Experiments in Acoustically-Induced Freezing

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***Abstract*— Water drops frozen prior to colliding with surfaces do not adhere to substrates as do liquid supercooled water drops when they strike and freeze. Therefore, deliberately freezing supercooled droplets before they collide with surfaces may reduce atmospheric ice accretion. Reports of problems with unintended freezing of supercooled droplets in acoustic levitators prompted us to investigate deliberate freezing of droplets using acoustics. Our goals were to experimentally investigate if we could induce acoustic freezing, and if successful to assess how temperature, drop size, and acoustic power and frequency influence freezing. Our work was conducted in an acoustic levitator incorporating a waveguide resonator tuned to provide maximum sound pressure on the levitated supercooled drops. Previous unsuccessful experiments by others in an icing wind tunnel concluded that sound pressures of 150 dB or higher may be necessary to cause drops to freeze. Our waveguide resonator was designed to subject nominally 1.0-mm diameter supercooled drops to 150 dB at 2.8 kHz.**

Developing a robust experimental procedure was challenging because of the need to levitate and supercool drops without inducing freezing by stray ice nuclei, the need to control drop size, and the need to impart high acoustic pressures on levitated drops without causing them to exit the levitator. These experimental challenges prevented the desired fully systematic, repeatable measurements. However, freezing was induced by acoustic stimulation of the supercooled drops on multiple occasions. We describe the experimental procedures, show freezing induced in a controlled manner, and describe work that should be done to more formally demonstrate and understand the process.

I. Introduction

Supercooled water can be prevented from freezing on objects by maintaining surface temperatures warmer than freezing, or by preventing liquid water from contacting surfaces. One method of preventing liquid water from striking surfaces is to freeze the supercooled droplets before they collide with the surface to be protected. Frozen drops will not adhere to surfaces, but instead bounce away.

This paper describes experiments conducted to freeze supercooled drops using acoustic energy. Acoustically freezing supercooled water drops before they strike surfaces could prevent ice accumulation on surfaces, and could be another mechanism for artificially seeding clouds or fogs.

II. Background

The physics of acoustics and supercooled drop interaction, and the process of inducing spontaneous freezing of supercooled drops with acoustic energy, are not well understood. Though the cavitation process of air bubbles in water and the acoustic manipulation of those bubbles have been studied, relatively little research has been conducted regarding the interaction of acoustic energy with water drops suspended in air [1].

In a 1947 patent, Van Straten and Van Allen [2] claimed “that sound waves of proper frequency and intensity may be focused in a beam and used to produce almost instantaneous crystallization of super-cooled water droplets.” They believed that sound waves of 160 dB and higher could cause adiabatic cooling, and that distortion stresses of the drops by the sound waves also contributed to initiating nucleation.

Alpert [3] and Swinbank [4] both describe results of experiments they claimed to be successful when supercooled drops were acoustically stimulated. Alpert [3] reported on work that suggests that low frequency irradiation of water droplets, from 8 kHz to 16 kHz, at high power levels can cause immediate freezing of drops supercooled only 1 or 2°C, whereas irradiation at 240 kHz caused 5 to 10°C of supercooling, but not nucleation. He also reports that sharp sound pulses such as from an automobile horn or revolver shot will cause supercooled fog to “flash into ice.” Swinbank [4] reports about an experiment conducted in 1940-1941 to nucleate supercooled drops using a shock disturbance to perturb drops in a wind tunnel. Though results were somewhat inconclusive with regard to downstream ice accretion, Swinbank concluded that the experiment provided significant evidence that ultrasonic vibrations had stimulated nucleation of the 20 μm diameter supercooled drops.

Worsnot et al. [5] conducted a wind tunnel test in the NASA Glenn Research Center Icing Research Tunnel (IRT) that, more closely than any other tests, represented conditions that may be operationally encountered. The intent was to irradiate supercooled drops in the tunnel within a duct upstream of an impingement surface. Evaporation was theorized to be the primary latent heat loss process as drops froze in flight after leaving the duct. A decrease in icing rates on the impingement surface, an airfoil, as compared to baseline conditions, was intended to demonstrate the capability of the process. The duct was located approximately 2-m upstream of the airfoil, and tests were conducted at wind speeds ranging from 22.4 m s^{-1} to 44.7 m s^{-1}, and in temperatures ranging from -18°C to -38°C. Acoustic frequencies used in tests ranged from 20 kHz to 650 kHz, and Sound Pressure Levels (SPL) within the volume of droplets was typically 115 dB SPL to 125 dB SPL. Tunnel supercooled liquid water content ranged from 0.6 g m^{-3} to 1.35 g m^{-3} and droplet median volume diameter ranged from 14 µm to 40 µm [5].

