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CHARACTERIZATION OF ACOUSTO-ELECTRIC CLUSTER AND ARRAY LEVITATION AND ITS APPLICATION TO EVAPORATION

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ABSTRACT

An acousto-electric levitator has been developed to study the behavior of liquid drop and solid particle clusters and arrays. Unlike an ordinary acoustic levitator that uses only a standing acoustic wave to levitate a single drop or particle, this device uses an extra electric static field and the acoustic field simultaneously to generate and levitate charged drops in two-dimensional arrays in air without any contact to a solid surface. This cluster and array generation (CAG) instrument enables us to steadily position drops and arrays to study the behavior of multiple drop and particle systems such as spray and aerosol systems relevant to the energy, environmental, and material sciences.

APPARATUS AND ARRAY FORMATION

Our acousto-electric levitator has a sandwiched ultrasonic horn and a concave reflector, between which there is established a standing acoustic wave (see Fig. 1) [1]. The distance between the horn and the reflector is about the twice the acoustic wavelength so that we can levitate three or more layers of drop arrays. A high DC voltage is applied between the horn and the reflector to form a static electric field. This electric field can charge drops and also provide an extra levitation force. A CCD camera is mounted above or on the side of the levitator to record the motions and changes of the drops.

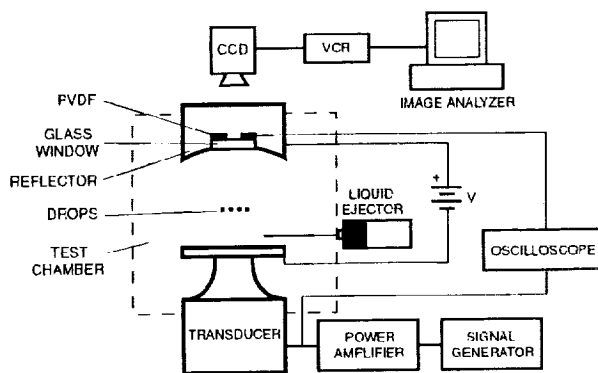


Fig. 1 Apparatus.

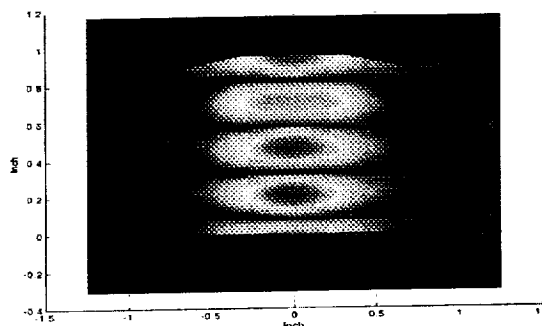


Fig. 2 The driving mode of levitator - one surface moving, one fixed.

If liquid like ethanol is placed on the surface of the ultrasonic horn, it atomizes into very small seed droplets whose diameters are around 25 to 50 μ m. These seed droplets fly into the levitator and form small 2-D clusters. Some of these flat clusters may contain a very large number of droplets, as many as 240. When the acoustic field increases, the droplets in a cluster will coalesce into a big drop. All of these larger drops form a stable 2-D array at a position near the pressure node. Several layers of these 2-D arrays can be levitated. The size of the drops, the

spacing between drops, and the total number of drops in one array can be controlled by varying the values of the voltage and the acoustic field intensity. Another high frequency acousto-electric levitator is also being developed to form a quasi 3-D drop array, in which the drop spacing and the distance between two layers are almost the same.

FEM NUMERICAL MODELING OF ACOUSTIC FIELD

The vertical levitation forces are the acoustic radiation force plus the electric force. The force that holds the array in the center of the levitator is the lateral acoustic force. In order to analyze the forces on the drop arrays, we employ a finite element method with numerical perfectly matched layers [2] to model the acoustic field in this open-sided acoustic resonator with a concave reflector. The results are shown in Fig. 2 for the driving mode. The forces on drops can be calculated from this acoustic profile.

EVAPORATION STUDIES

This device has been used to study the evaporation of single and multiple component drops. The theory of evaporation of a pure isolated drop follows the d^2 law if a quasi-steady state is assumed, which means that the diameter squared of the drop decreases linearly with time when the evaporation continues [3]. For a multi-component drop, both the equation of energy and continuity should be applied to each species. We also assume fast mixing processes inside the drop and use Raoult's law for the vapor pressures around the drop. Since the temperature, liquid, and gas components change with time during evaporation, we have to solve several coupled differential equations numerically. The materials in the evaporation study are heptane, octane and dodecane, which are the primary components of gasoline fuel. Since it is impossible to charge pure alkanes, an additive called Statis 450 is added to the alkane samples to increase their conductivities. Experiments show that a small amount of Statis 450 does not change the evaporation rates of alkanes. To avoid acoustically induced flows, a minimum acoustic force plus the electric force are used to levitate drops. The minimum acoustic field also reduces the deformation of the drop's shape. Using both fields provides the flexibility for controlling the position of drops. Results of single component drops with minimum acoustic field show that the evaporation is similar to the results of drops suspended by a thin glass fiber; whereas with a strong acoustic field the evaporation rate is somewhat affected. Experimental results for multicomponent drops of octane and dodecane agree reasonably well with theoretical calculations. Experiments on multi-component drop arrays are currently in progress.

REFERENCES

- [1] R. E. Apfel, Y. B. Zheng, and Y. R. Tian, "Studies of acousto-electrically levitated drop and particle clusters and arrays," *Journal of the Acoustical Society of America* 105 (5), L1-L6 (1999).
- [2] Z. S. Sacks, D. M. Kingsland, R. Lee, and J. F. Lee, "A perfectly matched anisotropic absorber for use as an absorbing boundary condition," *IEEE trans. Antennas Propagat.*, vol. 43, 1460-1463 (1995)
- [3] K. Annamalai, and W. Ryan, "Interactive Processes in Gasification and Combustion .1. Liquid-Drop Arrays and Clouds", *Progress in Energy and Combustion Science*, 18 (3), 221-295 (1992).

