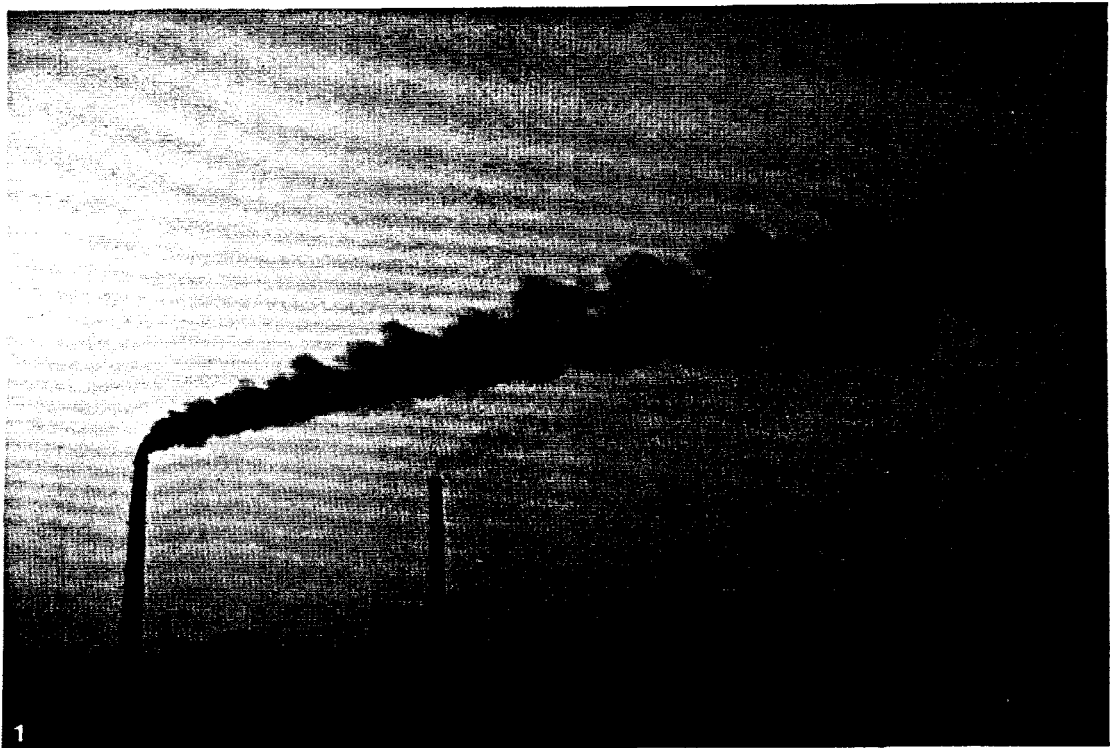
Fig. 1. Photograph of the Badarpur smoke stack located south of New Delhi, India.
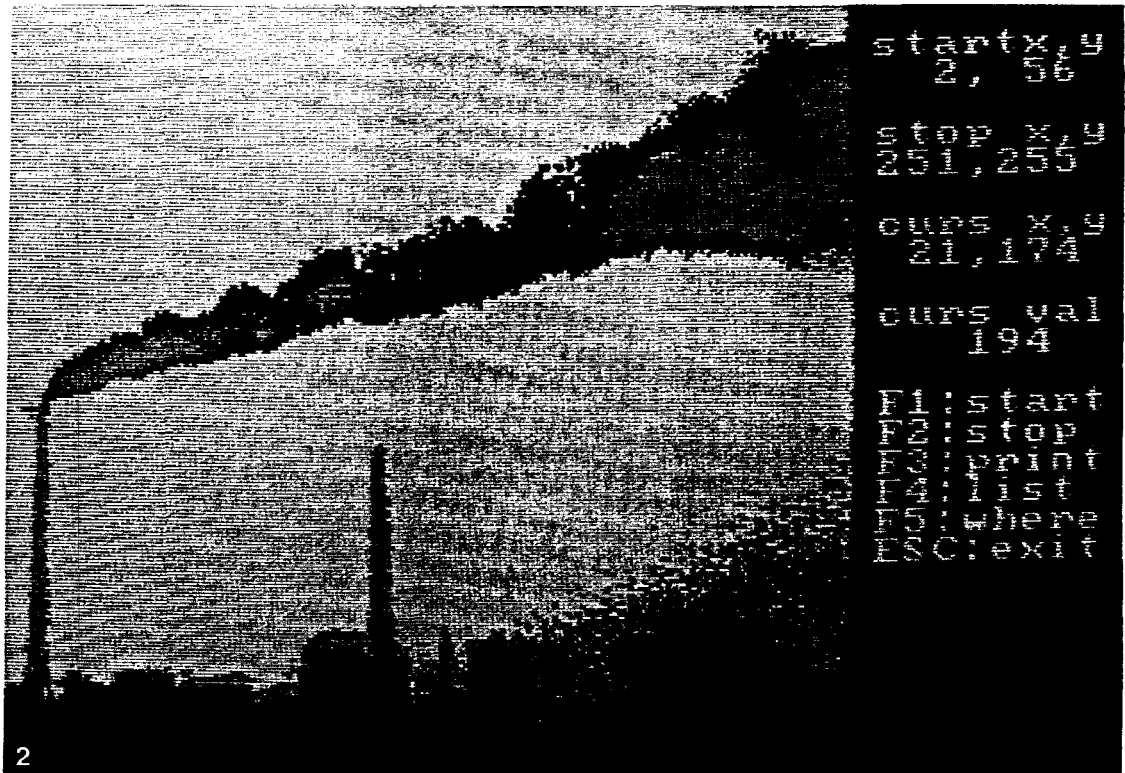