The Worsnot et al. [5] IRT tests showed no significant difference in ice accumulation on impingement surfaces when an acoustic signal was delivered to the supercooled droplets. They concluded that it may be necessary to increase acoustic power to at least 150 dB SPL and increase the freezing time. They argued that these tests could be better conducted in a cloud chamber.

The development of acoustic levitators in the 1970s [6], and electrodynamic Paul-trap levitators [7], have allowed improved observation of the response of individual supercooled drops to freezing stimuli. Levitators remove the effects of the walls of the containment vessel and thus any of their influence on heterogeneous nucleation [8].

In 1991, Lupi and Hansman [9] reported nucleation of individual water drops in an acoustic levitation chamber, and in a vertical updraft tunnel, at Massachusetts Institute of Technology. Experiments in the levitation chamber, at -13°C, caused deformation of 3.6-mm diameter drops due to hydrostatic, surface tension and acoustic forces. Danilov and Mironov [10] also theoretically describe the deformation and breakup of drops with radii varying from 0.1mm to 1.0 mm in an ultrasonic acoustic field. Their theory shows flattening of drops, growth of small-scale instabilities at their edges, the growth of surface capillary waves, and eventual breakup of the drops when sound intensity exceeds 150 dB to 170 dB.

Ohsaka and Trinh [11] observed the formation of ice crystals associated with the collapse of bubbles in supercooled distilled water when the bubbles were excited at about 21 kHz. As bubbles were excited, they appeared to distort. As distortion occurred, the bubbles would shatter or collapse, and in its place a dendritic ice crystal would typically form that grew at a rate of 0.4 cm s^{-1}. The ice crystal then formed a nucleus that would allow the remaining water to freeze from heterogeneous nucleation. Water without the bubble did not form ice when excited. They explain that the ice formed from shifting of the freezing point to a higher temperature due to the high pressure pulse that resulted when the bubble collapsed, causing cavitation. High pressure pulses associated with the collapsing bubble can cause pressure increases of over 2 GPa [11]–[12]. The rapid high pressure pulse raises the freezing point temperature of the water sufficiently on the water phase diagram to cause nucleation of a high pressure phase of ice. This, in turn, causes nucleation of normal ice as the pressure decreases to atmospheric. Chow et al. [13] conducted a similar experiment and concluded that nucleation will not occur in bulk supercooled water that is acoustically stimulated unless a bubble is present.

Small 1 to 5 µm diameter cloud drops typically undercool to about -40ºC if free of freezing nuclei [14], with larger drops spontaneously freezing at higher temperatures [15]. Researchers studying supercooling with acoustic levitators have reported undesired instances of nucleation and freezing of drops under insonification from the levitator. For example, Chinese researchers have attempted to subcool large precipitation-size drops, 2.5 to 4 mm in diameter, to low temperatures [16]-[17] using acoustic levitation operating at a frequency of 16.7 kHz to eliminate wall effects. These experiments achieve significant subcooling, to -24°C, but are limited by freezing that are believed to be caused by the acoustic energy of the levitation process. They find that distilled water subcools more deeply than tap water, and that the magnitude of drop deformation caused by the acoustic energy appears to be related to subcooling, with deeper subcooling related to less drop deformation. Drops that are oblate in shape undercool more deeply than drops that attain a disk shape. Moreover, they observe that bubbles in the drops migrate to the surface of the drops, which are then driven into resonant oscillation by the acoustic energy and may collapse causing a localized high pressure pulse at the bubble wall due to cavitation similar to that described by Ohsaka and Trinh [11]. The bubble collapse may cause localized pressures of 5 GPa [17] which adiabatically raises the freezing temperature of water, increasing supercooling, and initiating freezing. Water bulk supercooled at -5°C, for example, when subjected to a pressure of 0.83 GPa, becomes supercooled by 67°C, and water bulk supercooled at -24°C and subjected to 0.44 GPa pressure supercools by 119°C [16]. The authors also indicate that water impurities also migrate to the drop surface which encourages nucleation [16]. Sonoluminescence is also occasionally observed as cavitation occurs.

