TECNIACUSTICA
VALLADOLID - 1993

VISUALIZATION OF PARTICLE AGGLOMERATION IN AN ACOUSTIC FIELD

Thomas L. Hoffmann, Gary H. Koopmann

Instituto de Acústica, CSIC, Calle Serrano 144, 28006 Madrid, España
Center for Acoustics and Vibration, The Pennsylvania State University,
157 Hammond Building, University Park, PA 16802, USA

ABSTRACT

New observations are presented of microscopic particle trajectories displaying agglomeration phenomena in a high intensity acoustic field. The observed particle motion is compared to numerically generated trajectories based on the so-called acoustic wake effect. The experiments are carried out in a small-scale observation chamber using a CCD-camera in conjunction with a video system. In a homogeneous acoustic velocity field, spherical glass microspheres (diameter 8.1 μm and 22.1 μm) and arbitrarily-shaped quartz particles (diameter < 50 μm) are used for the observation of agglomeration trajectories under the influence of an intense acoustic velocity field (rms 1.2-0.57 m/s @ 400-800 Hz). The recorded digitized images show one distinct interaction pattern that resembles the shape of a tuning fork (thus called the tuning fork agglomeration). The latter appears to be the predominant agglomeration mechanism leading to rapid particle approach and multiple, subsequent particle interactions at high frequencies and large acoustic velocities. The comparison of this interaction phenomenon with existing theoretical models reveals a semblance to the so-called acoustic wake effect. Based on the experimental results, tuning fork agglomeration constitutes the principal mechanism for particle agglomeration of similarly sized particles. No experimental evidence was found to support the orthokinetic agglomeration hypothesis.

1. INTRODUCTION

Acoustic agglomeration is a process which has potential use in air pollution control to enhance the performance of conventional particle filtering devices. More specifically, it is a process that increases the average particle size in aerosols. Conventional filter techniques are generally inefficient for particles of small size. An acoustic agglomerator can increases this efficiency by preconditioning the aerosol and shifting its size distribution to a range of larger particles. However, to achieve a satisfactory shift in the size distribution of an aerosol, extremely strong acoustic fields have to be employed. This is at least the assumption found in most of the existing literature. The current knowledge about the agglomeration effect is mainly derived from large scale experiments with focus on the practical use of the technology. Very little is known about actual particle interaction phenomena that cause convergence between individual particles and finally lead to agglomeration. The uncertainty about the interaction mechanisms supports continuing interest on the topic in the theoretical world. As a result, numerous theories exist which describe interaction phenomena that have never been observed in reality. In addition, some of these theories are contradictory in their description of the agglomeration process. This discrepancy between theoretical knowledge and stage-of-the-art experiments motivated this research. The work focuses on a small scale experimental investigation with the goal to visualize particle interaction and agglomeration. The objective is to achieve a fundamental understanding of agglomeration mechanisms and the experimental verification (or rejection) of existing theories.

2. THEORY: THE ACOUSTIC WAKE EFFECT

An approach to compute hydrodynamic interactions between two particles was proposed by Pshenai-Severin[1] and later refined by Dianov.[2] The models are based on the asymmetry of the flow field around a moving particle at moderate or high Reynolds numbers. Consider two closely spaced spheres moving along the acoustical axis in on-axis orientation. The leading sphere will disturb the quiescent fluid and, in dependence on the Reynolds number, build up a wake in the area behind itself (see Figure 1). If the second sphere is located close enough it will travel within this disturbance. The wake leads to a pressure reduction in the area behind the leading particle so that the trailing particle experiences a drag reduction and moves with a higher speed than the "leader." If one considers two particles in an oscillating flow, the same effect will occur with the only difference that the roles of the leading and the trailing particle are switched twice per acoustic cycle (this effect is here called the "acoustic wake effect"). Thus, for the given on-axis orientation, the particles will converge during a number of acoustic cycles. Dianov[2] derived an analytical expression for the mean convergent velocity between the two particles based on Oseen's equation by linearizing the convective term of the Navier-Stokes equation. The expression $\bar{u}_{12} = 3/2\left(U_0/\pi r\right)\left(a_1 l_1 + a_2 l_2\right)$ was obtained after neglecting small terms containing an $1/r^2$-dependence on the separation distances r; here the index i indicates the Particles 1 and 2 and l_i is the relative slip coefficient in the Oseen regime. U_0 is the velocity of the incoming acoustic wave and a_i the particle radius. The slip coefficients l are defined in reference[2] as functions of the acoustic velocity and frequency as well as of particle radius, particle density, fluid density, and fluid viscosity. This expression was applied to model particle trajectories numerically for comparison with the experimental observations in the investigation. In addition, a number of other interaction mechanisms such as orthokinetic entrainment, scattering, and acoustic radiation pressure were implemented in the numerical approach, but are not discussed here in more detail (see reference[3]).

