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DYNAMIC BEHAVIOUR OF PARTICLE CLOUDS

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Abstract: This paper examines the dynamic behaviour and structure of the flow produced by the release of a cloud of dense particles into a fluid medium. Laboratory experiments indicated that the initial flow was thermal-like with strong internal circulation. The size of the cloud increased linearly with distance from the point of release and its velocity reduced inversely with distance in accord with the known behaviour of miscible thermals. As the velocity of the cloud approached the fall velocity of individual particles, the internal circulation was suppressed and its velocity approached a constant value. It was found that the different regimes of cloud behaviour could be described in terms of a local cloud parameter expressing the ratio of the fall velocity of individual particles to a characteristic velocity based on the cloud buoyancy and size.

INTRODUCTION

Waste particulate matter is sometimes disposed of by ocean dumping where it disperses as a particle cloud before finally settling onto the sea floor. Previous attempts to model the flow produced by particle clouds have treated the particles as a distributed density excess in the same manner used for miscible buoyancy. There is substantial experimental evidence to show that the distributed buoyancy approximation is valid in some circumstances and has been used to predict the behaviour of bubble plumes (Cederwall and Ditmars, 1970) and turbidity currents (Simpson, 1982).

Koh and Chang (1973) adapted a self-preserving thermal model for miscible fluids (Turner, 1973) to describe the behaviour of dense particulate matter dumped into the ocean. More recently Nakatsuji et al. (1990) applied the miscible fluid assumption to model the particle clouds and reported systematic departures from the miscible thermal model under certain conditions.

The present study aims to identify the various phases of particle cloud behaviour and identify a characterising parameter.

THE BEHAVIOUR OF PARTICLE CLOUDS

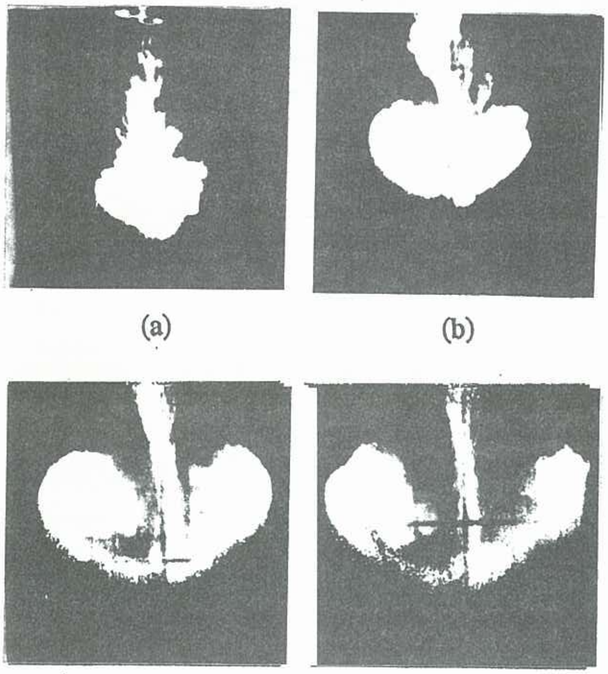
A series of experiments was undertaken in which a cloud of dense particles was released without initial momentum into a homogeneous, stationary body of water. At the point of release the particles were closely packed and following release three distinct phases of motion were observed.

Initial Acceleration Phase. When the cloud of particles was first released it was closely packed and accelerated from the rest as a solid body. Shear forces at the boundary of the cloud produced turbulent instabilities which dispersed the particles, thereby reducing the effective density of cloud which together with the acquired velocity of the cloud caused it to enter the second phase of motion.

Self Preserving Phase. During this phase the particles acted as a distributed buoyancy within the cloud and its behaviour and structure were similar to that of a negatively buoyant thermal as is evident in photographs in Figures 1b, 1c and 1d. A strong internal circulation which is characteristic of thermals was observed inside the particle cloud. During this phase of motion the size of the cloud continued to increase with time, however, its velocity reduced in line with the known behaviour of thermal-like flows (Turner, 1973).

Dispersive Phase. Ultimately as the velocity of the thermal approached the settling velocity of the particles within it, the internal circulation which characterises thermal motion was suppressed and the particles entered the final phase of motion where they settled in a dispersed cloud with all particles moving downwards. The cloud continued to grow during this phase due to weak dispersive influences between adjacent particles and its velocity approached a constant value.