Most recently, Lü et al. [18] experimented with the effects of acoustic pressure to better understand the processes causing supercooled, acoustically levitated drops to freeze. Drops were suspended in a 16.7 kHz acoustic levitator. Five-hundred experiments demonstrated that 180-mm diameter supercooled drops exposed to sound intensities of 164.4 dB froze at a warmer temperature, -9°C, than drops exposed to lower sound pressures, which froze at -14°C at 160.6 dB. They also demonstrated that acoustic freezing is drop surface dominated, and that the "acoustic stream" around the drop, and cavitation near the drop surface, are the primary reasons for nucleation.

Observations by Lü et al. [17]-[18] suggest that freezing may be most efficiently initiated near the resonant frequency of drops, or near the resonant frequency of bubbles that migrate to the surface of drops. Liquid water drops between 10 and 1000 µm in diameter have resonant frequencies ranging from 2 MHz to 2 kHz [19]. Exciting drops at their resonant frequency causes them to deform which may cause bubbles to migrate to the drop surface. Bubbles vibrating at their resonant frequency may collapse and initiate drop freezing.

In summary, though there is no consensus, researchers believe that acoustic oscillation of drops, especially at their resonant frequency, creates bubbles within the drops. The bubbles migrate to the drop surface where the bubbles oscillate under acoustic pressure. If the bubbles collapse, pressure pulses of several GPa locally raise the freezing point temperature. Since the droplet remains near its supercooled bulk temperate despite the adiabatic processes occurring within the bubble, the droplet is locally more deeply supercooled because of the higher freezing point temperature. This initiates localized freezing creating ordinary ice, or a high pressure phase of ice which in-turn causes the formation of ordinary ice. The presence of ice crystals in the supercooled water, heterogeneous nucleation, then continues the freezing process.

III. Methodology and Procedures

Our primary goal was to demonstrate that we could induce freezing of supercooled water drops in a controlled manner using insonification. If that was accomplished, we also wished to evaluate temperature, drop size, drop purity, acoustic energy and frequency effects on nucleation efficiency.

We developed two methodologies, the oscillation and the resonation methods, for experimentally freezing drops; both using an acoustic levitator. We had considered using a droplet free-fall apparatus as described by Wood et al. [20], but instead used an acoustic levitator approach because it provided more experimental control and allowed droplets to be more thoroughly observed. In addition, the acoustic levitator provided control over drop oscillation, a component of the drop freezing process described, for example, by Lü et al. [17]-[18].

A. Oscillation Methodology

Both methodologies utilized a tec5 AG ultrasonic levitator. This levitator was designed to levitate drops of about 15 µm to 2.5 mm diameter, and operated at 58 kHz. Drops had to be supercooled, and the levitator had no provision for cooling. In addition, airflow across the levitation volume had to be minimal or droplets would lose levitation, and chamber air had to be kept as free as possible of dust or ice nuclei to prevent nucleation from sources other than acoustic. The chamber was provided with ports for injecting drops with a hypodermic needle, measuring air temperature near the levitating drops, a light source, and a camera for recording events. The levitator vibrating platen was located below the sample volume, and an adjustable reflector was located above the sample volume for adjusting drop levitation and oscillation. Fig. 1 and Fig. 2 show the levitation chamber as configured.

Cooling was provided by a Thermo Electron Neslab ULT80 Bath Circulator. It chilled the levitator chamber to approximately -20°C using ethylene glycol. Droplets were imaged with a video camera, and indications of drop freezing were verified by visual changes in drop shape and opacity. A polarizing filter was later added to the camera to improve our ability to detect drop nucleation.

