Ultrasonic trapping of gases

Acoustic levitation has been applied as a technique for suspending liquid and solid samples of micrometer-to-millimeter range in the pressure nodes of a stationary ultrasonic field (SUSF). This effect was discovered in the 1930s and mainly developed in the 1970s and 1980s by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), who used this technique to fix small samples for various zero-gravity experiments in their space laboratories. However, in the last two decades acoustic levitation has also been applied as a useful and powerful tool for handling small samples under terrestrial conditions, that is, with gravity. Several investigations based on acoustic levitation have been carried out in different research areas, such as fluid dynamics, materials, atmospheric sciences, and analytical chemistry.

Levitation of liquid and solid samples. Stationary ultrasonic fields can easily be arranged between an ultrasonic transducer and a concave reflector by emitting a sound wave along the central levitation axis perpendicular to the surface of the transducer. If the distance between the transducer and reflector is a multiple of half of the sound wavelength, resonance conditions are met and a series of nodes and antinodes of sound pressure and sound velocity occur along the levitation axis. At high sound pressure levels in the range 150–180 dB, second-order forces can be used to suspend small liquid and solid samples at each pressure node of the field (Fig. 1). This single-axis geometry of an acoustic levitator is convenient and provides easy access to the suspended samples, while a three-axis geometry offers stronger acoustic forces.

Acoustic levitation is limited by the gravity of the sample, which has to be balanced by the acoustic levitation forces. However, W. J. Xie and B. Wie have recently demonstrated with a single-axis levitator that acoustic levitation is possible for very high density materials such as tungsten (specific density 18.92 g/cm³).

The size of the suspended samples is also limited by the stationary ultrasonic field and its geometry. The maximum diameter of the samples has to be smaller than half of the wavelength used for the ultrasonic field. For example, with an ultrasonic frequency of 20 kHz and at standard conditions of pressure and temperature of the gaseous environment (for example, 1013 kPa and 20 °C, or 29.92 °F) only samples with a diameter smaller than 8.5 mm (0.33 in.) can be levitated. The lower limit of sample diameter for acoustic levitation is given mainly by the viscosity of the gaseous environment and the sound frequency. Under standard conditions, this limit is of the order of a few tenths of a micrometer for typical frequencies of 20–100 kHz.

Trapping of heavy gases. In the late 1990s, it was shown that under suitable experimental conditions samples of cold gases, such as ice aerosol, are sucked into the stationary ultrasonic field, and gather in temporarily stable, rotational ellipsoidal systems around the pressure nodes of the field (Fig. 2). These systems are well separated in temperature from the ambient gaseous environment by a strong temperature gradient at the borders of the systems. Therefore, they can be called cold-gas traps.

The trapping of cold gases has been studied in more detail, using sample gases with various mass densities (such as octafluorocyclobutan, krypton, bromine, carbondioxid, nitrogen, and helium) and at various temperatures in the range from approximately −100 °C (−148 °F) to 100 °C (212 °F). In these experiments it was demonstrated that the effect is primarily controlled not by the difference in temperature but by the difference in density of the sample gas and the surrounding gaseous environment. Sample gases with higher mass densities than the gaseous environment are always sucked into the stationary ultrasonic field, while sample gases with lower mass densities are always displaced from this field. There is no evidence for a direct temperature effect in this process. Therefore, not only cold gases but also heavy gases gather in ellipsoidal systems around the pressure nodes in the stationary ultrasonic field, so that this phenomenon can be described more generally as heavy-gas trapping in stationary ultrasonic fields.

