NUMERICAL MODELING OF DENSE GAS CLOUD DISPERSION OVER IRREGULAR TERRAIN

by

John T. Lee * and Robert N. Meroney +

Fluid Mechanics and Wind Engineering Program
Department of Civil Engineering
Colorado State University
Fort Collins, CO 80523

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ABSTRACT: A depth-integrated numerical model has been developed to calculate the behavior of heavy and cold fluid dispersion. The model is time dependent, three dimensional, and permits intrusions and entrainment. Calculations were performed on a CYBER 205 vector computer, where typical runs are completed in under 30 seconds CPU time. The model has been validated against the field-scale dense gas cloud studies at Porton Downs, U.K., and laboratory-scale dense gas cloud studies at Colorado State University. The model has been used to calculate time dependent horizontal variations of fluid depth and concentration as a dense cloud interacts with irregular surface boundaries. Example calculations were made under calm and wind conditions for the dispersion of freon-air mixtures and liquefied-natural gas releases over terrain which includes ramps and gorges.

* Graduate Research Assistant
+ Professor and Director
Fluid Dynamics and Diffusion Laboratory

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1.0 INTRODUCTION

Computational techniques for dense gas cloud dispersion generally fall into three categories depending on the simplicity of the models--box models, slab models, and K (or 3-d) models. As the complexity increases the opportunity for numerically generated dispersion and distortion appears to increase. The more versatile 3-d models generally require larger computers, mores esoteric software techniques, more training, and are most expensive to run. Typically box models are fast, can be installed on a PC microcomputer, require little training, and are very inexpensive. Unfortunately, the box models do not allow for terrain inhomogeneities in surface contour, surface roughness, or surface temperature. The slab or depth-integrated model approach may permit a compromise evaluation at modest cost, time and training (For an extensive review of such models see Hanna and Drivas, 1987).

Recent developments with a quasi-three dimensional slab model by Meroney (1984a, 1984b, 1984c, 1985a, 1986) have shown that a computationally fast and numerically simple model can produce reliable behavior results. Such a model can include surface heat transfer; instantaneous, finite, or continuous source configurations; and the presence of spray mitigation devices. These models currently run on PC size microcomputers, and provide results in real times of 15 minutes to one-half hour. Unfortunately, these "cross-section" averaged models presume axially or radially symmetric advected clouds.

A numerical model for dense cloud dispersion is desired which reproduces the detailed nuances or behavior perceived during laboratory and field experiments over sloping or complex terrain (Hall et al., 1974; Meroney, 1986; Heinold et al., 1987).

2.0 NUMERICAL APPROACH

A full 3-d type model can conceptually compute the influence of terrain inhomogeneities on dense cloud dispersion, but such models can be very expensive in computer storage and time. Fortunately, when the flow situation is only weakly three-dimensional, so that one dimension can be decoupled from the other two, a set of relations obtained by integrating the conservation equations over that dimension realistically describes fluid motions. To be accurate such "depth-integrated" equations must have negligible vertical or lateral dynamic pressure gradients; hence, flow quantities are generally assumed to be constant or to have a similar distribution in the vertical direction.

Depth-average (advanced-slab, shallow-layer) models devised to describe heavy gas dispersal have been recommended by several investigators. Previous models developed by Zeman (1982), Colenbrander (1980), Morgan, Morris and Ermak (1983), Havens and Spicer (1985), or Meroney (1984a, 1984b, 1985, 1986) have all been "cross-section" averaged models which presume cloud axial symmetry. Any lateral variations in cloud depth and concentration presume similarity in cloud shapes. Predictions of centerline cloud width, cloud depth, and peak concentrations are inserted into similarity profiles to reconstruct a full three-dimensional plume.

Researchers in surface hydrology, oceanography, and hydraulics have frequently used depth-integrated equations of motion to calculate the movement of flood headwaters over uneven terrain, thermal and density outfalls along the ocean bottom, and the implications of damn failures (Ponce and Yabusaki, 1980; Holly and Usseglio-Polatera, 1984; Rodi, 1980). The formalism for creating depth-averaged conservation equations has been discussed in some detail by Ponce and Yabusaki (1980) and Rosenzweig (1980).

