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Particle-particle aggregation with $1/r^2$ forces in reduced gravity environments

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We report on experiments during which we recorded the aggregation of calcium carbonate and sodium chloride powders in the reduced gravity environment of a plane in parabolic flight. We describe the apparatus that we have developed for these experiments and discuss the results. This apparatus allows the simultaneous recording of two perpendicular views, giving us the possibility of reconstructing the trajectories in three dimensions. The analysis of the data obtained during the flights shows that the force responsible for the particle aggregation is of the r^{-2} type.

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Many aggregates are of a fractal nature, and the application of the concept of fractal geometry to the phenomenon of aggregation can greatly simplify the study of the process. However, as mentioned in the literature [1] the fractal dimensions and the site growth probability measures of the resulting fractal structures strongly depend on the properties of the forces that cause the aggregation. In order to determine such forces, we studied the aggregation dynamics of calcium carbonate and sodium chloride powders in reduced gravity. The advantage of reduced gravity (10^{-2}–10^{-3} g) for such studies is mainly the significant reduction of sedimentation and convection processes that make possible the recording of aggregation free from the movement caused by the two above mentioned processes. It is then possible to study the force without extraneous interference.

We have built an apparatus to study the aggregation dynamics in the reduced gravity condition of a KC-135 plane in a parabolic flight, and a schematic diagram is shown in Fig. 1. It consists of a closed cell (A) where the experiment is performed. A system of two bellows (B) is used to blow dry air inside this cell while the air is transferred from one bellow to the other. The powder was composed of small (1 μm) calcium carbonate or sodium chloride particles. These small particles aggregate easily, and the flow of air inside the cell was used to disaggregate and put the particles into suspension prior to the reduced gravity periods. However, as predicted [2], this system was capable of producing particle sizes around 5 μm (as seen from our recording). Outside the cell, two lenses (C) were used. They were placed in front of the camera (D) to obtain microscopic capability with adjustable magnifying power. With a 28-mm lens used in front of the video camera, we obtained a field of view of 2.65 mm×2 mm on screen with approximately a 1.2-mm depth of field at maximum magnifying power. The use of two flat mirrors (E) combined with an aluminized 90° prism (F) in front of the camera allows the simultaneous recording of two perpendicular images and thus the reconstruction of the trajectories in three dimensions. The apparatus is completed by a television monitor (not shown) and a fiber-optic light source (G) with a focusing lens. The apparatus was flown on a NASA aircraft (KC-135) in parabolic flight to simulate near zero-g conditions, and many aggregations were recorded during the reduced gravity portion of the flights.

The images from this camera were calibrated and analyzed frame by frame to extract the distance between the interacting particles. The knowledge of the time intervals between camera frames allows us to reconstruct the aggregation as a function of time. Figure 2 shows a graphical representation of such an aggregation for which we have plotted the distance as a function of time (the curve and the various parameters shown in this figure will be discussed later in the paper). The error in the distance is ±4.2 μm and corresponds roughly to the size of the data points. As for the error in time, we have verified that the camera takes 30 frames per second and the error was tak-

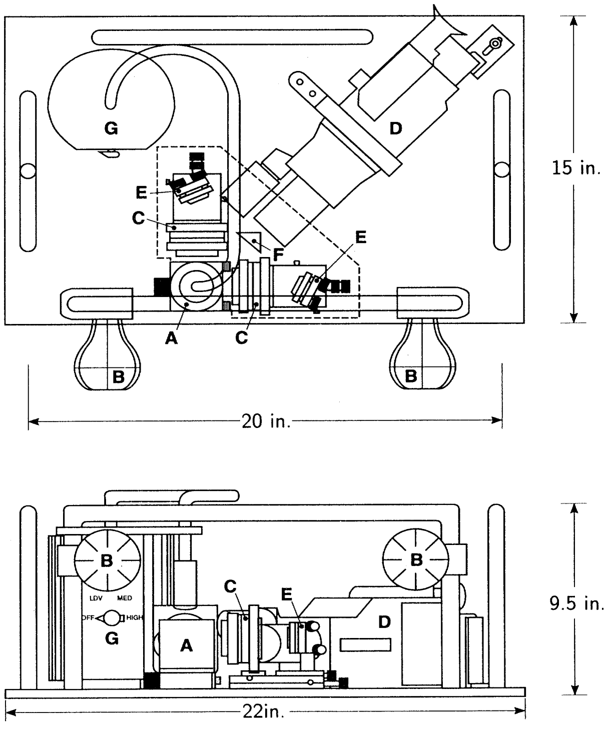

FIG. 1. Schematic diagram of the apparatus.

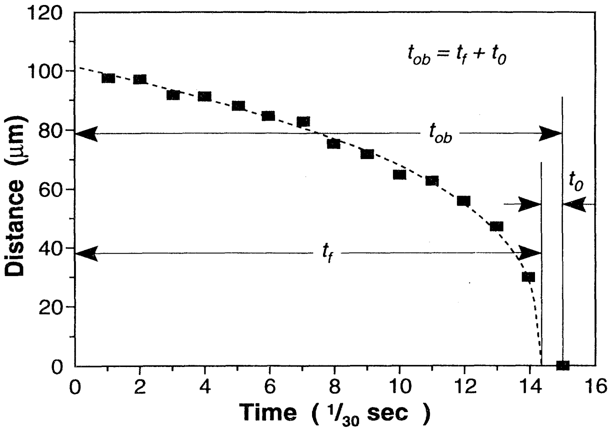

FIG. 2. Graphical representation of an aggregation.

