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THE TRANSITION TO THE SWARM PHASE FOR A PARTICLE CLOUD

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ABSTRACT

The different modes of behaviour for a particle cloud are predicted on the basis of scaling. In particular, the transition of the particle cloud to the swarm phase is examined. Laboratory data is presented in support of the scaling analysis. It is shown that the transition to swarm behaviour essentially occurs when the fall velocity of the particle cloud is equal to the fall velocity. The influence of the initial parameters is classified using three non-dimensional parameters.

INTRODUCTION

Particle clouds are commonly formed by the dumping of spoil into the ocean and in a number of industrial processes where liquid/bubble and liquid/solid two-phase flows occur. Thus the spread of the particulates in particle clouds is of both environmental and industrial concern. This paper aims to clarify the modes of spreading or behaviour which occur in particle clouds.

The behaviour of clouds of particles either rising or sinking in a homogeneous environment has been experimentally examined by Nakatsuji et al. (1990), Buhler and Papantoniou (1991), Rahimipour and Wilkinson (1992), Noh and Fernando (1993), Topham et al. (1994) and Nitsche and Batchelor (1997). Key phases identified for turbulent particle clouds are the acceleration phase, the thermal phase and the swarm phase.

The acceleration phase occurs when the particles are first released. Essentially, the particles accelerate from rest under the influence of gravity with entrainment of ambient fluid occurring. The acceleration phase is typically followed by a thermal phase during which the particles act as a distributed buoyancy and a thermal like circulation exists within the cloud. During this phase the cloud continues to entrain ambient fluid. The final phase is the swarm or dispersive phase in which the particles separate and move ahead of the thermal like circulation and entrained fluid. This final phase occurs when the fall velocity of the cloud is around that of an individual particle.

For the case of low Reynolds number particle clouds there is no entrainment of fluid into the particle cloud (although fluid is entrained into a wake). In this case the cloud accelerates to terminal velocity and a slow leakage of particles to the wake occurs (Nitsche and Batchelor, 1997). We shall refer to this terminal velocity phase as a non-entraining thermal.

In this paper we focus on classifying the transitions between these regimes in terms of non-dimensional parameters. Firstly, scaling is presented to determine the relevant non-dimensional parameters. This is followed by experimental data which supports the scaling.

SCALING OF A PARTICLE CLOUD

The behaviour of a group of particles released from rest into an unstratified fluid depends upon the properties of the individual particles, the amount and spacing of the particles at release, and the properties of the receiving fluid. The individual particles can be characterised by their diameter d_p and density ρ_p. The amount of particles and their spacing can be represented by the mass M of particles released and the volume V_o encompassing the particles at release respectively. The fluid is characterised by its density ρ_f and kinematic viscosity ν. The introduction of an effective gravity g' allows the introduction of the forcing. The independent variables are then:

Particle properties:

$$M\ (kg), \rho_p (kgm^{-3}), d_p\ (m), V_o\ (m^3)$$

Fluid properties:

$$\rho_f\ (kg\ m^{-3}),\ \nu\ (m^2 s^{-1})$$

Forcing

$$B = M\ g' \text{ (where } g' = \frac{\rho_p - \rho_f}{\rho_p} g \text{)}$$

Where g is gravitational acceleration and B is the total buoyancy of the particles (we will use the convention of dense particles having positive buoyancy). Note that the terminal fall velocity w_p of a particle is a function of the particle diameter d_p, density of the particle ρ_p, and the density ρ_f and kinematic viscosity ν of the receiving fluid.