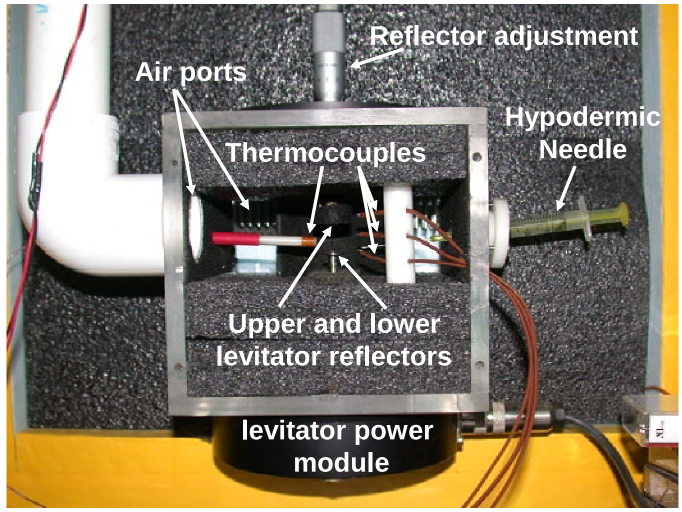

Fig.1. Oscillation levitator and environmental chamber. The grey background material surrounding labeled components is foam insulation.

Fig. 2. Air is chilled by a heat exchanger within the insulation-filled box. The video camera attaches to a plastic cover on the front of the levitation chamber.

B. Resonation Methodology

Though supercooled drops were induced to freeze in the oscillation methodology, we could not obtain consistent nor repeatable freezing of drops. To improve capability, we developed a waveguide resonator that would subject supercooled drops to 150 dB SPL and be compatible with the acoustic levitator system [21]. Worsnot et al. [5] after their test in the NASA Glenn Research Center IRT, Van Straten and Van Allen [2] in their patent, and Danilov and Mironov [10] in their drop breakup experiments all indicated that a SPL near 150 dB may be necessary to sufficiently oscillate drops and cause cavitation and freezing. In addition, Lü et al. [17]-[18] indicated that freezing may be most efficiently initiated near the resonant frequency of drops or of bubbles that migrate to the drop surface.

To increase the acoustic pressure and tune the frequency to the approximate drop size, a resonator was designed to operate at 2.8 kHz to cause resonance in 850µm diameter droplets and produce the desired pressure within the waveguide at the location of drop levitation. The resonator chamber is 12.7 cm long and 3.2 cm in diameter. At the second harmonic frequency of 2.8 kHz, these dimensions provide pressure maxima at the ends and center of the waveguide, while the pressure minima/velocity maxima are located 0.25 wavelengths, about 3.2 cm, from the ends (at 2.8 kHz). Fig. 3 shows the resonator initial design, and Fig. 4 shows the resonator as built.

Penetrations were placed in the resonator sides and ends for the speaker, cold air flow ports, optics, hypodermic needle, and levitator platen and reflector. The holes were placed at locations of high acoustic impedance in the resonator to minimize disturbance of the acoustic signal [21]. Cold air flow across the levitation space was also minimized to reduce drop levitation disturbance.

Small, 10-cm diameter long-throw acoustic speakers were used to excite the resonator volume. Tests of a prototype resonator, but without the numerous penetrations, attained a 150 dB SPL at 2.8 kHz 7.1 cm from the speaker end of the waveguide, and the cavity resonance frequency was also verified at 2.8 kHz [21].

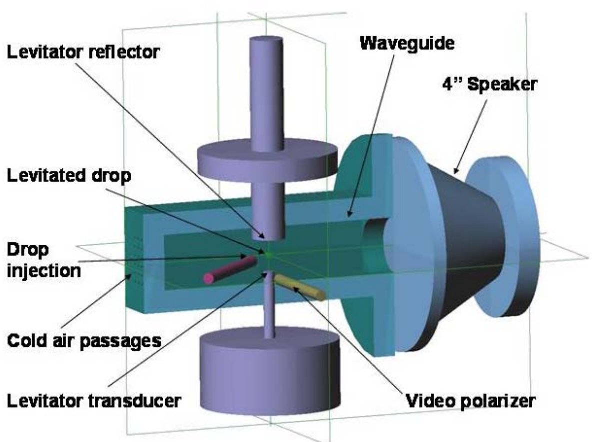

Fig.3. Resonator as designed [20].

The speaker was driven by a 100 Watts/channel Insignia amplifier. A Hewlett Packard 3312A Function Generator created the signal frequency. The acoustic signal was measured with two 0.64 cm B&K high pressure microphones powered by GRAS power modules and recorded with a Summit data system operating at a sampling rate of 32 kHz per channel.