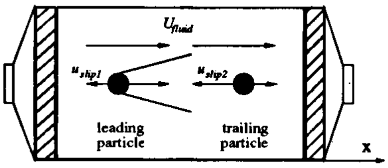

Figure 1: The acoustic wake effect for two particles aligned along the acoustical axis, the trailing and leading particles are defined in terms of the relative slip-velocity u_{slip}

3. EXPERIMENT: OBSERVATION OF PARTICLE AGGLOMERATION

The design process for the particle observation chamber was guided by the goal to achieve a small and controlled environment in which the particles could be excited into homogeneous motion by a relatively strong velocity-field. Thus the observation chamber was designed as a narrow enclosure (width 75mm) with two opposing "moving walls" (170×170mm). Rectangular speakers with flat honey-comb membranes were employed to match the shape of the observation chamber's side walls. These speakers were driven in in-phase motion leading to a relatively homogeneous acoustical velocity field. Small amounts of glass microspheres (diameters 8.1μm and 22.1μm) and arbitrarily shaped quartz particles (<50μm) were fed into the chamber and illuminated by a laser light sheet. The motion of the particles was observed with a high resolution CCD-video camera through an optical arrangement consisting of a 100mm spherical lens and a 80-210mm Olympus zoom camera lens. A personal-computer-based image processing system was used to evaluate the on video tape recorded particle trajectories. To reconstruct trajectories for time spans longer than a single frame (1/30 sec) of the video camera partial cuts of trajectories from subsequent frames were pasted into a new, common picture. Figures 2 to 5 show examples of the reconstruction. Experiments were carried out in the frequency range 400-800Hz with acoustic velocity amplitudes 1.2-0.57m/s (rms), respectively. At the lower frequencies strong orthokinetic particle entrainment and relative particle motion between differently sized particles could be observed. However, particle interaction or agglomeration did not even occur at the high velocity level of 1.2m/s. Thus the orthokinetic agglomeration hypothesis cannot be supported from the results of these experiments. In the frequency range from 600-800Hz a variety of interaction and agglomeration phenomena were found in the experiments with monodisperse microspheres. More specifically, one can classify the observed agglomeration trajectories as a) on-axial alignment of pairs of particles, and b) tuning fork agglomeration. Figures 2 to 5, show the particles moving vertically under the influence of gravity and horizontally due to the effects of the acoustic field (acoustical axis in horizontal direction). At 600Hz and higher acoustic velocities, the Type a) interaction could be found frequently. Here, the particles merge first onto a common path but due to their strong entrainment motion no actual agglomeration occurs. The particles continue to travel commonly without touching each other (Figure 3). Towards higher frequencies (800Hz; smaller particle displacements) and at high acoustic velocities (0.45-0.57m/s rms) the character of the interaction changed to Type b), the so-called tuning fork agglomerations (Figure 4). Here, the particles merge with high convergent velocities (in the range of mm/s) from initial separation distances up to 300μm. All agglomerations initiate from the on-axis orientation, i.e. the particles are aligned along the acoustical axis. This and the increase in the convergent velocity during the particle approach give the effect its characteristic appearance similar to the shape of a tuning fork. It was found that this type of interaction occurred at a drastically increased rate once a certain critical level of the acoustic excitation velocity was reached (0.45m/s rms, 800Hz). In some cases "chain reactions" were observed with numerous agglomerations occurring consequently within short periods of time (0.1sec; see Figure 5). *From these observations, the tuning fork interaction is proposed to constitute the dominant mechanism for acoustic agglomeration between similarly sized particles.* Similar effects could not be observed between particles of different size. Therefore, at least for the range of experimental parameters applied, *the results of the study do not support the hypothesis of agglomerations between differently sized particles.* From the results it is more conclusive that similarly sized particles first agglomerate to larger clusters, which then again find agglomeration partners in their own size range. The study also revealed a strong dependence of the interaction phenomena on the overall kinetic energy of the particles. It was observed that particles with very large kinematic energies tend to rebound during collisions rather than agglomerate; therefore one can hypothesize that very strong acoustic excitation can generate undesired high convergent velocities and lead to rebound of the particles. *This hypothesis questions the common understanding that more sound power enhances the agglomeration effect.*