Characterization of acousto-electric cluster and array levitation and its application to evaporation

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Outline

- Introduction
- An acousto-electric levitator
- Acoustic field profile in a levitator with an acoustic open resonator (a finite element approach)
- Cluster and array generation
- Evaporation of drops and arrays
- High frequency levitator
- Conclusion and future work

Introduction: acoustic levitation

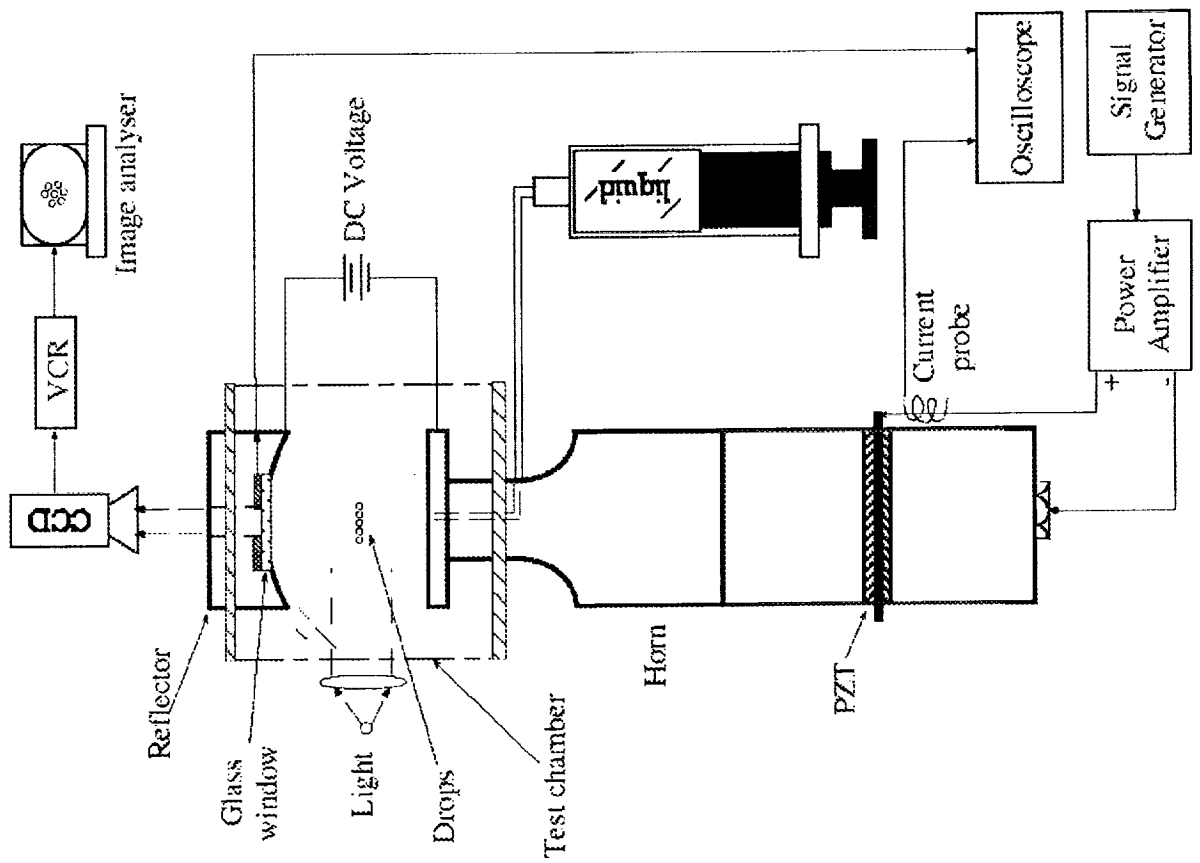
- An acoustic levitator uses a standing acoustic wave to levitate a drop or particle.
- The acoustic levitation force for a small single incompressible drop in a one-dimensional standing acoustic field is

$$F \propto -a P \langle \nabla P \rangle_t$$

- In air, this force always points to a pressure node.
- The drop is suspended a little bit below the pressure node.

An acousto-electric levitator

- An acousto-electric levitator uses both a vertical acoustic standing wave and an electric static field.
- Liquid drops or metal-coated solid particles are charged by the electric field.
- The levitation force is provided by the acoustic radiation force and the electric force, which give us more flexibility to control.
- Drops or particles are separated by Coulombic force and form arrays.

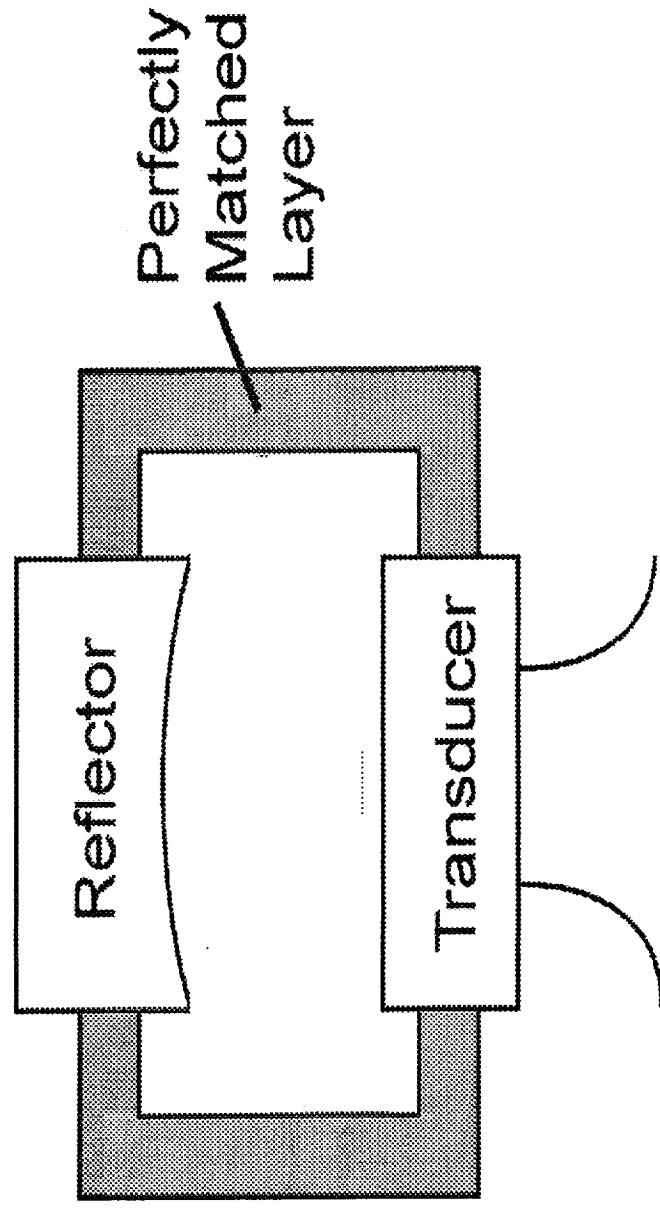


Experimental apparatus

- Transducer frequency: 28 to 100 kHz
- Acoustic wavelength in air: 1.23 to 0.34 cm
- DC voltage range: 500 to 3000 V