As with the initial oscillation methodology, droplets were imaged with a video camera. However, indications of drop freezing were verified by using a polarizing filter.

Fig. 4. Resonator as constructed. Cold air flows in, and out, through the plastic tubing. The video camera attaches to the open port on the lower left. The thumb-knob on top controls the levitator reflector height. The loudspeaker used to insonify the chamber is on the right.

C. Experimental procedures

Considerable experimentation was necessary to create a procedure for successfully cooling the chamber, injecting drops, and imaging the drops in their liquid and frozen states. Experimental challenges included injecting drops into the levitation volume, hypodermic needle freezing, fogging of optics, insufficient chamber cooling, and drops being pushed out of the levitation volume by acoustic pressure and cooling air flow.

At the start of each experiment the temperature data logger was started and the levitation chamber and later the resonator were chilled to the desired operating temperature. Once cooled, video and acoustic data loggers were started. Drops were injected into the levitator by touching the hypodermic needle to the vibrating levitator platen and injecting water. The vibrating platen overcame surface tension holding drops to the needle, and typically caused multiple drops to become levitated at the acoustic node points (Fig. 5). Since we usually desired fewer drops in the sample volume, excess drops were removed by attaching them to the hypodermic needle and pulling them into the needle. Typical drops were approximately 1-mm diameter.

The resonation methodology was overall more successful than the initial oscillation methodology. We also learned to slowly increase speaker SPL because sudden increases in SPL caused drops to be pushed from the levitator. In addition, the high operating SPL caused frequent destruction of speakers. Loss of speakers caused eventual termination of experiments.

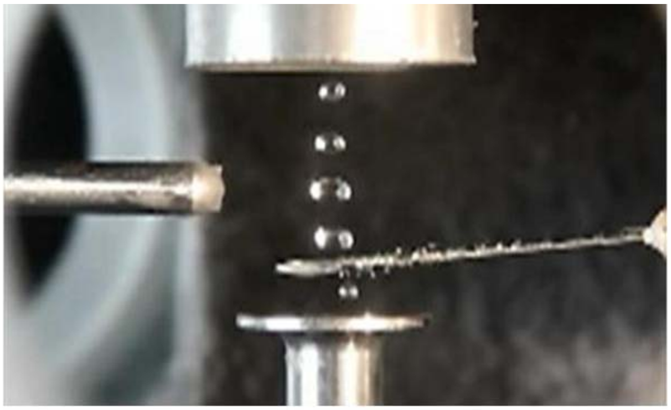

Fig. 5. Multiple drops were often initially levitated because water droplets injected into the chamber were captured by several levitator acoustic nodes. Drops were removed by attaching them to the hypodermic needle.

IV. RESULTS

Our initial goal was to demonstrate that we could freeze drops using acoustic energy to stimulate nucleation. We then wished to obtain statistically-significant repetitions of freezing events to allow evaluation of temperature, drop size, drop purity, acoustic energy and frequency effects on nucleation.

A. Oscillation Results

We initially experimented with drop oscillation to attempt to stimulate bubble formation and cavitation. An oscillating drop may form an oblate shape, and can oscillate vigorously (Fig. 6). Occasionally, this process caused drops to break or exit the levitation volume. Results were inconsistent and effectiveness of drop oscillation in promoting nucleation could not be determined. However, we noted that most freezing is associated with some drop oscillation or movement, sometimes being simple side-to-side motion equivalent to 0.5 to 1.0 drop diameter in magnitude.