4. COMPARISON BETWEEN THEORY AND EXPERIMENT

To jointly visualize the experimental and computational trajectories, the latter were pasted with a transparent frame onto the digitized images (see Figure 2). In the comparison between the observed tuning fork agglomerations and the numerical trajectories of the acoustic wake effect good agreement between the theory and observed interactions could be found in a few cases. However, more generally, the acoustic wake effect tends to overestimate the convergent velocity of the particles. Also, the shape of the observed attraction patterns suggests a higher order dependence on the separation distance than that of the $1/r$-trajectories proposed by the acoustic wake model. Thus the model describes the general features of the observed phenomenon but lacks certain refinements with respect to accurate quantification of the effect.

5. REFERENCES

1. Pshenai-Severin, S.V., *On the Convergence of Aerosol Particles in a Sound Field under the Action of the Oseen Hydrodynamic Forces*, Doklady Akademii Nauk SSSR, 1959, 125(4): p. 775.
2. Dianov, D.V., Podolskii, A.A., and Turubarov, V.I., *Calculation of the Hydrodynamic Interaction of Aerosol Particles in a Sound Field Under Oseen Flow Conditions*, SP - Acoustics, 1968, 13(3): p. 314.
3. Hoffmann, T.L., *Visualization of Particle Interaction and Agglomeration in an Acoustic Field*, Ph.D. Dissertation, The Pennsylvania State University, 1993.

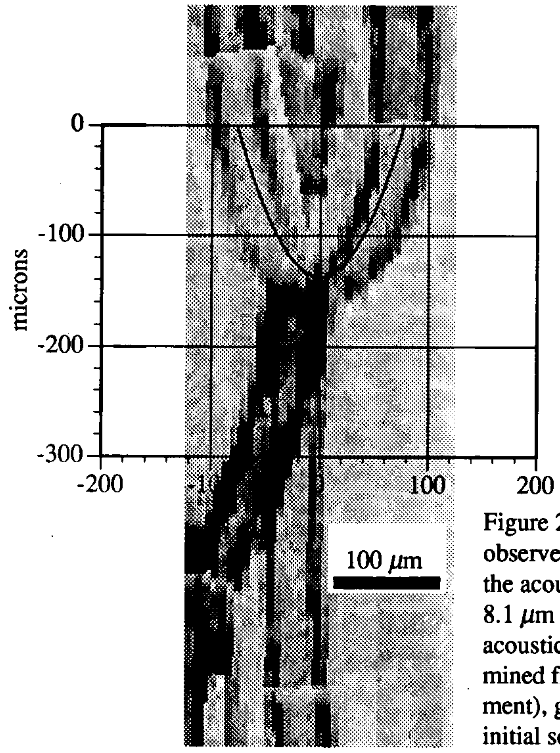

Figure 2: Comparison between an observed tuning fork agglomeration and the acoustic wake model, 8.1 μm microspheres, frequency 800 Hz, acoustic peak velocity 0.41 m/s (determined from observed particle displacement), gravitational velocity 16.7 mm/s, initial separation distance 150 μm