The preceding seven variables result in four non-dimensional groups:

$$\Delta = \frac{\rho_p}{\rho_f}$$

$$N \approx \frac{M}{\rho_p\, d_p^3}$$

$$\mathbb{R}_{so} = \frac{d_o\, w_p}{\nu} = \left(\frac{V_o}{N}\right)^{1/3} \frac{w_p}{\nu}$$

$$\mathbb{R}_p = \frac{d_p\, w_p}{\nu}$$

The non-dimensional variables are: Δ, the relative density of the particles; N, the number of particles; $\mathbb{R}_{so}$, a spacing Reynolds number where d_o is the average distance between particles at release; and, $\mathbb{R}_p$, the particle Reynolds number. These Reynolds numbers can be rewritten without the fall velocity by noting that a force balance between buoyancy and drag for a single particle exists at terminal velocity:

Laminar:

$$\frac{Mg'}{N} \sim \tau\, d_p^2 \sim \rho_f\, \nu \frac{w_p}{d_p} d_p^2$$

$$\Rightarrow w_p \sim \frac{Mg'}{N\rho_f\, \nu\, d_p} = \frac{\beta}{N\nu\, d_p} \sim \frac{d_p^2\, \Delta\, g'}{\nu}$$

Turbulent:

$$\frac{Mg'}{N} \sim \tau\, d_p^2 \sim \rho_f\, d_p^2\, w_p^2$$

$$\Rightarrow w_p \sim \left(\frac{M\, g'}{N\, \rho_f}\right)^{1/2} \frac{1}{d_p} = \frac{\beta^{1/2}}{N^{1/2}\, d_p} \sim \left(d_p\, \Delta\, g'\right)^{1/2}$$

where the specific buoyancy $\beta = Mg' / \rho_f = B / \rho_f = mg'$ where m is the specific mass. Substituting these into the definitions of the particle Reynolds number leads to:

$$R_p = \begin{cases} \dfrac{\beta}{N\nu^2} \sim \dfrac{d_p^3\, \Delta\, g'}{\nu^2} & \textit{laminar}\ (\mathbb{R}_p < 1) \\[2ex] \left(\dfrac{\beta}{N\nu^2}\right)^{1/2} \sim \dfrac{(d_p^3\, \Delta\, g')^{1/2}}{\nu} & \textit{turbulent}\ (\mathbb{R}_p > 1) \end{cases}$$

The preceding non-dimensional variables (Δ, N, $\mathbb{R}_{so}$ and $\mathbb{R}_p$) characterise the release or initial conditions. Local parameters are discussed in the following.

CLOUD BEHAVIOUR

Local variables are the depth z and fall velocity w (assuming a descending cloud) of the cloud. The velocity w of the different regimes of a particle cloud can be scaled as follows:

Acceleration phase: $w_a = K_a \left(g'\, z\right)^{1/2}$

Thermal phase:
$$\begin{cases} w_{te} = K_{te} \dfrac{\beta^{1/2}}{z} & \textit{entraining} \\[2ex] w_{tn} = K_{tn} \dfrac{\beta^{1/2}}{V_o^{1/3}} & \textit{non-entraining} \end{cases}$$

Swarm phase: $w_s = w_p$

The acceleration phase is based on the assumption of negligible drag and entrainment. The entraining thermal phase assumes a buoyancy inertia balance with entrained fluid dominating the mass of the cloud. The non-entraining thermal relationship is based on a buoyancy drag balance at terminal velocity w_{tn} (the cloud retaining its original size). The coefficients K_a, K_{te} and K_{tn} are of order one and are dropped in the following sections.

The velocity and length scales for the transitions between the different phases are:

Acceleration to entraining thermal:

$$w_{a-te} \sim \frac{\beta^{1/2}}{m^{1/3}} = \beta^{1/6}\, g'^{1/3} \quad ; \quad z_{a-te} \sim m^{1/3}$$

Acceleration to non-entraining thermal:

$$w_{a-tn} \sim \frac{\beta^{1/2}}{V_o^{1/3}} \quad ; \quad z_{a-tn} \sim \frac{m}{V_o^{2/3}}$$

Acceleration to swarm:

$$w_{a-s} = w_p \quad ; \quad z_{a-s} \sim \frac{w_p^2}{g'}$$

Entraining thermal to swarm:

$$w_{te-s} = w_p \quad ; \quad z_{te-s} \sim \frac{\beta^{1/2}}{w_p}$$

The non-entraining thermal essentially maintains its speed at terminal velocity. In practice, loss of buoyancy to the wake behind the cloud (Nitsche and Batchelor, 1997) will result in a gradual reduction in terminal velocity. We shall not concern ourselves further in this paper with the behaviour of the non-entraining thermal phase once terminal velocity has been attained.

