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Gravity Spreading in the Dispersion  
of Dense Gas Plumes

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# GRAVITY SPREADING IN THE DISPERSION OF DENSE GAS PLUMES

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## *Introduction*

The atmospheric dispersion of a denser-than-air release is affected by several physical phenomena that either do not occur or are unimportant in a trace gas release. The main phenomena are directly related to the density structure of the dense gas cloud. They are damping of the turbulence level due to stable density stratification within the cloud and alteration of the ambient velocity field due to gravity flow resulting from horizontal gradients in the cloud density. In this paper we address the phenomena of gravity spreading of a denser-than-air cloud dispersing over flat terrain. Specifically, we attempt to interpret the gravity spreading results observed in wind-tunnel studies<sup>1</sup> conducted by CPP Inc.

These experiments involved dense gas dispersion under conditions of large surface roughness where the height of the surface roughness elements was comparable to the height of the dispersing dense gas cloud. The gravity spreading results were investigated by Roberts et al.<sup>2</sup> who found a transition in the dependence of the gravity flow velocity on the hydrostatic pressure head within the dense gas cloud. Near the source, the gravity flow velocity followed the well known square root dependence; however, at larger downwind distances, the dependence appeared to become linear. They interpret this transition using arguments proposed by Linden and Simpson<sup>3,4</sup> to describe the gravity flow rates observed in their lock-exchange experiments, but do not develop criteria for the onset of transition.

Here we provide an alternative interpretation of these gravity flow results in terms of a vertically averaged form of the conservation of momentum equations. This approach has been used in several models using the vertical averaging concept<sup>5,6</sup> to simulate atmospheric dispersion of denser-than-air releases. The vertically averaged momentum equation is essentially a balance between inertial, entrainment (diffusion), gravity, and surface friction terms. We explore the form of the momentum equation that occurs when different terms are assumed to dominate and develop criteria for the existence of these regimes. Comparing theory and wind-tunnel results, we attempt to interpret the changes in the gravity flow rates observed in the CCP experiments.

## *Background*

In the analysis of Roberts et al., the gravity flow velocity  $V_g$  close to the source follows the well known empirical relation

$$V_g = C_E [g \cdot (1 - \rho_a / \rho) \cdot h]^{1/2} \quad (1)$$

where  $C_E$  is an empirical constant of value 1.15,  $g$  is the acceleration of gravity,  $\rho_a$  is the ambient air density and  $\rho$ ,  $h$  are the dense gas cloud density and height, respectively. Further downwind, this equation begins to overestimate the gravity flow velocity and better agreement is achieved by using

$$V_g = \frac{g \cdot (\rho - \rho_a) \cdot h^2}{3 \cdot C_D \cdot \rho \cdot \omega_e \cdot B} \quad (2)$$

where  $C_D$  is an empirical constant,  $B$  is the cloud half width and  $\omega_e$  is the vertical entrainment rate (Roberts et al. express Equation (2) in terms of the vertical diffusivity  $K$  which we relate to the entrainment rate by  $K = \omega_e \cdot h$ ). The form of Equation (2) was obtained from a balance between turbulent dissipation and the horizontal pressure gradient. The empirical constant  $C_D$  was added to obtain agreement with experiment and the best fit was found using a value of  $C_D = 5$ .

Roberts et al. base their interpretation of this transition upon the conclusions of Linden and Simpson regarding their lock-exchange experiments. In these tests, a transition in the gravity flow velocity was induced by injecting air bubbles into the liquid working fluids from the bottom of the tank. The resulting turbulence destroyed the existing gravity current interface between the dense and ambient fluid and produced a diffuse layer that propagated into the ambient fluid at a much lower velocity. When the air bubbles were stopped the original gravity current reformed. Roberts et al. propose that something similar occurs in the CCP dense gas dispersion experiments. They attribute the transition in the dense gas gravity flow velocity to a similar breakdown in the gravity current resulting from an instability in the flow, possibly due to vortices shed from the roughness elements.

