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MODEL INVESTIGATIONS OF THE SPREADING OF HEAVY GASES RELEASED FROM AN INSTANTANEOUS VOLUME SOURCE AT THE GROUND

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INTRODUCTION

Sudden release of a dense gas near the ground is accompanied by horizontal spreading caused by gravitational forces. Such clouds will drift downwind from the source location at ground level, providing an opportunity for ignition if the gas is flammable or perhaps for acute toxic effects to life in its path. An initially hemispherical volume slumps rapidly toward the ground after a sudden release. The diameter increases rapidly with an associated decrease in vertical dimension until such time as entrainment is significant. The ratio of vertical height to diameter remains quite small over most times of interest. The initial potential energy of the dense gas is converted rapidly to kinetic energy; however, this energy is also transmitted to the surrounding ambient fluid and is dissipated by turbulence at the head of the spreading plume.

The mixing of such plumes is still poorly understood despite a significant research effort of many years. The relative influence of gravity forces, viscous forces, entrainment at the plume front, entrainment at the upper surface, and modification of the background turbulent field due to stratification effects have been active subjects of discussion.

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Fay (1980) reviewed the various analytical models which have been proposed for describing the processes, and it is evident that further refinement awaits experimental verification. Hartwig and Flothmann (1980) also identify the need for new time dependent, three dimensional source experiments independent of initial gas generation or release mechanisms.

Restricting attention to instantaneous volume source behavior one finds field experiments performed by van Ulden (1974) on the sudden release of Freon-12 with an initial mixed specific gravity of 1.25, and spills of liquid natural gas (LNG) on land (AGA, 1974) or water (Feldbauer et al., 1972) with initial specific gravities near 1.5. Most recently, Picknett (1978) describes the release of air/ Freon gas mixtures with initial specific gravities ranging from 1.03 to 4.17. The LNG experiments are complicated by release mechanisms, and the recent Freon experiments suffer from instrument placement problems (Fay, 1980). Equivalent laboratory experience is limited to various lock-exchange experiments in water (Maxworthy, 1980; Huppert and Simpson, 1980), where the initial depth ratio of current to intruded fluid is often significant (Benjamin, 1968), or to finite time releases of heavy gases from area sources (Hall, 1979; Meroney and Neff, 1980).

This paper considers the results of experiments performed to examine the behavior of dense plumes during periods of gravity spread/air entrainment dominance. Havens (1977) discerned that these periods determind the lower flammability limit for LNG hazard analysis. A modified box model is presented to provide a framework of interpretation for the experiments. The experimental equipment and procedures are described. Finally, the data are evaluated and the order of magnitude of entrainment constants specified.

MODIFIED BOX MODEL FOR DENSE GAS CLOUDS

Fay (1980 has presented a generalized box model for the spread of a dense gas cloud in the form of a simple expanding cylindrical volume. The model assumes the Boussinesq assumption (ie. small density perturbations), entrainment proportional to frontal velocity, frontal velocity proportional to excess hydrostatic head, and atmospheric turbulence entrainment proportional to friction velocity. This model has been modified to retain initial inertial effects by removing the Boussinesq assumption. Hence in Fay's notation the governing relations are :

$$\frac{dR}{dt} = \alpha_1 \quad (g'H)^{1/2} \qquad (1)$$

$$\frac{dV}{dt} = \pi R^2 U_z + 2\pi RH \; U_r \tag{2}$$

$$U_z = c_z \; (g'H)^{1/2}; \; U_r = c_r \; (g'H)^{1/2} \tag{3}$$

where $g' = g(1 - \rho_a/\rho)$, H = plume height, R = Radius, t = time and V = plume volume. Various proposals have been made for the values of constants c_r and c_z. Fay observes most recent plume entrainment models can be stated in terms of equivalent expressions. A survey of such models suggests the magnitude for coefficients shown in Table 1. An analytical and empirical consensus seems to exist that $\alpha_1 \simeq 1.0$, and $c_r \simeq c_z \simeq 0(0.05)$.