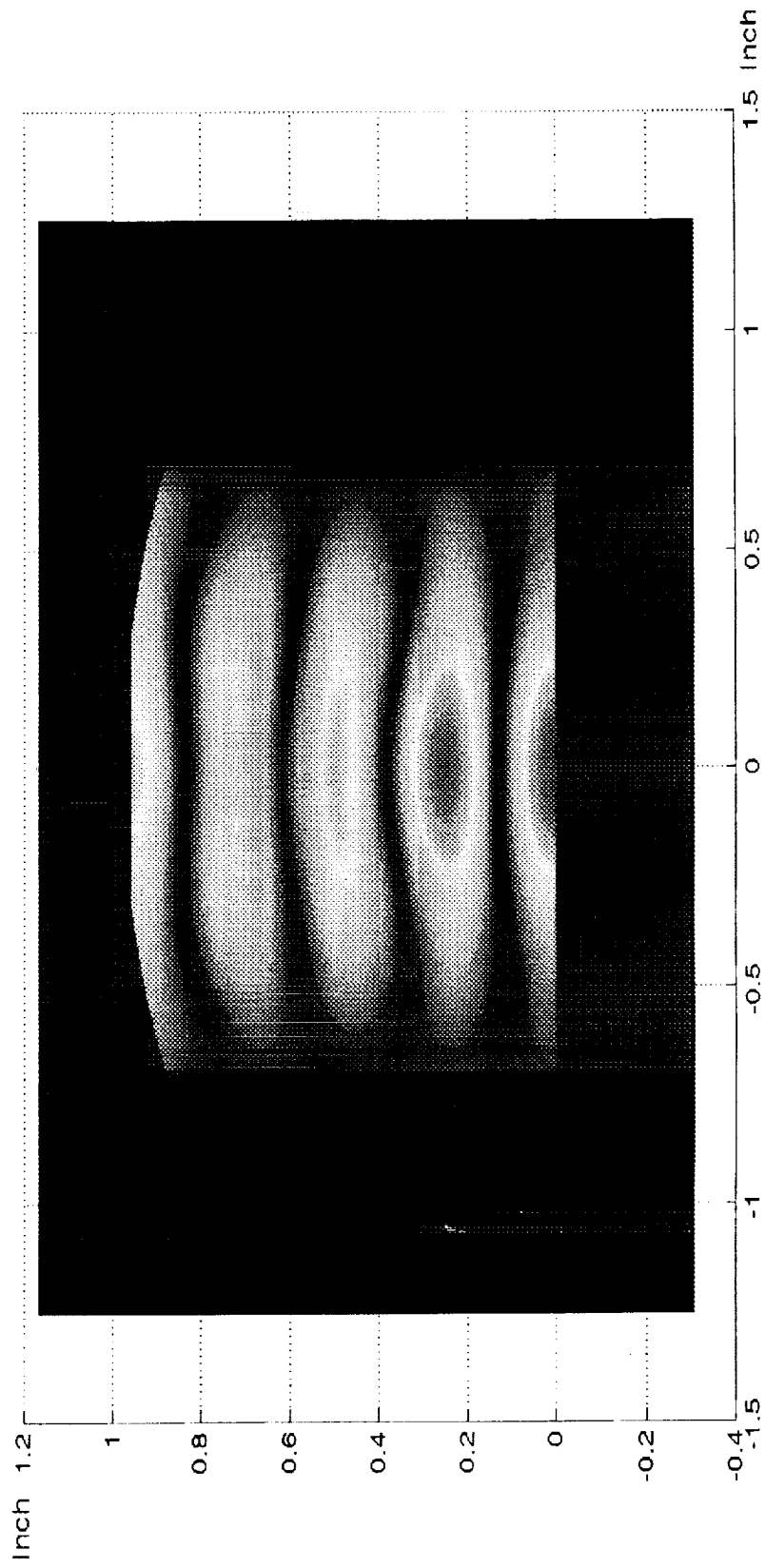
FEM analysis of the acoustic field

- 2-D finite element analysis of an open acoustic resonator with a concave reflector and artificial anisotropic perfectly matched layers (PML)