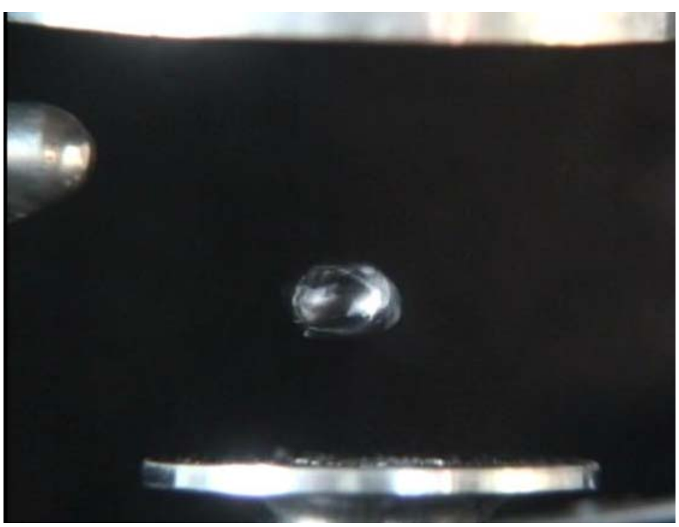

Fig. 6. As the levitator reflector (top) was moved up or down, droplets could be made to oscillate. However, this also occasionally caused droplets to lose levitation and fall.

Drop nucleation during oscillation suggests that cavitation may be occurring. Fig. 7 shows a drop that nucleated at a temperature of -6.7°C. The upper left inset shows the drop before freezing, and the upper right insert shows the frozen drop resting on the hypodermic needle after capture.

Additional drop freezing events occurred in the levitator, provoked to nucleate we believe only by inducing oscillation. Several examples follow.

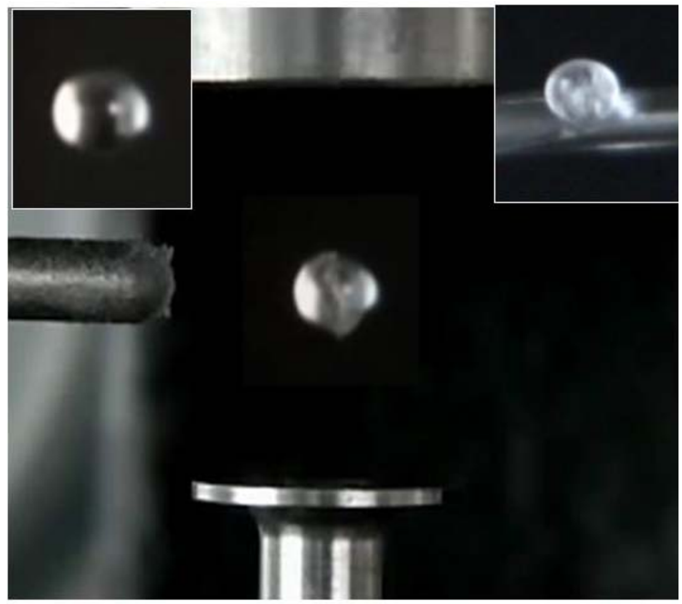

Fig. 7. A nucleation event during the oscillation experiments. The upper left inset shows the drop before freezing, and the upper right inset shows the frozen drop resting on the hypodermic needle after capture.

During a series of experiments on 19-20 December 2006 drops often nucleated, but no temperature information accompanies the events due to logging system failure. In one event two drops were created in the levitator at about 4:27 PM. Neither drop froze until oscillation began. Both drops, in the top of Fig. 8, are vigorously oscillating as indicated by the bulges in their sides. Polarization shows that the right drop had frozen about 5-seconds later as shown in the in the lower image of Fig. 8. The left drop remained liquid for several more minutes until the drops were lost from the levitator.

Another experiment on these dates demonstrates two drops freezing in sequence after individually oscillating (Fig. 9). Three drops were placed in the levitator at about 10:26:40. The bottom drop in the image began oscillation shortly after injection due to air flow through the chamber, or due to characteristics of the levitator acoustics, or perhaps because three drops were being levitated simultaneously. The top left frame of Fig. 9 shows that the bottom drop was unfrozen at 10:32:29, but nucleated within that second as shown in the top middle frame. Several minutes later the middle and top drops began oscillating laterally with a magnitude equivalent to 0.5 to 1.0 drop diameter (upper right and lower left frames). At 10:34:04 levitation of the top drop became unstable and the drop was lost. The middle drop then nucleated, perhaps due to acoustic perturbations that caused, or were caused by, the loss of the top drop

Fig. 8. The drops in the top frame are vigorously oscillating as indicated by their shape. In the bottom frame, the right drop has nucleated, but the left drop did not freeze. The top of each image is up.