Tabel 1 Entrainment Coefficients

Author	α_1	c_r	c_z
van Ulden (1974)	1.0	0.05	0.0
Germeles & Drake (1975)	$\sqrt{2}$	0.0	0.1
Picknett (1978)	0.94	0.82	$\sim 0.008^*$ (Ri> 7)
Simpson & Britter (1979)	1.4	0.053	-
Cox & Carpenter (1980)	1.0	0.6	$\sim 0.00013^*$
Eidsvik (1980)	1.3	1.0 - 0.0	$0.0005 - 0.015^*$
Fay (1980)	1.0	$\sim$ 0.01	$\sim$ 0.01
Current Experiment	1.0	0.05 - 0.1	0.05 - 0.1

*Under conditions modeled here

Specifying the conservation of buoyancy and an initial (index i) cloud volume where $R_i = H_i$ results in the following dimensionless (superscript $*$) expressions :

$$t^* = \frac{1}{\alpha_1 \pi^{1/6}} \int_1^{R/R_i} \frac{\left[\frac{\Delta\rho i}{\rho a} + A\,\xi^a + B\,\xi^3\right]^{1/2} \xi}{\left[A\,\xi^a + B\,\xi^3\right]^{1/2}}\, d\xi \tag{4}$$

$$\frac{V}{V_i} = A\left(\frac{R}{R_i}\right)^a + B\left(\frac{R}{R_i}\right)^3 \tag{5}$$

$$\frac{H}{H_i} = A\left(\frac{R}{R_i}\right)^{a-2} + B\left(\frac{R}{R_i}\right) \tag{6}$$

where

$$\begin{aligned} a &= 2\,c_r/\alpha_1 \\ A &= 1 - B \\ B &= c_z/(3\alpha_1 - 2c_r) \end{aligned} \tag{7}$$

When the wind speed is finite, drift distance must be adjusted for wind speed at cloud height, H. One may relate drift speed to undisturbed wind speed by

$$dX^*/dt^* = U^*(\beta H) + dR^*/dt^* \tag{8}$$

and

$$X^* = (\alpha_1 \pi^{1/6})^{-1} \int_1^{R/R} \bar{U}^*(\beta H)\,(\rho_a/\rho)^{1/2} d\xi + R^* \tag{9}$$

where β is an empirical constant near unity. Since $\bar{U}^*$ may be expressed in terms of a logarithmic law as

$$\bar{U}^* = \frac{U^*_*}{k} \ln\left\{\beta \frac{H_i}{z_o}\left(\frac{H}{H_i}\right)\right\} \tag{10}$$

and H/H_i as a function of R/R_i the relation is directly integrable. The final functional form for drift distance over a given time is

$$X^* = \frac{\bar{U}^*_{H_i}\,(C_f/2)}{k\,\alpha_1\,\pi^{1/6}}\,\psi\left(R^*, \frac{H_i}{z_o}, \frac{\rho i}{\rho a}\right) + R^* \tag{11}$$

Since V_i/V is a function of R one perceives that when selfgenerated entrainment is dominant the travel distance to a given maximum varies as $\bar{U}_*$.

A sudden release of volume V_i of vapor is characterized by a lenght scale $L = V_i^{1/3}$, and a time scale $T = V_i^{1/6}/(g_i')^{1/2}$ where $g_i' = g(\rho_i/\rho_a - 1)$. Huppert and Simpson (1980) suggest the initial-slump phase only exists when the depth ratio of intruding to ambient fluid is greater than 0.075. In a fluid of inifinite depth this phase is essentially instantaneous. Initial inertial/buoyancy phenomena will be present from $t^* = t/T = 1.0$. Buoyancy/viscous effects are significant from $t^* = [(g_i' V_i^{1/2}/\nu]^{1/3}$ if significant entrainment does not begin first from $t^* = c_z^{-2/3}$. Finally background turbulence enhances mixing from $t^* = g_i' V_i^{1/3}/\bar{U}^2$, until it completely dominates beyond $t^* = g_i' V_i^{1/3}/U_*^2$. These dominance regimes are displayed in Table 2 for the experiments presented. Only limited buoyancy/viscous effects or shear turbulence effects are expected. Hence the experiments should clearly specify the values of c_r, c_z and α_1. Data are plotted in terms of t^*, $R^* = R/V_i^{1/3}$, and V_i/V.