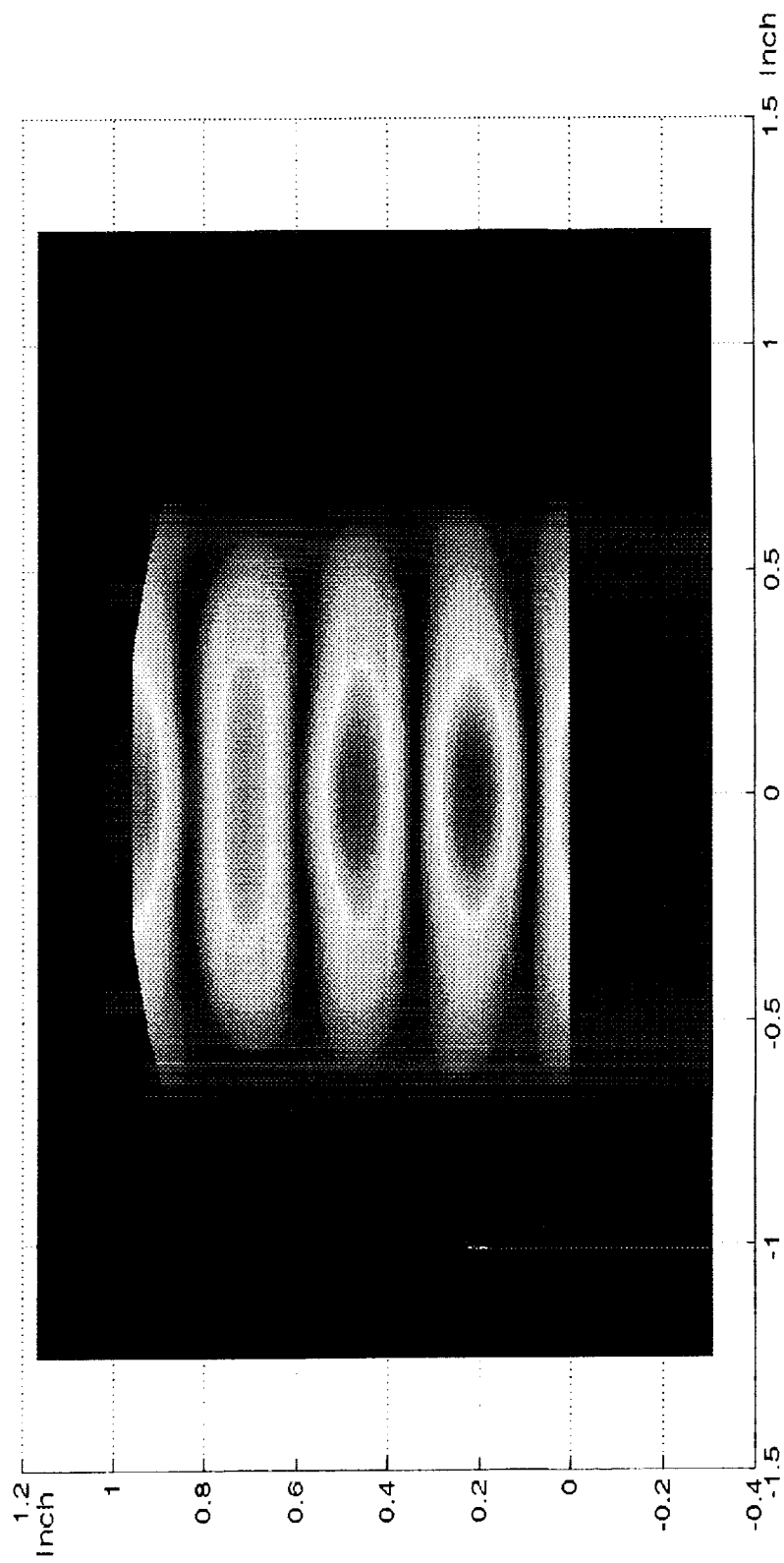


Resonance mode of the acoustic resonator

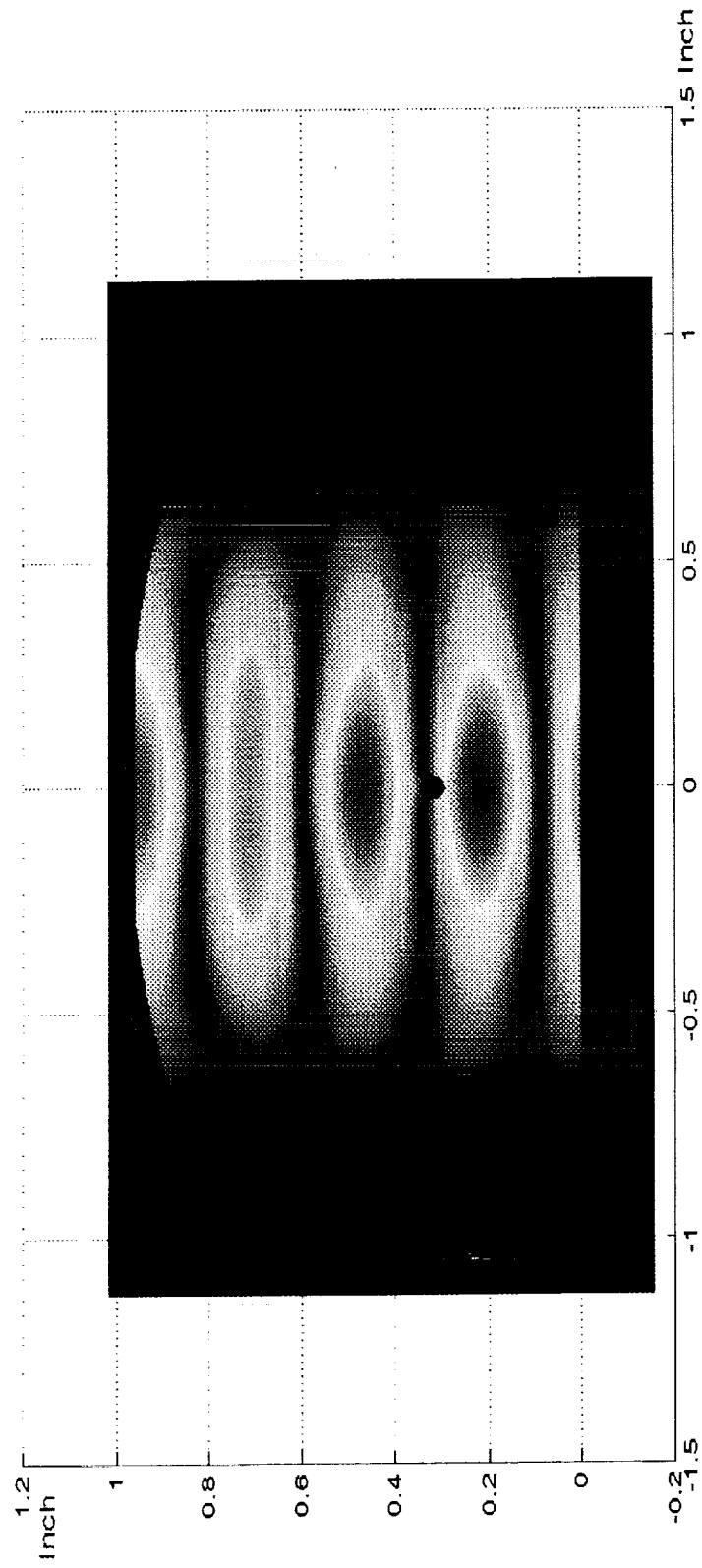
- The fourth resonance mode of our acousto-electric levitator



Acoustic field driven by the vibration of the transducer



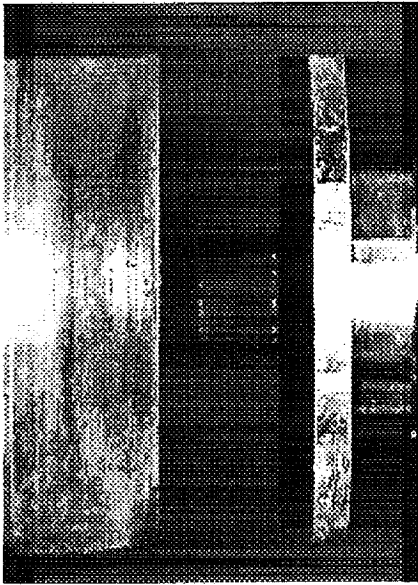
Acoustic field with a levitated 1mm particle



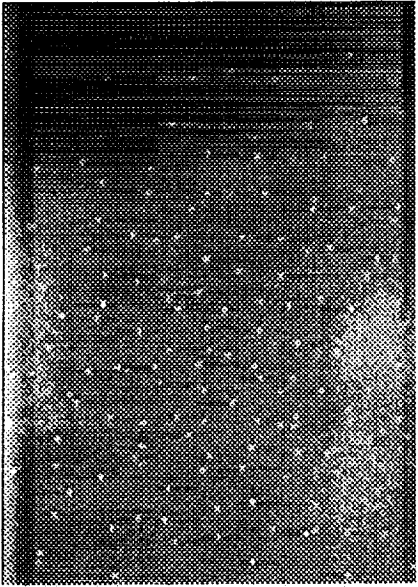
Cluster and array generation

There are two ways to generate drop arrays.