![Fig. 1. Single-axis acoustic levitator. (a) Stationary waves of sound pressure and sound velocity between the ultrasound transducer and reflector as a function of distance along the levitation axis z. (b) Polystyrene balls of a diameter of approximately 5 mm (0.2 in.) suspended in the pressure nodes of the stationary ultrasonic field of a 20-kHz levitator.](image-url)
A first theoretical explanation of the effect was based on a model of acoustic levitation of liquid and solid samples. The difference in the density of the gases in the stationary ultrasonic field causes a levitation potential at the pressure nodes, which is attractive if the sample gas is heavier than the surrounding gas and repulsive in the opposite case. Besides the difference in densities, the effect depends mainly on the supply of the (heavy) sample gas and the sound pressure level of the stationary ultrasonic field. Both effects have been experimentally demonstrated. The effect is increased by a more rapid supply of sample gas into the stationary ultrasonic field, in the range 5–25 mL/s, and disappears within a second after the supply of sample gas is stopped. This abrupt termination is caused by gas convection and diffusion within the stationary ultrasonic field. Ultrasonic trapping of heavy gases has been detected using frequencies of 4, 20, and 58 kHz, and at sound pressure levels between approximately 120 and 180 dB, with a maximum between 150 and 160 dB. The decrease of the trapping effect at higher sound pressure levels may be caused by an increase of acoustic streaming and convection inside the stationary ultrasonic field.

Ice particle formation. When cold ice aerosols are trapped in stationary ultrasonic fields in an ambient environment, the formation of larger ice particles from the primary aerosol particles can be observed. These secondary ice particles generated in the stationary ultrasonic field show a great variety of sizes (ranging from tenths of a micrometer to a few millimeters), shapes, and structures (Fig. 3). Four different mechanisms and effects are responsible for the ice particle formation in stationary ultrasonic fields:

1. Acoustic agglomeration of primary particles. This effect is well known for liquid aerosols, such as liquid water and ethanol fog, and can also be used for cleaning industrial exhaust fumes. The sound generates relative motion of the primary particles inside the stationary ultrasonic field. The relative motion of the particles leads to a higher collision rate with other particles, a precondition of agglomeration.

2. Quasi-liquid layers (QLLs) on the surfaces of the primary aerosol particles. Due to acoustic...
agglomeration, the primary particles stick together by adhesive forces. The adhesion between the primary particles is caused by liquid layers on the surfaces of the particles (or is even better if the particles are completely liquid). Ice particles down to temperatures of approximately \(-25^\circ C (-13^\circ F)\) are covered by such a liquid layer, so that agglomeration occurs. (The suggestion that ice crystals are covered by a thin layer of liquid water is attributed in part to Michael Faraday, and that idea has been developed during the past few decades.) At lower temperatures of the ice particles and also for dry aerosol particles, like flour dust or icing sugar, particle formation due to the stationary ultrasonic field has not been observed. This is due to the absence of the liquid layer which produces adhesive forces between the primary particles.

3. Acoustic levitation. Particles with sizes larger than a few of tenths of a micrometer are gathered and suspended in the pressure nodes of the stationary ultrasonic field because of the acoustic levitation forces. There ice particles with sizes up to a few millimeters can be generated. The fixed location of particle formation in the pressure nodes of the stationary ultrasonic field allows these processes to be studied easily with physical and chemical methods.

4. Dendritic growth of ice particles. The ice particles can degrade or grow by sublimation or desublimation of water molecules from the gas phase due to a typical dendritic crystallization structure on the surface of the ice particles.

Scientific and technical potential. Acoustic levitation is a useful tool for the containerless handling of liquid and solid samples and for physical and chemical research. The trapping of cold and heavy gases in stationary ultrasonic fields offers the possibility of adjusting gaseous environments within the field with regard to the composition, species, and temperature of the gases and aerosols trapped around the pressure nodes of the field and the suspended liquid and solid samples. This can be useful not only in various technical applications but also for basic research in such areas as material science and atmospheric science. Acoustic levitation using the ice-particle-formation process in stationary ultrasonic fields seems to be a promising tool for physical and chemical research on ice particles and snowflakes. The trapping effect for cold and heavy gases can be used to develop miniaturized laboratories for gas or particle-gas reactions without any wall contact. But it is questionable whether the trapping effect is strong enough to be useful in gas separation processes.

For background information see ACOUSTIC LEVITATION; AEROSOL; CRYSTAL GROWTH; NONLINEAR ACOUSTICS; PARTICulates; ULTRASONICS in the McGraw-Hill Encyclopedia of Science & Technology.

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