EXPERIMENTAL CONFIGURATION

An experiment was designed to examine in the laboratory dispersion of instantaneous volumes of dense gas released near the ground in a shear flow. The gases were released as bubbles beneath water in a boundary-layer wind tunnel, burst at the surface, and were monitored by an aspirated-hot-film katherometer.

Wind Tunnel and Bubble-Generation Equipment

A 20 cm diameter by 50 cm deep cylinder of water was mounted flush to the test section floor of the 180 cm wide by 75 cm high boundary-layer wind tunnel of the Institut Wasserbau III (Figure 1). A 50 cm^3 cup was located inverted within the cylinder. This cup was filled to the brim with the dense test gas. When the cup was rotated the gas volume formed a gas bubble which rose through the water to burst as an instantaneous volume source at the cylinder center on the water surface *. Visualization experiments and concentration measurements at the source suggest the volume release occurs with limited initial dilution and release generated turbulence.

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* A similar system for neutrally buoyant instantaneous volume release was used by Yang and Meroney (1972).

Table 2 Dominance Regions

Regime	Definition	t	
Initial Slump $H_i = .03$, $H = 1m$	$t^* < A$	∿ 0	
Inertial/Buoyancy	$t^* > 1$	1.0	
Buoyancy/Viscous	$t^* > Re^{1/3}$	13.8	
Inertial/Buoyancy Entrainment $c_z = 0.05$	$t^* > c_z^{-2/3}$	7.4	
Entrainment/Shear Turbulence $c_z = 0.05$ $\psi = 0.045$ $U_* = .15\ \bar{U}^*_L$	$Ri(\frac{c_z}{\psi})^2 > t^* > Ri\frac{c_f}{2}$		
	$\bar{U}^*_L$	FROM	TO
	0		
	0.05	460	7×10^4
	0.10	115	2×10^4
	0.20	29	5×10^3
	0.30	13	2×10^3

where

$$A = \frac{3}{2}^{-1/6} \left(\frac{H_i}{H}\right) \left(5.62\left(\frac{H_i}{H}\right)^{2/3} - 1\right), \quad \frac{c_f}{2} = \left(\frac{U_*}{U_L}\right)^2$$

$$Re = \frac{(g_i')^{1/2} V_i^{1/2}}{\nu}, \quad Ri = \frac{g_i' V_i^{1/3}}{U_*^2}, \quad t^* = \frac{t(g_i')^{1/2}}{(V_i)^{1/6}}$$

$$U^* = \frac{U}{V_i^{1/6} (g_i')^{1/2}}$$

It is possible that initial values of V_i/V lie between one and 0.5; however, it will be assumed in all data reduction that V_i/V initially equals one. The moment of volume release was monitored by an electricial conductivity device at the water surface; thus a timing mark registered release during each experiment on a chart recorder. Visualization indicated some releases occured off coordinate origin or with finite initial lateral velocity in a random direction.