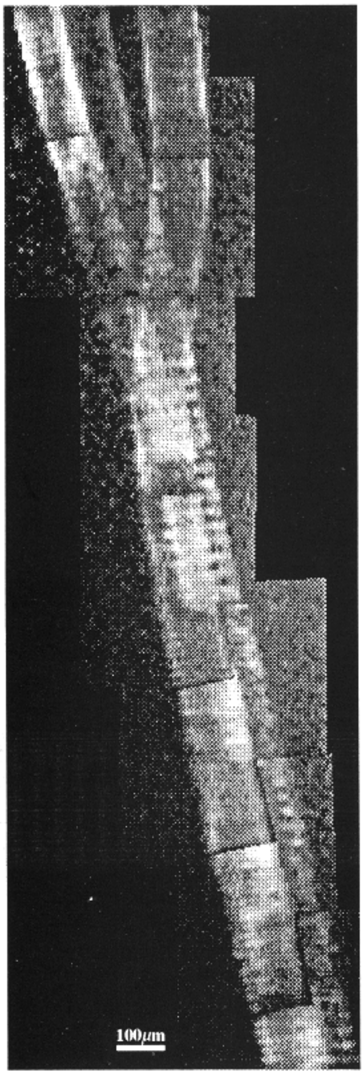

Figure 3:
Commonly moving pairs,
8.1 μm microspheres,
frequency 600 Hz,
acoustic velocity 0.60 m/s

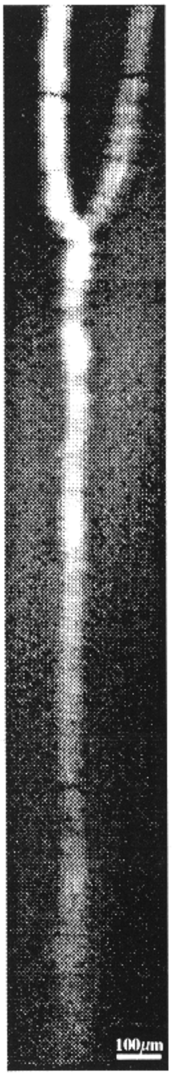

Figure 4:
Tuning fork agglomeration,
8.1 μm microspheres,
frequency 800 Hz,
acoustic velocity 0.57 m/s

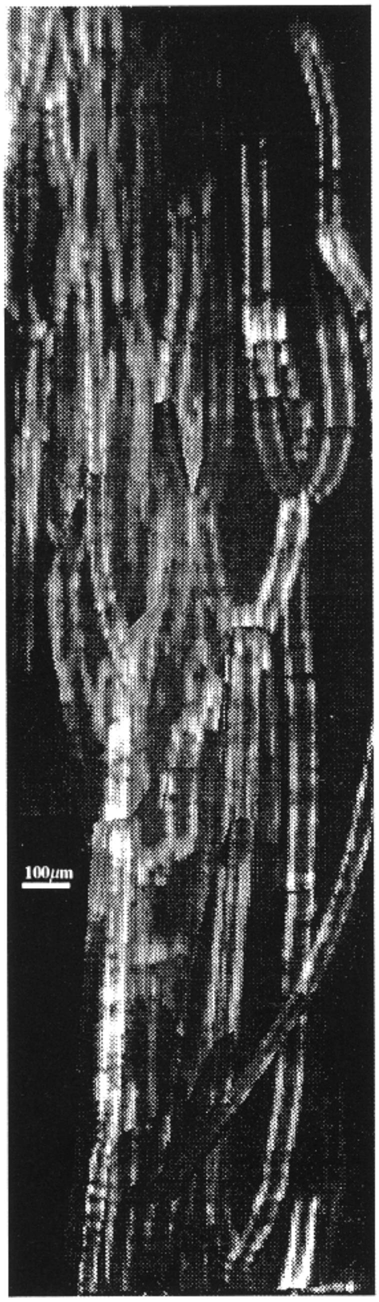

Figure 5:
Multiple agglomerations
(Chain reaction),
8.1 μm microspheres,
frequency 800 Hz,
acoustic velocity 0.45 m/s