Fig. 2. Digitized image of the Badarpur smoke stack. Yellow represents optical density values between 190 and 255, red represents optical densities which fall between 165 and 190, green represents values that fall between 135 and 165, and black 135.
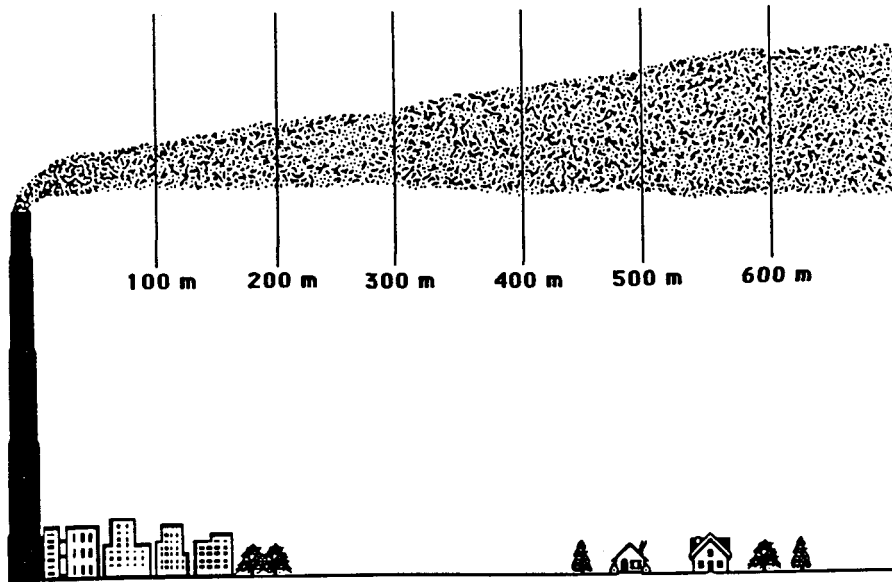
Fig. 3. Diagram indicating selected vertical cross-sections downwind of the stack.
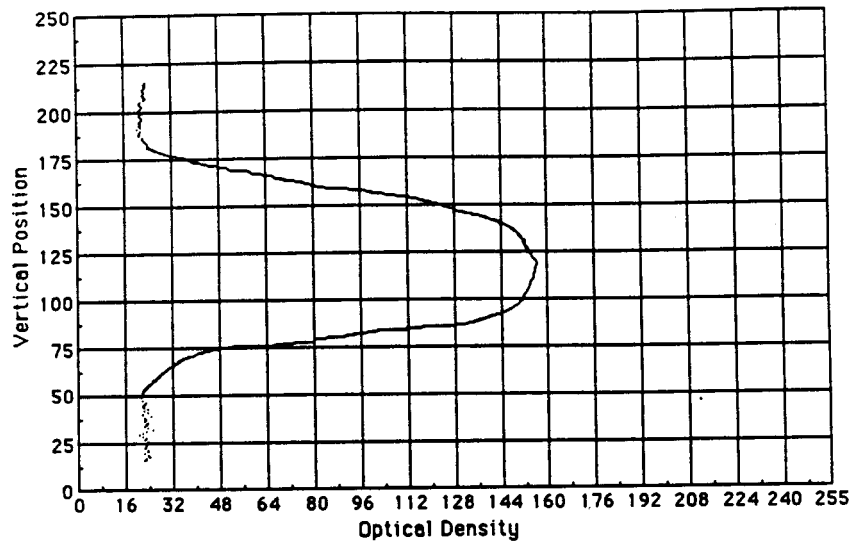

Fig. 4. Graph of optical density vs vertical pixel position. This shows a curve which may
be considered Gaussian.