Figure 2 shows the velocity of a particle


(a) (b)

(c) (d)

Fig. 1- Photographs of the particle cloud using slit illumination at different stage of descent. . **a.**Initial acceleration phase, **b.**Transition to thermal phase, **c,d.**Thermal-like behaviour.
V_0=4.2 Cm^3, 0.15 mm<d<0.18 mm

cloud in terms of distance from the point of release in a typical experiment. The expected behaviour of a miscible thermal is indicated by the dashed line. The phases of cloud motion just described are evident in this figure. The phase of initial acceleration occurs between A and B. At B the cloud reaches its maximum velocity and thereafter its behaviour is more like that of a miscible thermal although it will be noted that its speed is greater than that of a miscible thermal with the same buoyancy. The discrepancy between the celerity of the particle cloud and that of a thermal continues to increase until at C the cloud reaches a terminal velocity close to that of individual particles.

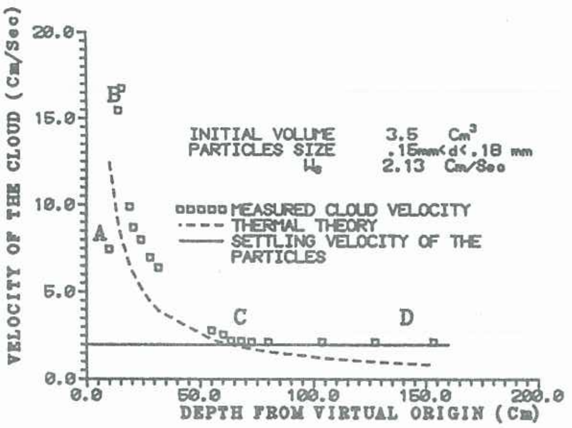


Fig. 2- Variation of cloud velocity with distance from a virtual origin compared with the predicted velocity of a miscible thermal with the same buoyancy.
AB- Initial acceleration phase,
BC- Thermal phase,
CD- Dispersive phase.

It was found that if the settling velocity of the particles was high and the initial volume of the cloud small, then the particle cloud would move from the acceleration phase to the dispersive phase without passing through the thermal phase.

SCALING RELATIONSHIPS FOR PARTICLE CLOUDS

An integral analysis is used to describe the dynamic behaviour of the particle cloud. It is assumed that the internal structure of the cloud changes only slowly so that changes to the internal velocity structure and the distribution of particles within the cloud can be neglected compared with changes to the velocity of the cloud and its bulk density.

Accordingly the relationship describing the bulk dynamics of the particle cloud can be written

$$[M(1-1/r)+\rho\,(1+C_v)\,V]\,\frac{dw}{dt} = B - C_D\,\rho w^2 A \qquad (1)$$

where M = total mass of the particles in the cloud
r = relative density of the particles
ρ = fluid density
C_v = virtual mass coefficient of the particle cloud
V = volume of the cloud
w = velocity of the centre of the mass of the cloud
t = time
B = buoyancy of the cloud
C_D = drag coefficient
A = plan form area of the cloud when viewed from above

The first term in the force balance expressed in Eq. (1) is the cloud inertia and includes the mass of the particles contained in the cloud, the mass of fluid in the cloud and the virtual mass of the cloud.

The first term on the RHS of Eq. (1) is the buoyancy of the cloud and is equal to the submerged weight of the particles so that

$$B = M(1 - 1/r)\,g \qquad (2)$$

where g = gravitational acceleration.

The final term in Eq. (1) is the drag force experienced by the cloud as it falls through the ambient fluid.

It is expected that the motion will be axisymmetric about the vertical so that the cloud can be characterised by two variables, R the maximum radius of the cloud, and a volume coefficient C defined by

$$V \equiv CR^3 \tag{3}$$

where V is the cloud volume. The plan form area of the cloud (A) appearing in Eq. (1) is therefore given by:

$$A = \pi R^2 \tag{4}$$

It will be noted that the set of Eqs. (1), (3) and (4) contain two unknowns, the cloud velocity (w) and cloud size characterised by R. Solution of these equations requires a further relationship which in turbulent flows of this type may take the form of an entrainment relationship coupling the rate of growth of the cloud to the rate of entrainment of ambient fluid. This can be expressed by

$$\frac{d(R^3)}{dt} = EwR^2 \tag{5}$$

where R^3 characterises the volume of the cloud
R^2 the surface area of the cloud
E is an entrainment coefficient

The chain rule of differentiation can be employed to express Eq. (5) as

$$3R^2\, w\, \frac{dR}{dz} = EwR^2$$

which reduces to $E = 3\dfrac{dR}{dz}$ (6)

In self preserving flows E is constant, however, in a particle cloud which is expected to exhibit different forms and regimes of behaviour it is not expected that E would be constant.

The changing nature of the particle cloud was attributed to changes to the pattern of the internal circulation characteristic of miscible thermals. As was seen in Figure 2 the velocity of the cloud reduced with distance during the thermal phase and there was a corresponding decrease in circulation velocities within the cloud. Ultimately this led to a breakdown of particle circulation in the cloud as circulation velocities approached the terminal velocity of individual particles.