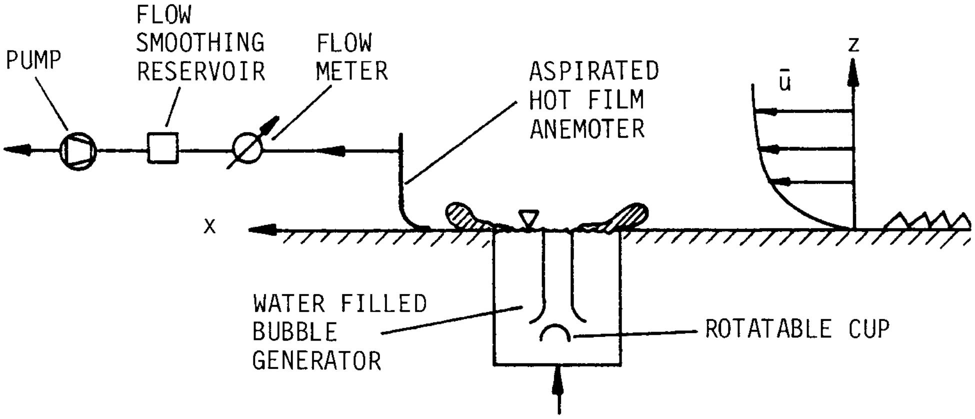

Figure 1 Experimental configuration

Shear Flow Measurements

The extremely low speeds (0.0 to 0.4 m/sec) that where required to simulate the dense cloud drift necessitated the use of a large pressure drop constriction in the wind tunnel and special calibration procedures for the hot wire anemometer used to measure velocities and turbulence. DISA 55A22 hot wires monitored by a DISA 55D01 anemometer were calibrated in a lowspeed nozzle whose speed was seth with low vloume flowrators. Velocity and turbulence measurements were made over the test section to detect the presence of any secondary cross currents. Velocities are reliable to U^* = 25 %.

Concentration Measurements

Dense gas concentrations were measured with an aspirated hot film anemometer (katherometer) constructed from a TSI 1441 detector in a tube. The aspiration velocity at the 1 mm diameter probe tip was set at 0.1 m/sec to assure approximately isokinetic sampling of the plume. A fiber filter was present at the probe tip to reduce system sensitivity to pressure perturbations during shear flow measurements. All tests were corrected for a slight time lag required for the sample to travel through the probe to the detection film. Extensive tests by Meroney et al. (1978) and again Wilson and Netterville (1980) indicate such a probe has a flat frequency response to 150 Herz, concentration sensitivity to 0.10 percent, and resolution within ± 5 percent of a measurement.

Since the probe is subject to drift and temperature effects it was recalibrated frequently. No significant deviations were detected.

During each realization of a volume release the katherometer response was registered on a Rikadenki DB6 chart recorder. Each sample point was recorded a minimum of three times. Time response was displayed within a resolution of $t = \pm 0.1$ sec ($t^* = \pm 3$)

RESULTS AND DISCUSSION

All experiments were performed with Freon-12 (Specific Gravity = 4.17) and a 50 cm^3 initial volume; hence, there were a length scale, $L = 0.037$ m, and a time scale, $T = 0.034$ sec. Velocities were varied from zero to 0.4 m/ sec at a reference height L.

Shear Flow Characteristics

Equilibrium boundary layers were developed over 8 m of upwind channel fetch. Velocity profiles were found to fit power law relations with the exponent $p = 0.45$, and surface characteristics $U_*/\bar{U}_L = 0.170$ and $z_o/L = 0.09$. Characteristic Richardson numbers, $Ri = g_i'V_i^{1/3}/U_*^2$, varried form ∞ to 250.

Local turbulence intensity profiles were characterized by magnitudes near the ground of 0.19; thus $\bar{U}/U_*$ values were 1.12, which is below the value 2.5 quoted for classical neutral turbulent boundary layers.

Dense Puff Dispersion During Calms

The time response of the katherometer during typical source realizations is displayed in Figure 2. Initially the arrival time is short and the concentration front is sharp, subsequently the arrival time lengthens and the front becomes diffuse.

The radial growth of a dense plume in terms of dimensionless coordinates R^* and t^* is shown in Figure 3. One notes the strong inertial correction required for such a dense gas. A Boussinesq assumption would not be justified. Radial growth does not appear to be strongly sensitive to the entrainment coefficients assumed. Figure 4 and 5 describes plume dilution V_i/V versus R^* and t^* respectively. Plume concentrations decay assymptotically as $(R^*)^{-3}$ and $(t^*)^{-3/2}$. Data agrees with the modified box model when entrainment coefficientes, $c_r = c_z = 0.1$, are chosen and if no initial dilution is assumed.