Values of relative concentration compare well with values obtained using the Gaussian diffusion equation. The trends of the two curves are similar and estimated concentrations using the two techniques differ by less than 10 per cent. A sampling interval of 2 min was used to calculate plume dispersion and relative concentration parameters of the digital technique. Briggs' values are more representative of 3 min averages. Some of the discrepancies found in this analysis may be due to this difference in sampling intervals and some to the effect of plume motion relative to the surrounding air on plume dispersion.

This technique may also be used to calculate σ_y. Using a video camera the plume may be taped from below looking vertically upwards. This procedure usually produces pictures with short travel distances. However, with tall stacks, distances as far as 300–400 m can be taped. Staylor (1977) has used a similar technique to calculate stack plume properties from satellite imagery. Although it is a more sophisticated technique, the basic principle is the same.

This digital technique is relatively inexpensive when compared to other forms of estimating dispersion (i.e. use of research aircraft and other similar methods) and results can be obtained within a short duration. It is also an easily portable system in that it only requires a portable computer, a video digitizer card and video camera.
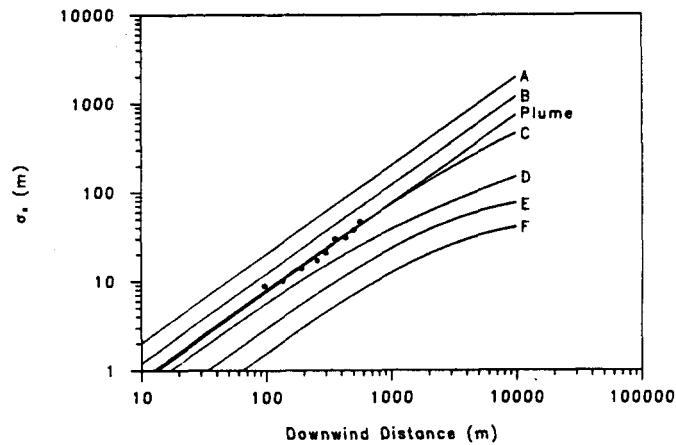
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Fig. 5. σ_z values obtained from the plume analysis plotted against travel distance and compared with Briggs' σ_z values for stability class C.
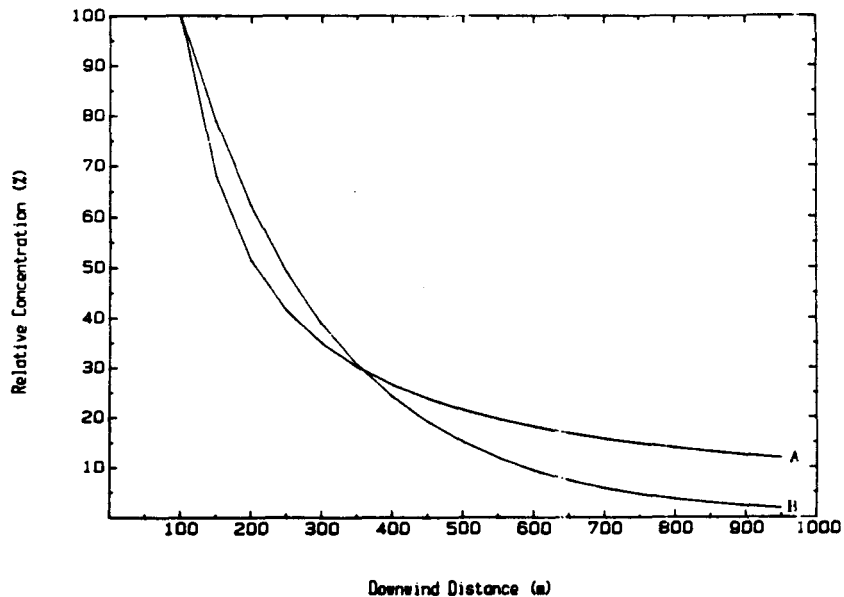

Fig. 6. Plot of relative concentration vs downwind distance. Curve A was calculated by integrating the Gaussian diffusion equation from $-2.15\,\sigma_y$ to $2.15\,\sigma_y$ and normalizing this value with the concentration found at 100 m downwind from the stack. Curve B was calculated using centerline optical density values normalized by the centerline optical density values at 100 m downwind from the stack.

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