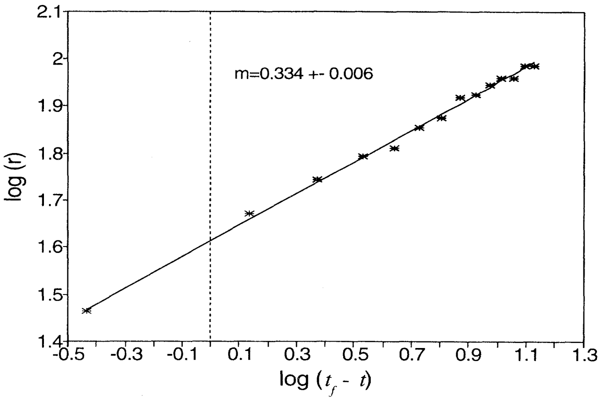

FIG. 3. Graph of the logarithm of distance as a function of the logarithm of time for the aggregation of Fig. 2 ($\log_{10}$).

en as ±1/120 sec corresponding again to the size of the data points.

In order to interpret these results, we developed the equations giving the distance between particles as a function of time during the aggregation, for a force of the type r^{-n} where $n=0,\ldots 4$. Following the method used in Ref. [3], we start with the equation of motion,

$$m\frac{d\mathbf{V}}{dt}=-\mathbf{F}_D+\mathbf{F}_i\ . \tag{1}$$

Here m is the mass of the particle, $\mathbf{V}$ the relative speed of these particles, $\mathbf{F}_D$ the drag force, and $\mathbf{F}_i$ the unknown attractive force. The expression for the Reynolds number is

$$\mathrm{Re}\equiv\frac{2aV\rho}{\mu}\approx 1.0\times 10^{-3}\ll 1\ , \tag{2}$$

where a is the particle radius, ρ the air density, and μ the air viscosity. Using the conditions of our experiment we can see that the Reynolds number is much smaller than unity, so we can write

$$\mathbf{F}_D=-6\pi\mu a\mathbf{V}\ . \tag{3}$$

In the same manner, the Stokes number will be given by

$$\mathrm{St}\equiv\frac{mV}{6\pi\mu a A}=1.0\times 10^{-3}\ll 1\ , \tag{4}$$

where A is the second particle radius. Since the Stokes number is also much smaller than unity, we can neglect the left side of Eq. (1). Considering the forces of type $|\mathbf{F}_i|=C/r^n$, where C is a constant, Eq. (1) can be written as

$$-6\pi\mu a V=\frac{C}{r^n}\ . \tag{5}$$

Grouping the constants and integrating, we then get

$$r=C_0(t_f-t)^{1/(n+1)}\ , \tag{6}$$

where $C_0=[(n+1)C/6\pi\mu a]^{1/(n+1)}$ and t_f is an integration constant necessary to account for the limit $r=0$ when $t=t_f$ (time when the aggregation take place). This time $t=t_f$, as shown in Fig. 2, is the difference between the time of observation (t_{ob}) (the time from the beginning of the observation to the aggregation) and the time calculated (t_0) (the time calculated is a fitted parameter that allows us to fix when, between the two last images, the aggregation really took place). The dashed line in Fig. 2 is the representation of our observations with the help of Eq. (6), and from it, we can extract the value n that best reproduces our observations from the KC-135 flights. The value of n for this particular aggregation was determined to be 1.97 ± 0.355. Figure 3 presents another way of representing the same aggregation. In this figure the slope (m) of the fitted line corresponds to the exponent of Eq. (6), and thus the value of n obtained is 1.995 ± 0.036. This second value was calculated without any error consideration on the data values, and it confirms the first value cited above. Figure 4 shows the result of our analysis on many aggregations. From this figure it is reasonable to conclude that an electrostatic force (between opposite charges) may be causing the aggregation.

These results are particularly interesting because, as

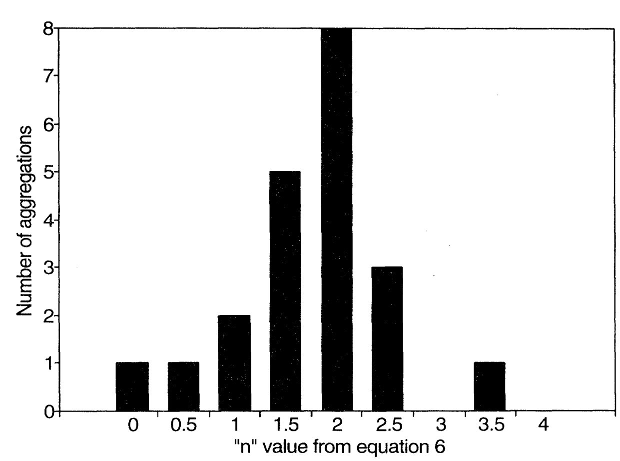

FIG. 4. Bar graph of the number of aggregations for each value of n.

shown in Ref. [1], the structure of the aggregate depends on the force that causes the aggregation. In order to study the aggregation processes, numerous computer programs have been written to simulate the growth of the aggregates, and we believe that the determination and inclusion of the proper aggregation forces is necessary in order to compare the results of the simulations with the real aggregate. Therefore, it will be possible to perfect computer simulations of aggregates and effect meaningful comparisons between simulations and experimental data.

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[1] A. Block, W. von Bloh, and H. J. Schellnhuber, J. Phys. A **24**, L1037 (1991).
[2] N. A. Fuchs and A. G. Sutugin, in *Aerosol Science*, edited by C. N. Davies (Academic, London, 1966).
[3] A. V. Filippov, J. Aerosol Sci. **23**, 203 (1992).