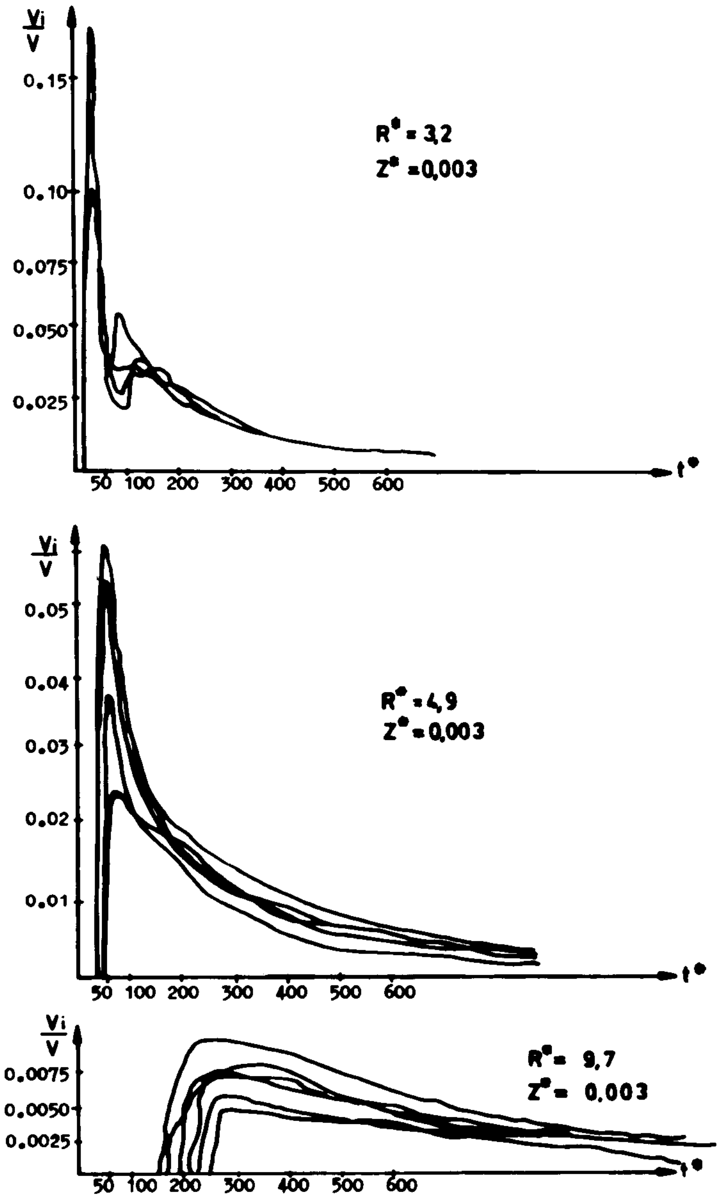

Figure 2 : Typical time response of the katherometer during calms at various positions.