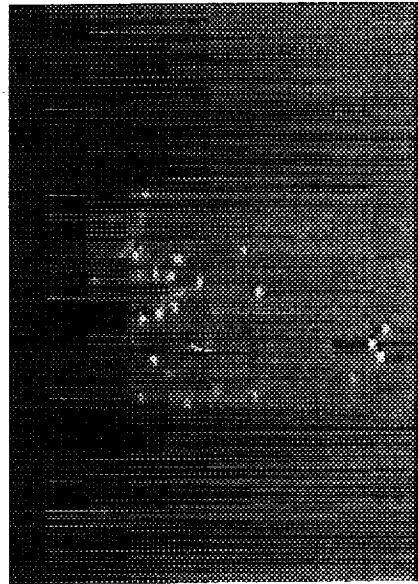
- Liquid atomization
- Liquid is first placed on the transducer surface and atomized to small charged seed droplets. In a stronger acoustic field, seed droplets form stable big drop arrays.
- Direct drop spray
- Directly spray charged drops into the levitator.
Good for drop evaporation study.



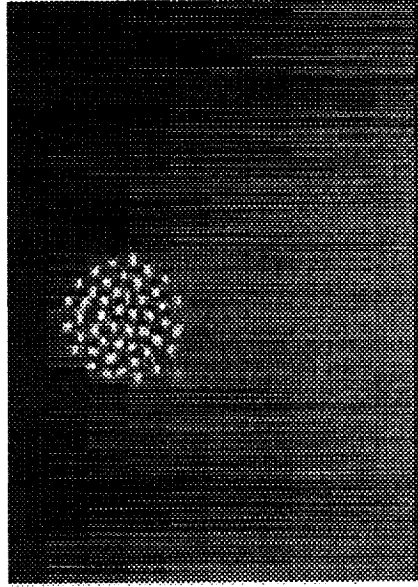
Two planes of collected ethanol drops near the acoustic pressure nodes in the acousto-electric levitator



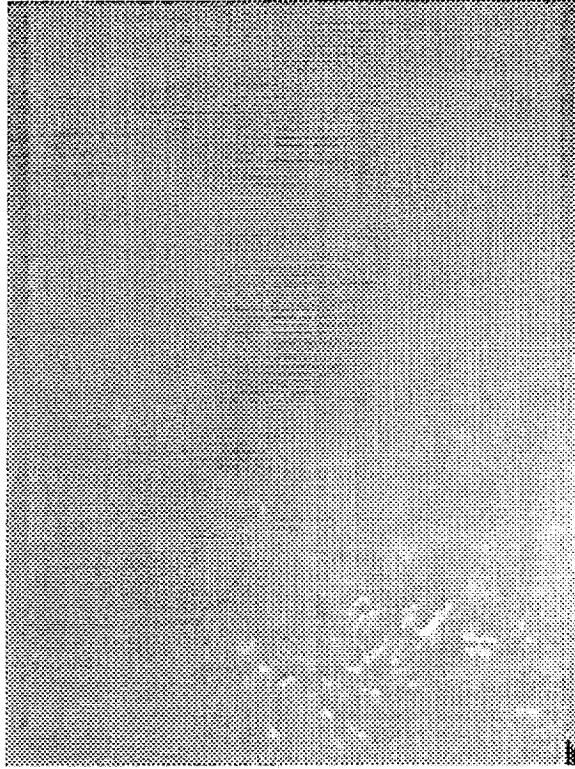
A mist of seed droplets (25-40 μm) rising from the bottom plate of the resonator

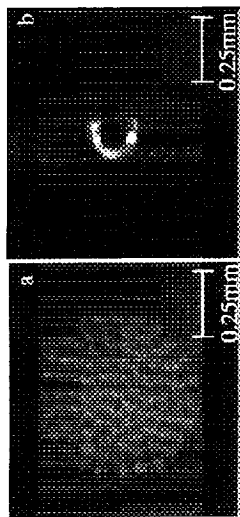


When the acoustic intensity increases a little bit, the seed droplets aggregate together into a two dimensional cluster, as shown in the above two-figure sequence. Because of the small electrical charge on each drop, they do not immediately coalesce.

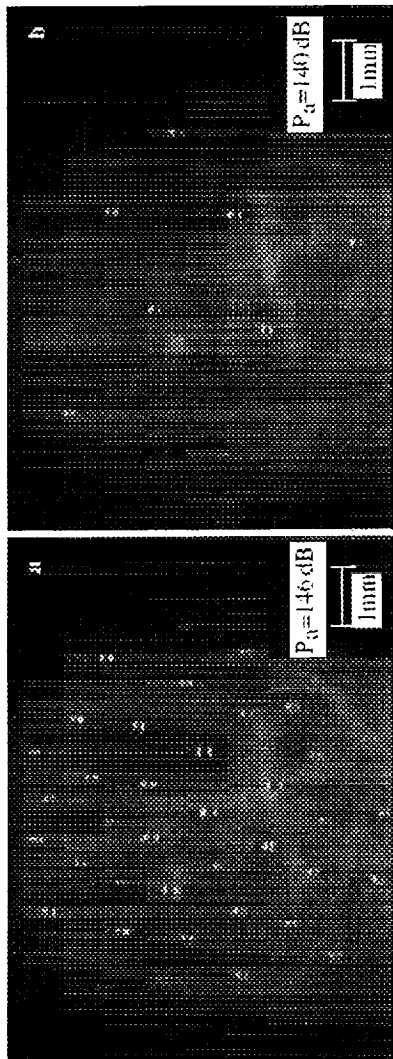


Drop array generation (video clips)