This explanation is certainly plausible; however, there are sufficient dissimilarities between the two sets of experiments and sufficient uncertainties regarding the origins of the transition in dense gas flow to allow for other possible explanations. In the following, we present an alternative interpretation that relies upon the presence of a Stokes type surface force that retards gravity flow.

### *Theory*

The crosswind averaged conservation equations for the steady state dispersion of a dense gas cloud from a continuous source are given in Ermak et al.<sup>5</sup> Here, we are mainly concerned with the conservation of mass

$$(\rho \cdot U \cdot B \cdot h)' = \rho_a \cdot \omega_e \cdot B + \rho_a \cdot v_e \cdot h, \text{ where } ( )' = \frac{d}{dx}, \quad (3)$$

and the conservation of momentum in the horizontal crosswind direction

$$(\rho \cdot U \cdot B \cdot h \cdot V_g)' = g \cdot (\rho - \rho_a) \cdot h^2 - f_s. \quad (4)$$

In the above,  $U$  is the velocity in the downwind direction  $x$ ,  $v_e$  is the horizontal entrainment rate,  $f_s$  is the surface drag force per unit length, and the remaining parameters are as

previously defined. The mass equation describes the increase in cloud mass due to entrainment at the top and sides of the cloud. The momentum equation is essentially a balance between the inertial-entrainment term on the left and the gravity and surface drag terms on the right.

In past work with this model<sup>5</sup>, we have represented  $f_s$  by a fluid resistance<sup>7</sup> that is proportional to the velocity squared. When used in Equation (4) to simulate the CCP experiments, the results were similar to those obtained using Equation (1); namely, the calculated cloud width was in good agreement near the source, but overpredicted the width further downwind.

To improve our predictions, we consider treating the gravity current as if it were a "bubble" moving through the atmosphere along the ground and represent  $f_s$  by a Stokes force of the form

$$f_s = C_S \cdot \rho \cdot \omega_{ea} \cdot h \cdot V_g \quad (5)$$

where  $\omega_{ea}$  is the ambient vertical entrainment rate, the product  $\omega_{ea} \cdot h$  is taken to represent the ambient diffusivity, and  $C_S$  is a geometric factor that depends upon the shape of the cloud and the proximity to walls. Treating the dense gas cloud as an elongated ellipsoid at ground level with the two halves of the cloud moving away from each other, we obtain an approximate value of  $C_S = 12.5$  for the geometric factor.<sup>8</sup>

Combining Equations (3-5) and neglecting the  $V_g'$  term, we obtain the following equation for the gravity flow velocity

$$V_g = \frac{g \cdot (\rho - \rho_a) \cdot h}{C_S \cdot \rho \cdot \omega_{ea} + \rho_a \cdot (\omega_{ea} \cdot \frac{B}{h} + v_c)} \quad (6)$$

This equation has the same linear dependence on the hydrostatic pressure head as does Equation (2). Furthermore, when the cloud height and half width are similar in length, the theoretically obtained weighting factor of Equation (6) is comparable to the empirical value found in the CCP experiments.

Equation (6) also approaches the form of Equation (1) near the source. In this region, the cloud half width is much larger than the cloud height; consequently, the  $\omega_{ea}$  and  $v_c$  terms can be neglected. In addition, if we assume that  $(B/h) \equiv (V_g/\omega_c)$ , then Equation (6) becomes

$$V_g = [g \cdot (\rho/\rho_a - 1) \cdot h]^{1/2} \quad (7)$$

which is essentially the same as Equation (1).

### **Comments**

The gravity flow velocity given by Equation (6) provides a continuous model for the dynamics of gravity flow in a steady state, dense gas cloud. The velocity was obtained by equating the hydrostatic pressure head term to the mass entrainment and Stokes surface

drag terms. Based upon this model, the transition from one gravity flow regime to another as observed in the CCP experiments is the result of the increasing role of the Stokes surface drag force as the cloud height grows. We are currently evaluating the model by comparing numerical simulations of the CCP and other dense gas experiments with the observed results.

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