The difference equations used here were obtained by using a second-order upwind difference scheme. Gas cloud properties such as cloud depth, and depth-averaged density, velocity or concentration were calculated explicitly in their dependence on space and time. An empirical clipping procedure was used to reduce numerical diffusion along the dense gas cloud front. Entrainment of surrounding air was parameterized to the relative velocity of the gas cloud and the background turbulence intensities typified by a friction velocity.

$$W_e = (0.12 + 0.2\ (U))(U) + a_4\ u_*/(a_4/a_6 + Ri_*\ u_*^2)$$

A simple entrainment relationship was used, since the primary intent of these calculations are to examine the relative influences of cloud slope and terrain variation.

3.0 NUMERICAL PREDICTION OF DENSE CLOUD BEHAVIOR

Calculations were performed for zero-slope field and laboratory dense gas releases to validate the numerical procedures and provide base cases for comparison. All calculations were performed on the Colorado State University CYBER 205, typical runs were completed in under 30 seconds CPU time.

3.1 Validation Experiments

Porton Trial Test No. 8 involved a release of 40 cubic meters of a Freon-air mixture (Specific gravity = 2) instantaneously from a collapsing tent under calm conditions on a flat field (Picknett, 1981). Figures 1 through 3 depict the development of the numerically equivalent cloud at a series of times after release. Calculated variations of the peak concentrations with distance shown in Figure 4 agree with the wind-tunnel experiments of Hall et al. (1982) and earlier predictions from box and cross-section averaged models (Meroney, 1984).

Meroney and Lohmeyer Test No. 7 involved a release of 165 cubic centimeters of pure Freon (Specific gravity = 4.17) from a suddenly rotated cylinder built into the floor of a small open-circuit wind tunnel. Wind speeds were 0.2 m/sec. Figures 5 through 7 depict the development of the numerically equivalent cloud at a series of times after release. Calculated rates of cloud growth and concentration decay are compared in Figure 8 with experimental measurements.

3.2 Slope and Terrain Variation Effects

Figures 9 through 11 follow a hypothetical plume of the same characteristics as the Porton Trial Test No. 8 as it disperses over a slope of 1:20. Figure 12 compares the downslope and upslope development of this hypothetical spill with the earlier results for a release over a horizontal surface. Note that the accelerated motion downslope increases entrainment, but more rapid advection downslope results in higher peak concentrations. The cloud also arives at downslope locations more quickly than a release over flat terrain.

Figures 13 and 14 follow a hypothetical plume of the Porton Trial Test No. 8 as it disperses into a V-shaped gorge with side wall slopes of 1:4.14 and a downslope gradient of 1:20. The plume rapidly exudes a pseudopod of gas down the gorge, but the high relative motion of the gas ground jet results in high air entrainment and subsequent cloud dilution.

4.0 CONCLUSIONS

Depth-averaged gas-cloud models can be constructed to account for the influence of gravitationally induced motions due to terrain irregularities. Such models can predict the influence of slope variation, gorges and ravines, hills and other obstacles.

Acknowledgements

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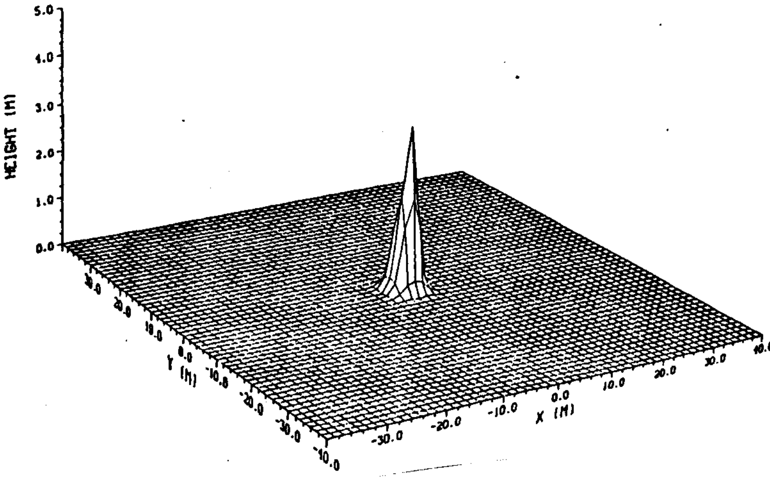

Figure 1 Cloud profile for Porton Trial No. 8, Volume = 40 cubic meters, Specific Gravity = 2.0, Wind speed = 0 m/s, $t^* = 1.0$, $t = 0.6$ sec.