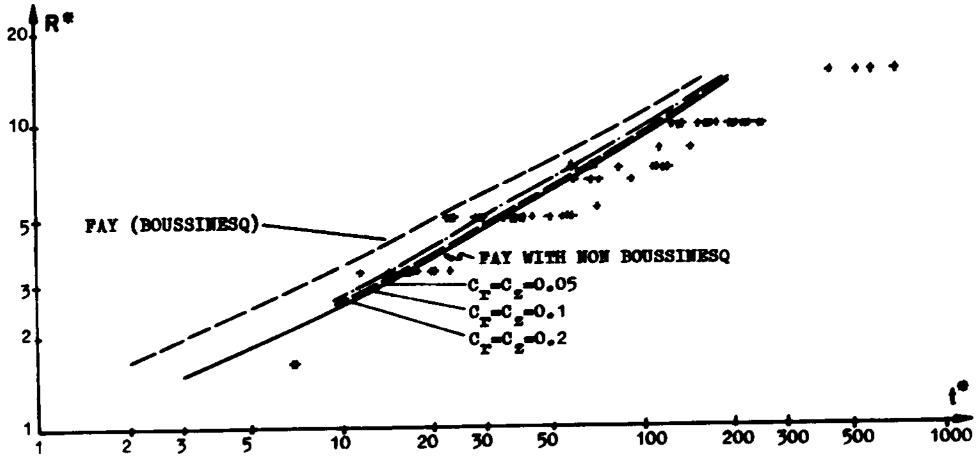

Figure 3 : Radial growth of a dense plume, $U_{*L} = 0$.

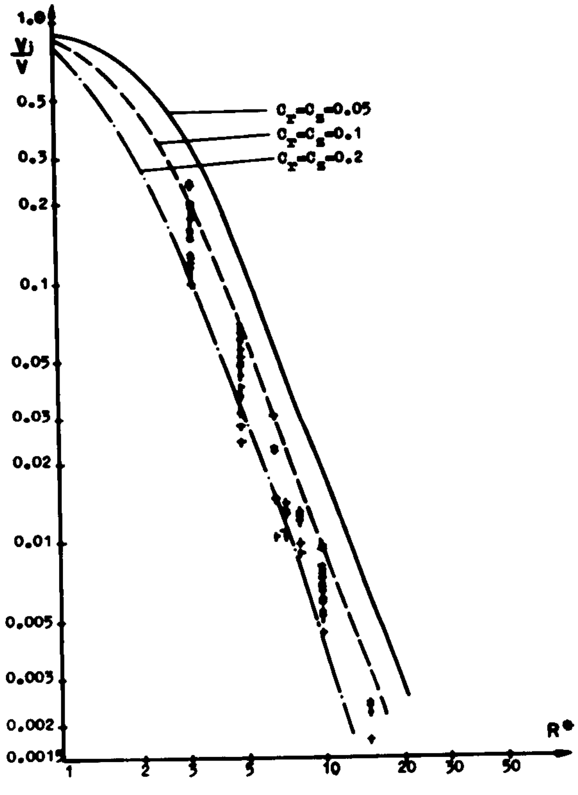

Figure 4 : Plume dilution V_i/V versus dimensionless radius R_*, $U_{*L} = 0$.