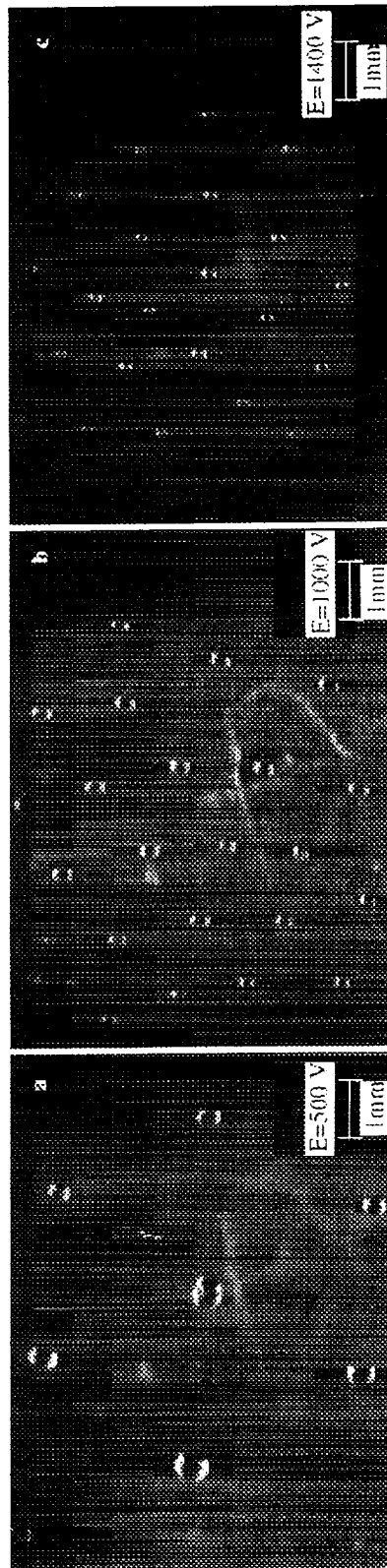




Droplet cluster coalescence. On the left is an 85 drop cluster; on the right is the drop resulting from the coalescence.



Charged drop array, varying pressure in a constant electric field.
Drop size is sensibly constant whereas spacing changes.



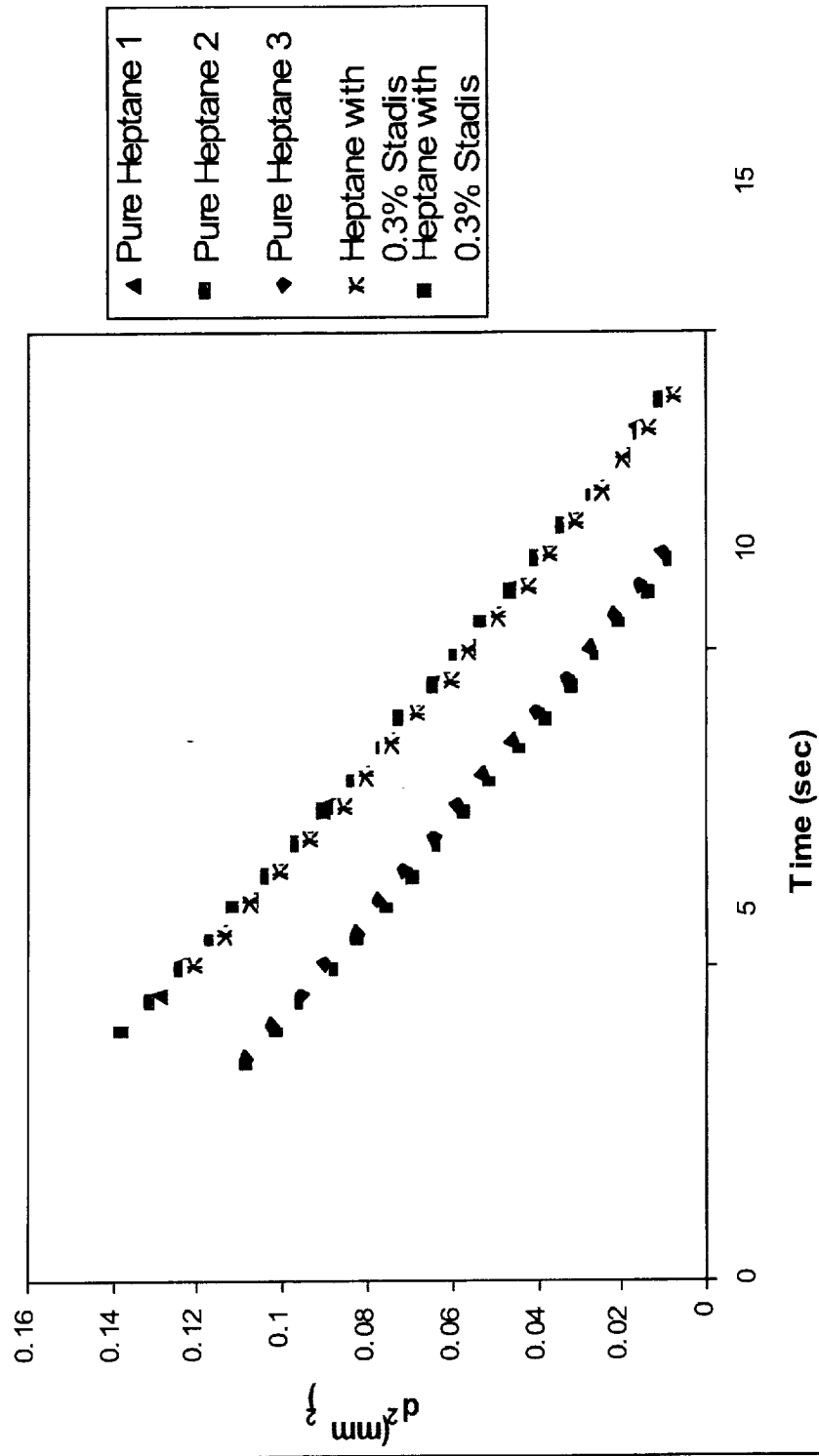
Charged drop array, varying electric field in a constant pressure field.

Application to drop evaporation study

- **Materials**
 - Heptane, Octane and DodecanePrimary components of gasoline fuel
- **Additive**
 - Stadis 450

It is added to alkanes to increase the conductivity so that alkanes can be charged. A every small amount of Stadis 450 (0.3% by weight) does not affect the evaporation of alkanes.