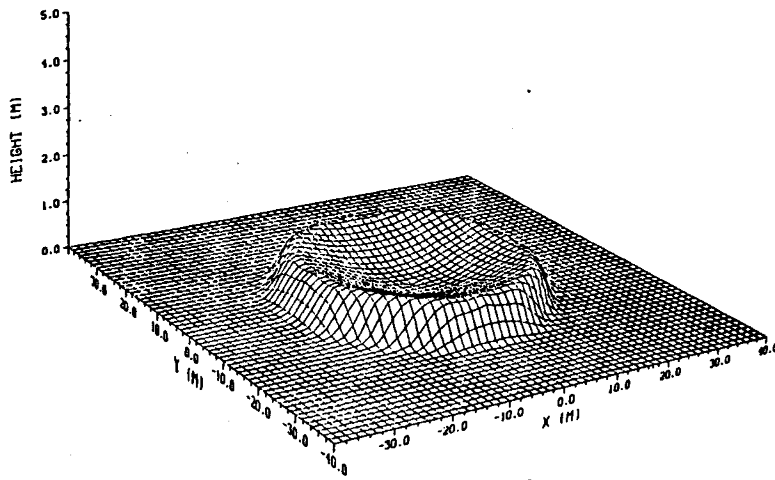

Figure 2 Porton Trial No. 8 (contd), $t^* = 55$, $t = 32$ sec.

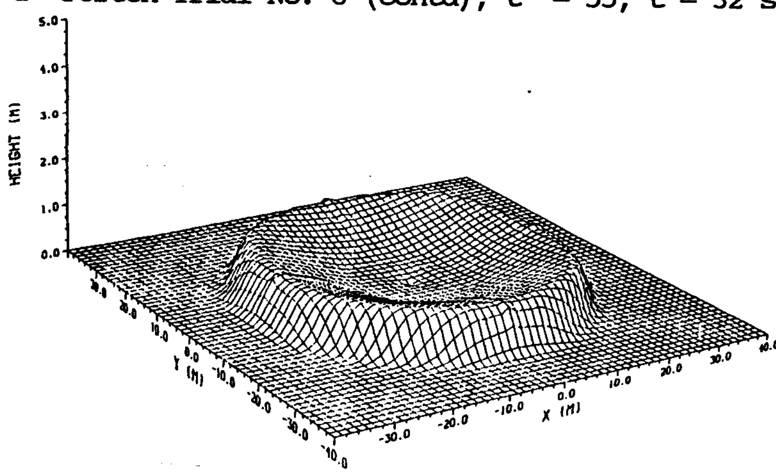

Figure 3 Porton Trial No. 8 (contd), $t^* = 100$, $t = 60$ sec.