Three basic modes of cloud behaviour can be identified based upon the above phases. These are:

MODE 1: acceleration → entraining thermal → swarm
MODE 2: acceleration → swarm
MODE 3: acceleration → non-entraining thermal

These modes are sketched in Figure 1.

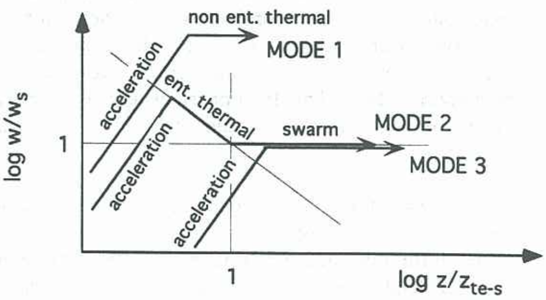

Figure 1. Hypothesised modes of particle cloud behaviour.

Implicit in Figure 1 is that particles separate from entrained fluid at $w = w_s$ for mode 1 and mode 2 behaviour. It can be shown that the effect of turbulence and blocking (low values of $\mathbb{R}_s$) on delaying the transition to a swarm will normally be minor. However, space limitations prevent these arguments being presented here. Mode 3 will only occur for a bulk Reynolds number $\mathbb{R}_{tn} = w_{tn} V_o^{1/3} / \nu \sim \beta^{1/2} / \nu$ less than around unity. Note that for an entraining thermal $\mathbb{R}_{te} \sim \beta^{1/2} / \nu$ so that for the thermal phase the bulk Reynolds number is:

$$\mathbb{R}_t \sim \frac{\beta^{1/2}}{\nu} \begin{cases} < 0(1) & \Rightarrow \textit{non-entraining thermal} \\ >> 0(1) & \Rightarrow \textit{entraining thermal} \end{cases}$$

We will not consider mode 3 further. Thus we are restricting ourselves to $\mathbb{R}_t >> 0(1)$ for which modes 1 and 2 can occur. When considering modes 1 and 2 it is useful to introduce the following ratio:

$$C_{a-te} = \frac{w_{a-te}}{w_p} \sim \frac{\beta^{1/2}}{m^{1/3}\, w_p} = \frac{\beta^{1/6} g'^{1/3}}{w_p}$$

We shall refer to C_{a-te} as the transition cloud number.

From examination of Figure 1 it is clear that:

$$C_{a-te} \begin{cases} > 0(1) & \Rightarrow \textit{mode } 1 \\ < 0(1) & \Rightarrow \textit{mode } 2 \end{cases}$$

We can examine mode 2 further by substituting the earlier relationships for the particle fall velocity w_p into the definition of C_{a-te} to give:

Laminar:

$$C_{a-te} = \left(\frac{N}{\mathbb{R}_p^3\, \Delta^2}\right)^{1/6} \qquad \mathbb{R}_p = \frac{w_p d_p}{\nu} \sim \frac{d_p^3\, \Delta\, g'}{\nu^2} < 1$$