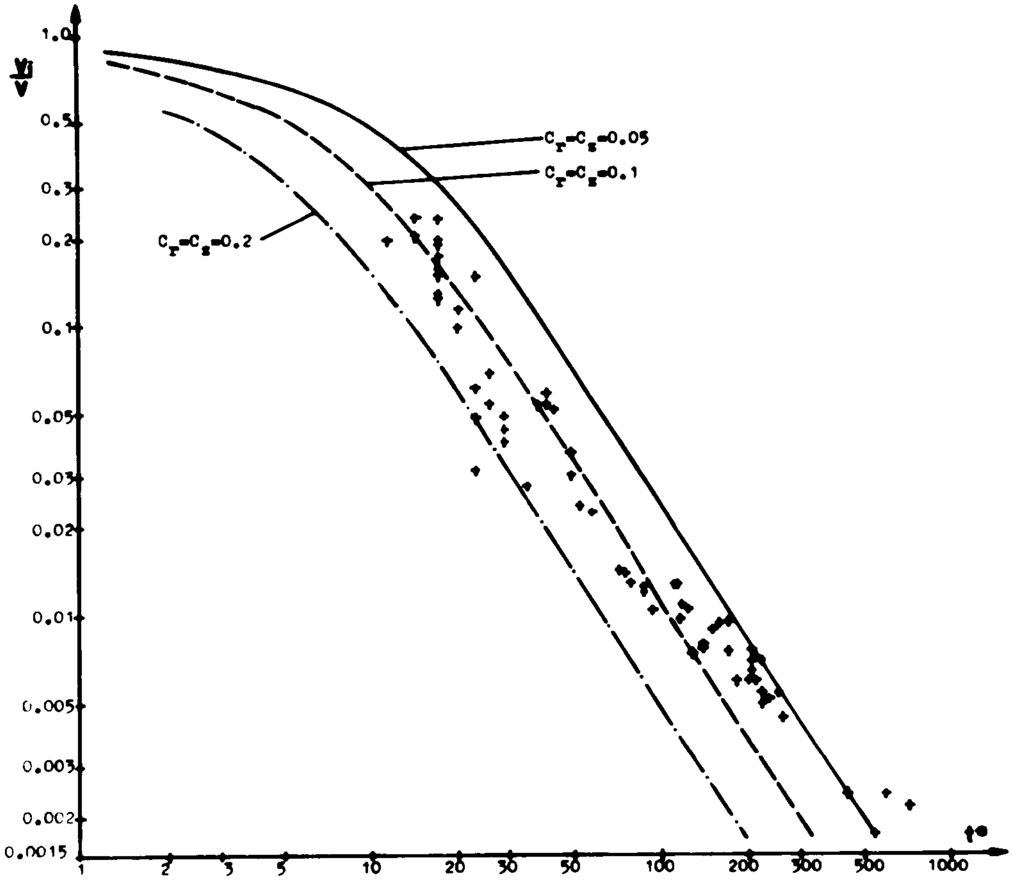

Figure 5 : Plume dilution V_i/V versus dimensionless time t_*; $U_{*L} = 0$.

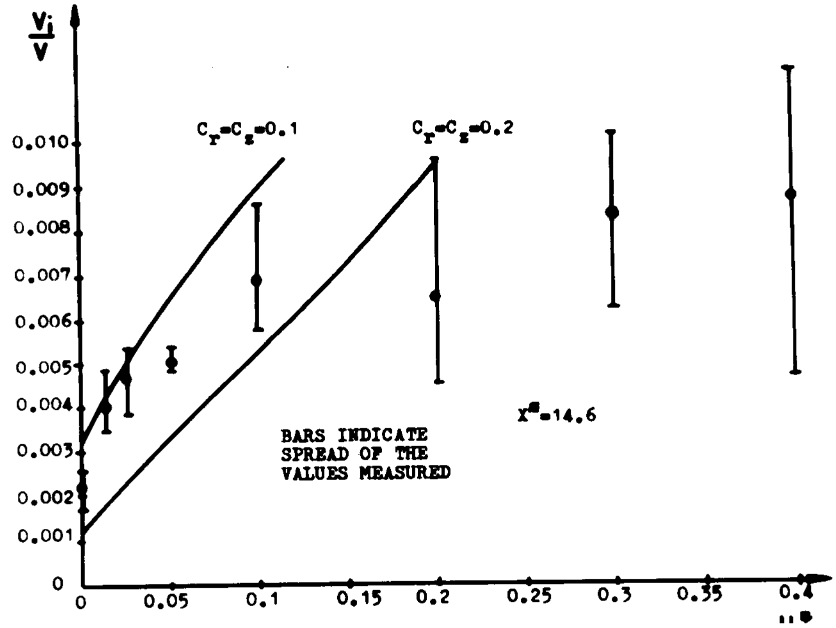

Figure 6 : Plume dilution versus dimensionless reference velocity U^*_L at a fixed distance X^* from the source.