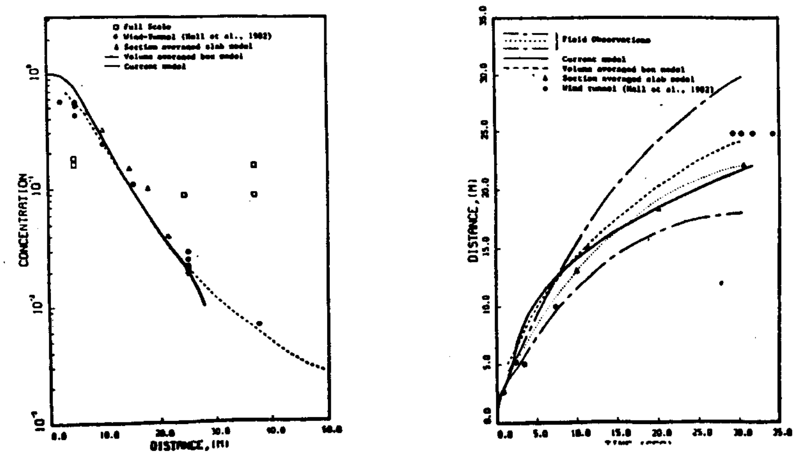

Figure 4a Porton Trial No. 8, Peak Concentration vs Distance (m).
4b Porton Trial No. 8, Gas Cloud Radius (m) vs Time (sec).

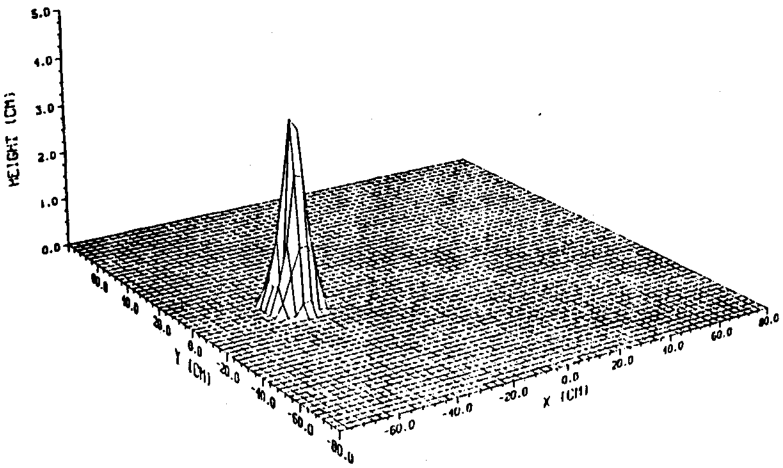

Figure 5 Cloud profile for Meroney & Lohmeyer Test No. 7, Volume = 165 cubic cm, Specific Gravity = 4.17, Wind speed = 0.2 m/s, t^* = 1.11, t = 0.15 sec.

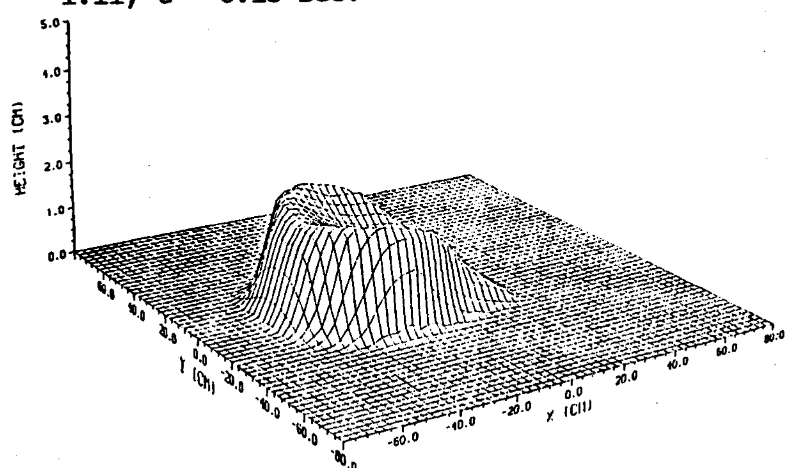

Figure 6 Meroney & Lohmeyer No. 7 (contd), t^* = 60, t = 9 sec.