Turbulent:

$$C_{a-te} = \left(\frac{N}{\Delta^2}\right)^{1/6} \qquad \mathbb{R}_p = \frac{w_p d_p}{\nu} \sim \frac{\left(d_p^3\, \Delta\, g'\right)^{1/2}}{\nu} > 1$$

where laminar and turbulent refer to the flow field around a particle. For mode 2 we require $C_{a-te} < 0(1)$. For the laminar (particle) mode 2 case $\mathbb{R}_p < 1$ which, using the preceding laminar relationship requires $N / \Delta^2 < 0(1)$ for $C_{a-te} < 0(1)$. We also end up with an identical requirement for mode 2 turbulent (particle) for $C_{a-te} < 0(1)$. This means that the number of particles N released cannot exceed Δ^2 if mode 2 behaviour is to occur. Given that Δ is, at most, around 10, this means that no more than 100 or so particles can be released for mode 2 behaviour. Thus mode 2 behaviour can only occur for C_{a-te} less than but near 0(1). Implicit in the definition of C_{a-te} is the presence of an entraining thermal-like flow. Quite clearly, if particles are released at a sufficiently large spacing they will fall as individual particles without an entraining thermal-like flow set-up. In this instance, mode 2 behaviour can occur for $C_{a-te} >$ 0(1). However, for a scattered release (ie, particles widely spaced at release), mode 2 behaviour is still precluded for C_{a-te} much less than 0(1). This is because the scaling for an individual particle and a cluster of particles ends up the same for mode 2 behaviour.

The different modes of behaviour are summarised in Table 1.

	Clump Release		Scattered Release	
	$\mathbb{R}_t$<0(1)	$\mathbb{R}_t$>>0(1)	$\mathbb{R}_t$<0(1)	$\mathbb{R}_t$>>0(1)
$C_{a-te} < 0(1)$	NOT POSSIBLE	NOT POSSIBLE	NOT POSSIBLE	NOT POSSIBLE
$C_{a-te} \approx 0(1)$	↑ MODE 3	MODE 2	↑ MODE 2	MODE 2
$C_{a-te} > 0(1)$	↓	MODE 1	↓	MODE 2

Table 1. Regimes of behaviour classified based upon release type, bulk Reynolds number $\mathbb{R}_t$ and transition cloud number C_{a-te}. A scattered release is one where particles are released at large relative spacings.

LABORATORY EXPERIMENTS

Laboratory experiments consisted of releasing particles into a 1m deep by 2m × 5m tank filled with water. The resulting particle cloud was illuminated with a 2mm thick light sheet oriented in the vertical plane. The light sheet was formed using a 20W argon laser beam projected onto a parabolic mirror via a number of small mirrors on the periphery of a rapidly rotating wheel. The release point was centred on the light sheet. Two types of experiments were undertaken; these are summarised in Table 2.

EXPERIMENT TYPE	A	B
Release	ball valve	electromagnet
Particles	0.4mm glass beads	iron powder
Particle Fall Velocity	6.5cm s^{-1} ±11%	0.7cm s^{-1} ± 30%
Release Mass	4 g or 6 g	0.25 g

Table 2. Summary of the two types of particle cloud experiments.

For the type A experiments, a ball valve was closed, particles inserted and then the valve was fully submerged prior to opening. This ensured that there was no 'gulping' and that the initial driving force was equal to the buoyancy B. For type B experiments, iron powder was held in place by a submerged electromagnet until release. The electromagnet was particularly suitable for allowing the initial particle spacing to be varied.

For both type A and B experiments, the tank was seeded with neutrally buoyant pliolite flakes less than 250μm in size. These flakes allow the fluid motion to be visualised. Both conventional photography and video were used to record the motion of the flakes and particles. The choice of a suitable exposure duration resulted in the paths of the flakes and particles being recorded on the (conventional) camera.

The photographic and video images allowed the position of the particles and associated circulation to be measured. In turn, the velocity of the particles and associated circulation were evaluated from a series of images. Figure 2 shows a plot of depth versus time for a particle cloud. It is clear from Figure 2 that the particles and cloud separate around a time of 2s. Values of the thermal velocity to particle fall velocity at the thermal to swarm transition ranged from 0.9 to 1.5 with the average transition value of w/w_p being 1.1 for the four experiments of type A. A plot of the normalised particle cloud velocity as a function of the normalised depth is shown in Figure 3. The velocity behaviour for $w > w_p$ in Figure 2 is that expected of an entraining thermal (ie $w_{te} \sim z^{-1}$).