Evaporation of Pure Heptane and Heptane with Stadis 450



Single component evaporation

- d^2 law

The mass and energy equations of such an isolated drop are

$$\begin{aligned}
 -mY &= 4\pi\rho D r^2 \frac{dY}{dt} = m \\
 -m\epsilon T &= 4\pi\kappa r^2 \frac{dT}{dt} - mL
 \end{aligned}$$

where m is the mass gasification rate at the drop surface. With a quasi-steady assumption, its evaporation follows the d^2 law, where d is the drop diameter and κ is the evaporation constant.

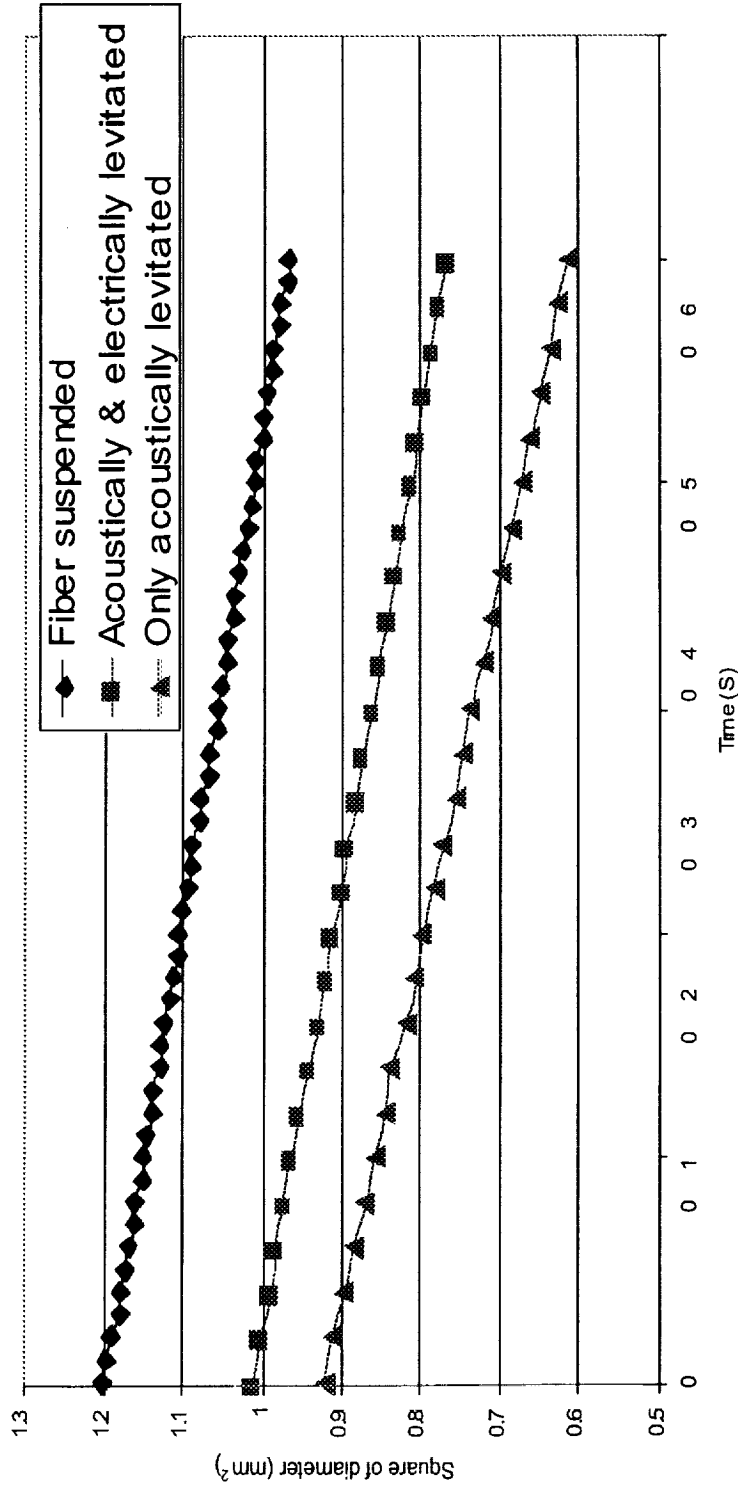
$$d^2 = d_0^2 - \kappa t$$

Experiment with minimum acoustic field

Even in the single drop evaporation study, both acoustic and electric levitation forces should be used.

- The acoustic field should be minimum to reduce the flows around the drop such as acoustic streaming, which affects the evaporation rate.
- Using both levitation forces can reduce the deformation of the drops.
- Easy to control the position of the drop when evaporation continues.

Experimental results for evaporation of pure octane drops levitated by a glass fiber, both electric and acoustic forces and only acoustic force