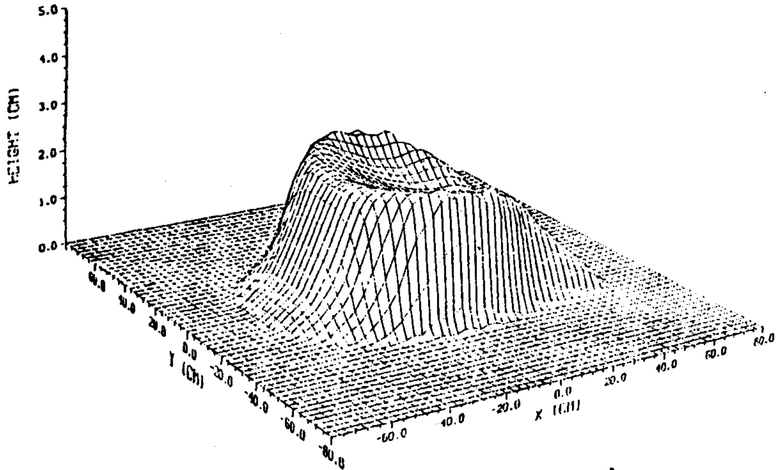

Figure 7 Meroney & Lohmeyer No. 7 (contd), $t^* = 100$, $t = 13$ sec.

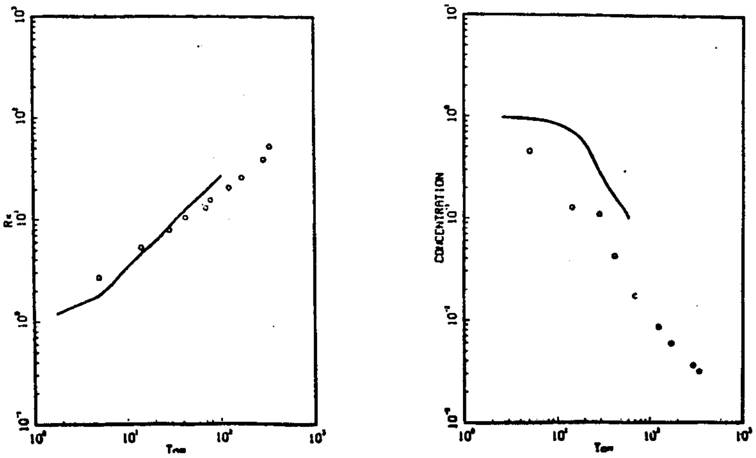

Figure 8a Meroney & Lohmeyer No. 7, Peak Concentration vs Arrival Time, T_a^*

8b Meroney & Lohmeyer No. 7, Plume Width, R_*, vs Arrival Time, T_a^*

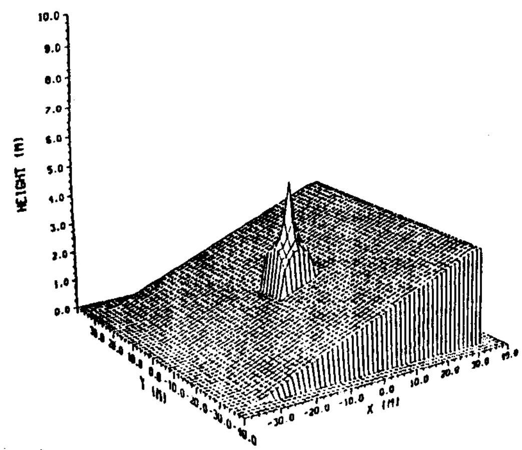

Figure 9 Cloud profile for Porton Trial No. 8, Slope 1:20, $t^* = 1$, $t = 0.6$ sec.

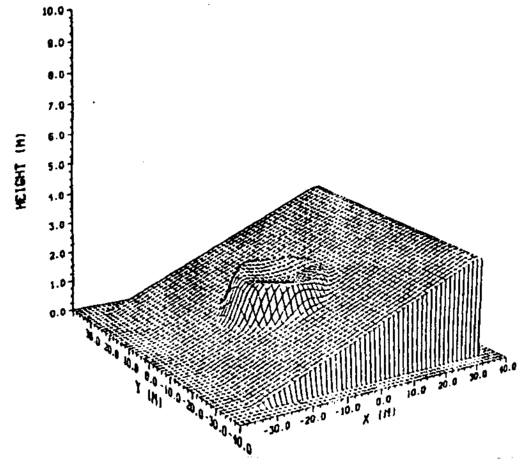

Figure 10 Porton Trial No. 8, Slope 1:20, $t^* = 17$, $t = 10$ sec.