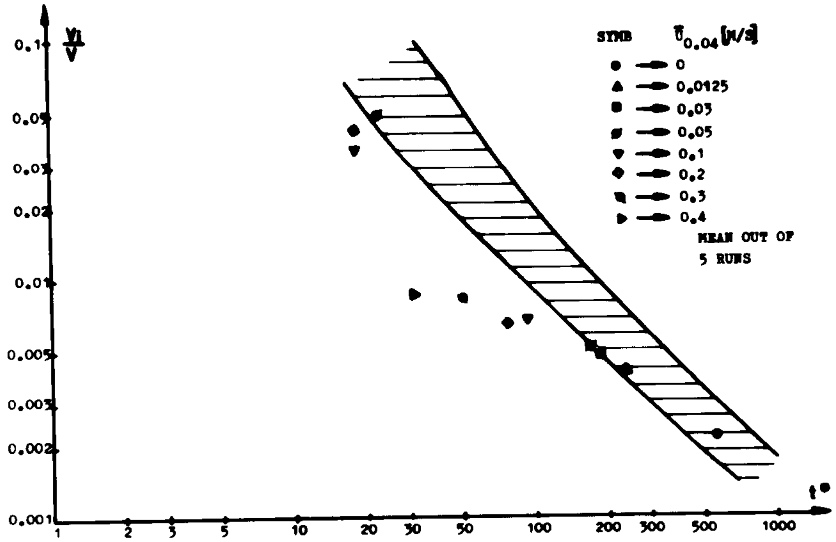

Figure 7 : Data from the wind shear experiments compared to the no wind data

If an initial dilution of two occurs then $c_r = c_z = 0.05$ are appropriate. No regions dominated by viscous effects are apparent before $t^* = 100$; however, subsequently spread rate slows to such low values that viscous effects result in deviations from the analysis. Error bars at long times are unexpectedly wide. Examination of replicated experiments do not seem to indicate source release mechanisms, chart recorder resulution, or katherometer response were at fault-perhaps an irregular advance of the front normally occurs.

Dense Puff Dispersion with Wind Shear

Results from experiments in the presence of wind shear are displayed in Figure 6 as V_i/V versus U_L^*. Note the displacement of higher concentrations to further downwind locations with increased wind speed. Only as the characteristic time scale for shear turbulence entrainment decreases to deviations from the inertial/buoyancy entrainment mechanisms occur. By use of the expression in (11) one can also examine plume behavior in terms of the viewpoint of an origin drifting with the wind. Data from the wind shear at $R^* = 4.9$ and 14.6 have been added to data of Figure 5 and replotted in Fig. 7. This permits one to note the reduced magnitudes of concentrations associated with dispersion by vertical shear not accounted for in the simple box model.

As the plume enters the mixing region dominated by shear turbulence one expects concentrations, V_i/V, to decay as $(R^*)^{-4}$ and $(t^*)^{-2}$. These data do not include distances or times suitable to discern such behavior. Fay (1980) discusses previous evidence for such dilution mechanisms in detail.

CONCLUSIONS

A series of experiments with sudden release of dense gas volumes at the ground in shear flows confirm that inertial/buoyant spreading is rapidly followed by a selfgenerated entrainment period. When Richardson numbers are sufficiently large the gas may be diluted well below 1 % before the effects of shear turbulence are evident. A modified box model for plume dilution suggests that the Boussinesq assumption is inappropriate for accurate calculation of concentration histories for very dense gases. Generalized entrainment coefficients at the plume front, c_r, and over the plume upper surface, c_z, should be between 0.1 and 0.05. Model experiments have reproduced dense plume behavior previously seen in field experiments at scales 350 times greater.

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DISCUSSION

A.P. VAN ULDEN

In table 1 you give a list of α values. I would like to note that Simpson and Britter used a different heigt scale than the one used in your paper. Thus the value is not directly comparable.

A. LOHMEYER

The box model is very simple and doesn't take into account a different height between the head and tail of a density front. In the box model the height H is just $V/\pi R^2$.

D. ANFOSSI

What evidence do you have that atmospheric turbulence was well simulated your wind tunnel.

A. LOHMEYER

The main interest of our experiments was in the no-wind cases. In the few experiments done with wind we just attempted to simulate first order effects to see in which direction the wind changed the situation.

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