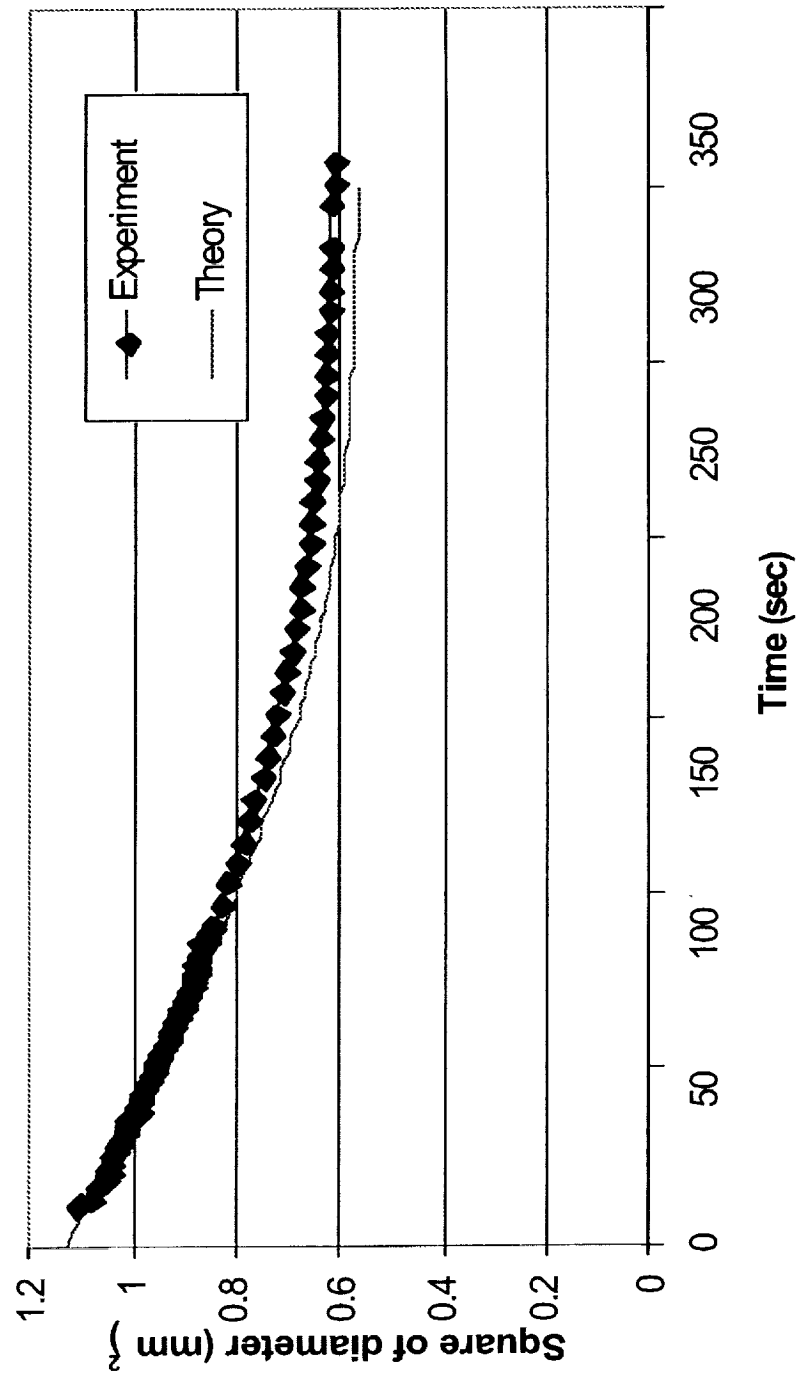


	Fiber Suspended Drop	Acoustically and Electrically Levitated Drop	Only Acoustically Levitated Drop
κ (mm ² /s)	0.0046	0.0048	0.0062

Multi-component drop evaporation

- Evaporation of an isolated multi-component drop can be solved by using the mass conservation law for each species and applying Raoult's law to the gas phase.
- The fast mixing process inside the drop is assumed.
- The drop temperature, liquid and gas phase component fractions all change with time and are updated at each step of calculation.
- Newton-Raphson and Runge-Kutta methods are used to solve coupled differential equations

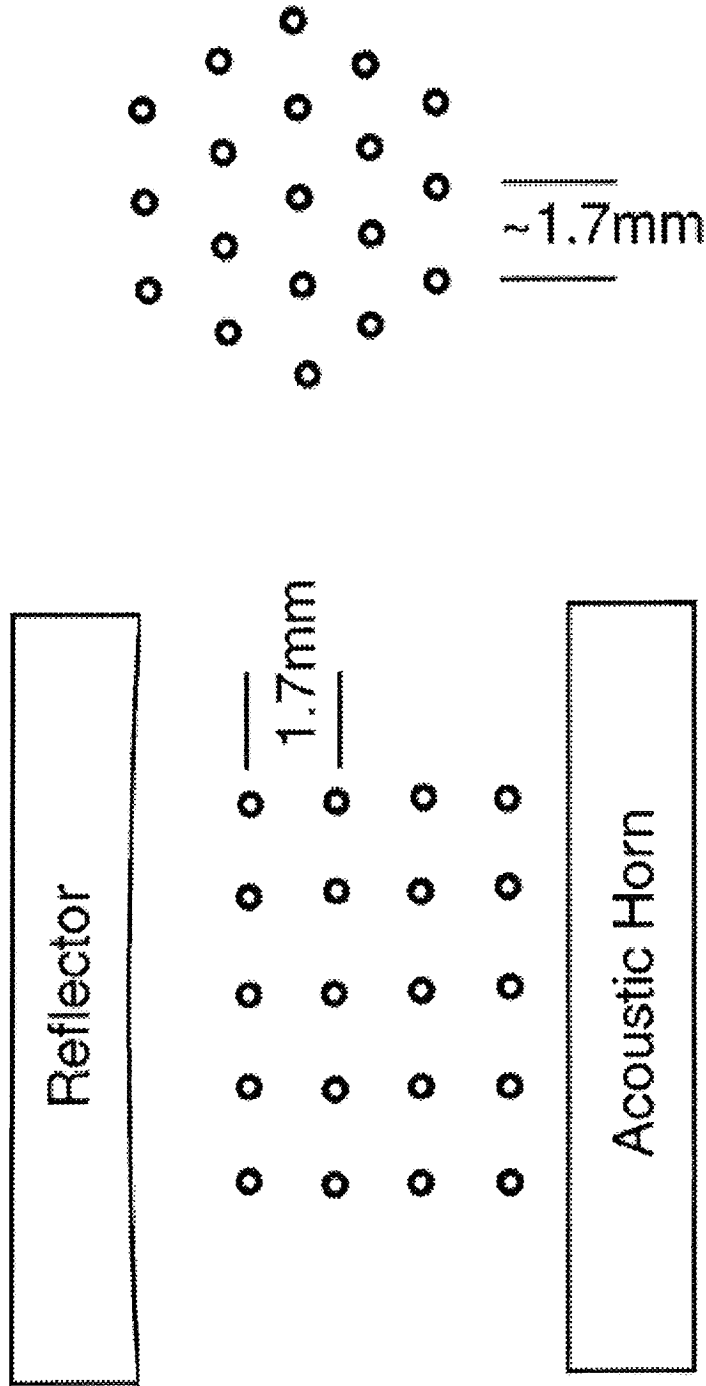
Evaporation of mixture of 70% octane and 30% dodecane (mole fraction)



High frequency levitator for 3-D arrays

- The operation frequency of the acousto-electric levitator has been increased to more than 100kHz.
- The spacing of 2-D drop layers is reduced to 1.7mm.
- Try to form a possible stable 3-D array for combustion study in drop tower or any stable 3-D array in microgravity environment in space.

3-D array



Side view of a 3-D array

Top view of a 3-D array

Conclusion

- The acousto-electric levitator can generate and stably levitate drop and particle arrays.
- Finite element analysis with anisotropic perfectly matched layers is successfully used to calculate the 2-D acoustic profile of an acoustic levitator in order to study acoustic forces on 2-D drop arrays.
- The data for isolated multi-component drops with minimum acoustic levitation are in reasonable agreement with the theory including both mass and energy transfer.

Future work

- Stable 3-D arrays for studies in drop tower and Space Station.
- Establish a benchmark experiment for both single and multiple component drop array evaporation.