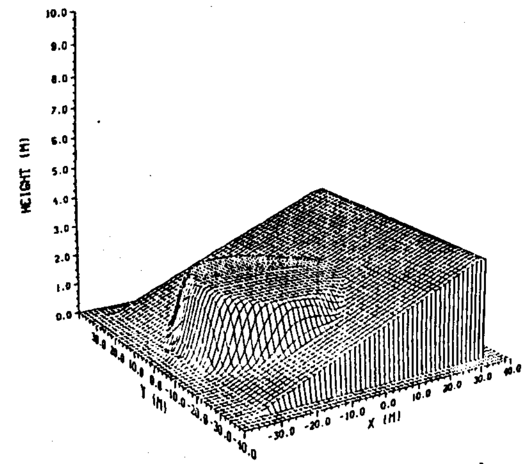

Figure 11 Porton Trial No. 8, Slope 1:20, $t^* = 51$, $t = 30$ sec.

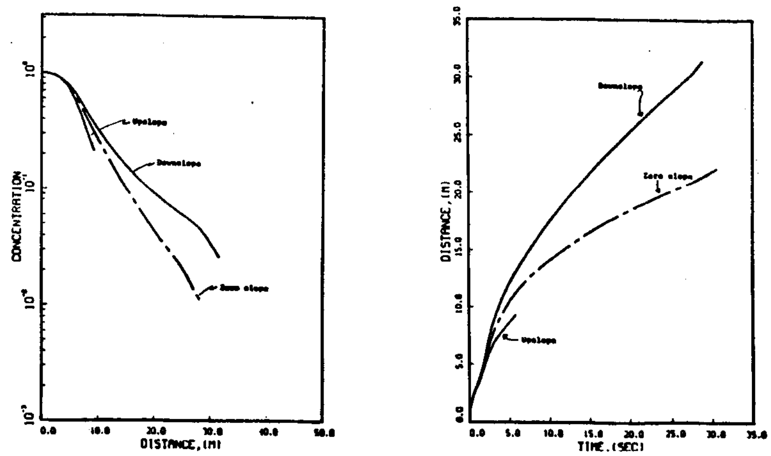

Figure 12a Porton Trial No. 8, Slope 1:20, Concentration vs Distance (m).
12b Porton Trial No. 8, Slope 1:20, Plume Extent vs Time (sec).

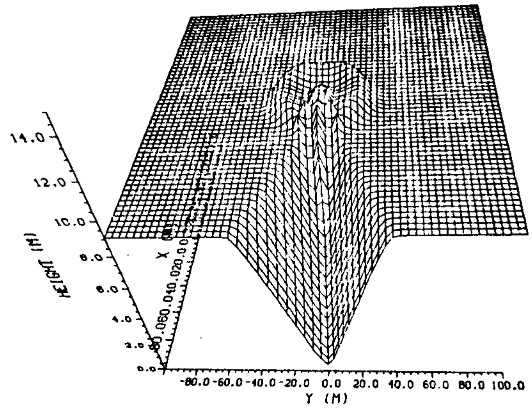

Figure 13 Porton Trial No. 8, Gorge Slopes, X direction 1:10 and Y direction 1:4.1, t^* = 20, t = 7 sec.

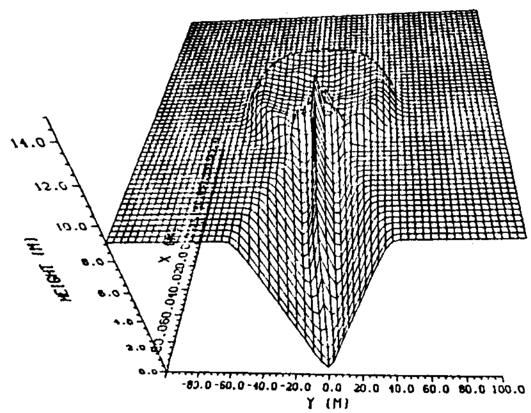

Figure 14 Porton Trial No. 8 (contd), Gorge Slopes, X direction 1:10 and Y direction 1:4.1, t^* = 100, t = 60 sec.