The preliminary data analysis shown here clearly supports the notion that the entraining thermal to swarm transition occurs around $w/w_p \approx 1$.

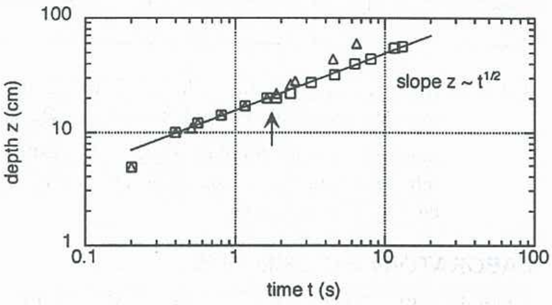

Figure 2. Depth of particles (triangles) and entrained fluid (squares) as a function of time. The thermal to swarm transition is indicated by the arrow.

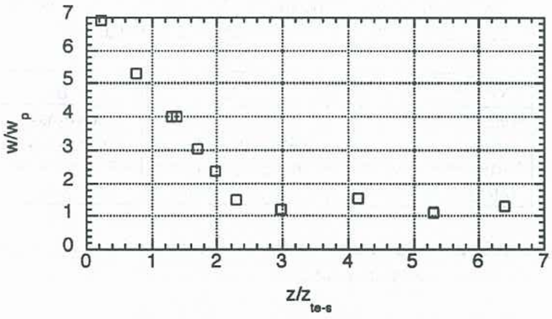

Figure 3. Normalised particle cloud velocity as a function of normalised depth for a type A experimental run.

The effect of particle separation was specifically examined in experiment type B. The release mass (of iron powder) was maintained at 0.25g while the release area of the electromagnet was 0.8, 0.8, 3.1, 7.1 and 15.2 cm^2 for runs B3, B7, B8, B9 and B10 respectively. For each of the runs the thermal to swarm transition was identified from viewing video recordings using two different criteria. The first transition criterion was that the majority of particles are grouped near the leading edge of the entrained fluid and a small fraction of the particles have escaped. The second transition criterion was when the majority of particles had escaped from the thermal. The depths at which these transitions occurred as a function of release area (ie, increasing particle spacing) are shown in Figure 4. Figure 4 clearly shows that sufficiently spreading particles at release will result in mode 2 (acceleration to swarm) type behaviour despite the released mass being sufficient to cause a thermal regime. It is also evident from Figure 4 that the criteria used to define the transition to swarm behaviour can make a significant difference to the transition depth determined from experimental data. This may explain why Noh and Fernando's (1993) data did not collapse when the transition depth was non-dimensionalised.

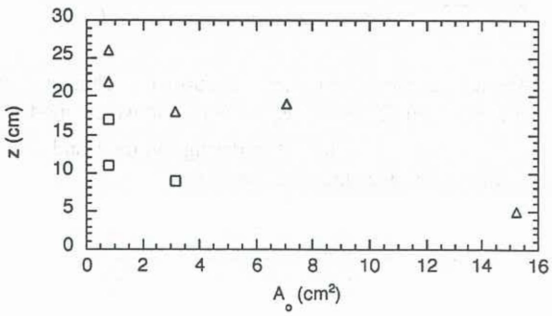

Figure 4. Depth at which the swarm transition occurs as a function of release area A_o. The first and second transition criteria are shown by squares and triangles respectively.

CONCLUSION

The transition to swarm behaviour for a particle cloud occurs when the fall velocity of the cloud is equal to the particle fall velocity. The nature or mode of the transition can be parameterised by the transition cloud number $C_{a\text{-}te}$, the thermal Reynolds number $\mathbb{R}_t$ and how densely packed the particles are at release. Attainable values of $C_{a\text{-}te}$ will be around or greater than 0(1).

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