The circulation velocity can be characterised by the kinematic buoyancy of the cloud (B/ρ) and the size of the cloud characterised by R. The ratio of the settling velocity of individual particles (w_s) to the characteristic circulation velocity $(B/\rho R^2)^{1/2}$ determines the behaviour of particles within the cloud and therefore the behaviour of the cloud itself. This ratio will be termed the cloud number.

$$N_c = w_s R \left[\frac{\rho}{B}\right]^{1/2} \tag{7}$$

and it will be noted that this is a local parameter whose value continually increases as the cloud grows in size.

If indeed the cloud number characterises the behaviour of a particle cloud then other characteristics of the cloud such as the value of the local entrainment parameter (E) and the characteristic velocity of the cloud (w/w_s) should be functions of N_c alone.

EXPERIMENTS

The experiments with particle clouds were performed in a tank 1.8 m deep and 0.9 m square. One wall of the tank was transparent and the two side walls had strip windows over their depth so that the cloud could be illuminated by a light sheet. Sheet lighting was employed so as to reveal the internal structure of the cloud. The motion of the cloud and the particles within it were recorded on video film for later analysis. The cloud was released without initial momentum using a spherical clam-shell mechanism. The particles themselves consisted of graded sand with diameters ranging from 0.150 to 0.350 mm and settling velocities of 2.1 to 5.1 cm/sec.

DISCUSSION OF EXPERIMENTAL RESULTS

Figure 3 shows the measured velocity of the particle cloud relative to that of a miscible thermal of the same size and with the same buoyancy plotted as a function of the local cloud number (N_c). It is evident that the data from the different experiments collapses to form a single curve. For small values of the cloud number the velocity of the cloud approaches that of a miscible thermal of similar size and buoyancy. In a miscible thermal the velocity of internal circulation scales directly with the velocity of the thermal itself which varies inversely with distance from the source. As a particle cloud falls and grows in size its velocity reduces until the internal circulation is unable to maintain the particles circulating within the cloud. At this stage the particles fall uniformly together and the celerity of the cloud approaches that of the particles themselves. During this dispersive phase the fall velocity of the cloud is greater than that of a similar cloud of miscible buoyancy and the discrepancy between the two velocities increases continuously as indicated in Figure 3.

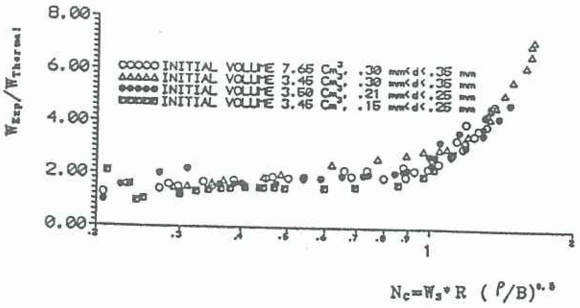


Fig. 3- Relative velocity of the particle cloud (W_{Exp}) to miscible thermal ($W_{Thermal}=1.54*B^{0.5}/Z$) with the same buoyancy at the release point vs. N_c.

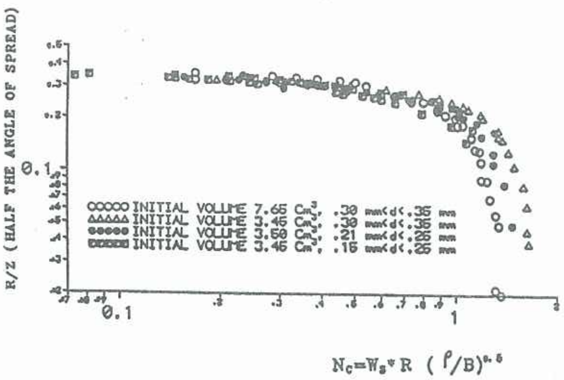


Fig. 4- Variation of entrianment coef. vs. N_c for different initial condition.

Figure 4 shows the half angle of plume spread, which is directly proportional to the entrainment coefficient (Eq. 6), as a function of the cloud number and again the experimental data collapses to form a single curve. For small values of the cloud number ($N_c < 0.3$) the spread is the same as that for a miscible thermal, however, as the internal circulation is suppressed with increasing cloud number, entrainment decreases. This decrease is particularly marked once the cloud number exceeds unity. The data in Figure 4 are closely approximated by the relationship

$$E = 0.93 \left[1 - 0.44 N_c^{1.25}\right] \quad \text{for } N_c < 1 \qquad (8)$$

which forms a closure relationship for particle clouds.

Growth of the particle cloud becomes very slow once $N_c \approx 1.5$ and particle dispersion caused by interaction between particles and wakes of other particles is the principal cause of subsequent growth. The size of the particle cloud when it enters this last phase is given by

$$R = 1.5 \left[\frac{B}{\rho}\right]^{1/2} \frac{1}{w_s} \qquad (9)$$

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