B. Resonation results

Construction of the resonator chamber to the design of Parkins and Parkins [21] allowed more effective control of freezing by allowing pulsing of drops with acoustic energy at selected times. All experiments were conducted at temperatures of about -20°C. Overall, six experiments were conducted that froze drops. All drops were formed from a mist and were unfrozen for durations of 20- seconds to several minutes until they were pulsed. In each experiment sound pressures ranged from 120 dB SPL to 130 dB SPL at a frequency of 2.936 kHz. Acoustic pulses were slowly increased in intensity because a rapid increase in sound pressure caused drops to lose levitation. The duration of acoustic pulses varied from 4-seconds to 25-seconds. Drop freezing occurred from 1-second to 10-seconds after the start of the acoustic pulse; an average of 3.8-seconds. Drop diameters were approximately 1.0 mm to 1.5 mm. Two of the experiments are described below.

Three drops are simultaneously levitated in Fig. 10. In the left frame all three drops are liquid and supercooled. The top drop is partially off of the top of the frame. The second frame was created with the polarizer in place, and because the drops are all liquid they are not visible. The three drops were acoustically pulsed between frames. The middle drop froze 2-seconds after the start of an eight-second long acoustic pulse. The third frame from the left shows the nucleated drop in the polarizer image. The other two drops are not visible because they remained liquid. The right frame, without the polarizer, shows the three drops with the middle drop frozen.

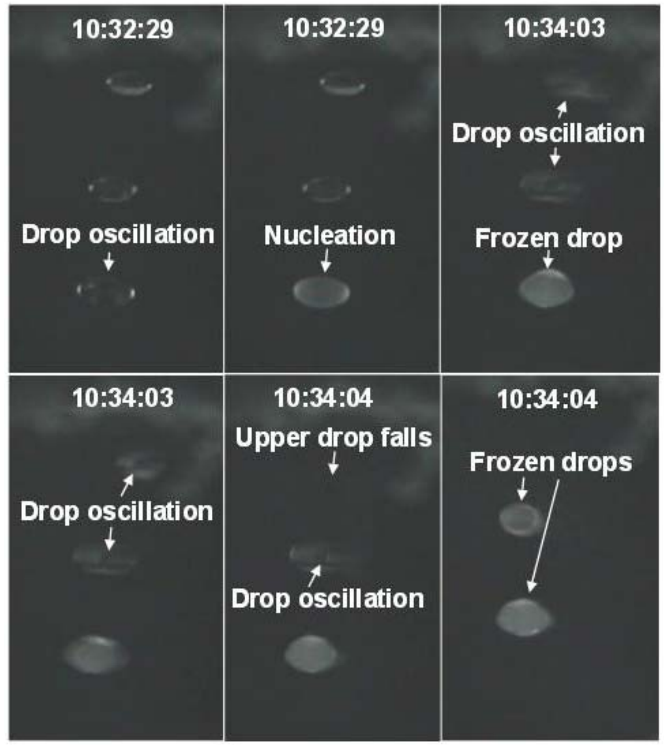

Fig. 9. A sequence of two drops freezing about 1.5-minutes apart due to oscillation in the levitator. The top of each image is up.

Two drops were simultaneously levitated during the experiment illustrated in Fig. 11. Both drops are visible in the left frame of Fig. 11. Though not evident except for the slight spike on the top and bottom, the lower drop had nucleated prior to the acoustic pulse. The second frame, polarized, shows the frozen bottom drop. A 13-second acoustic pulse was used to attempt to nucleate the top drop, which nucleated after only 1-second of acoustic stimulation. The third frame shows that the upper drop has frozen, evident from the oblate shape and the spike on the bottom.

V. DISCUSSION

The principal goal of our project was to demonstrate that we could nucleate drops acoustically. The work accomplished that goal. The oscillation experiments were difficult to control, and there were no obvious conditions that consistently froze drops. There was typically some amount of oscillation prior to drop freezing. However, there were many cases where we stimulated drops to oscillate over a wide range of intensities, and the supercooled drops did not freeze. Since many of the results obtained during the project did not have temperature records, we cannot assess whether the degree of supercooling was related to nucleation success. We also have insufficient information to assess whether there is a relationship between supercooled drop size and nucleation success. Though the levitator successfully levitated a wide range of drop sizes (size judged by eye), some of those sizes may not have been well-matched to the optimal drop size that could be levitated, a function of the levitator frequency [22], which could have affected freezing success.

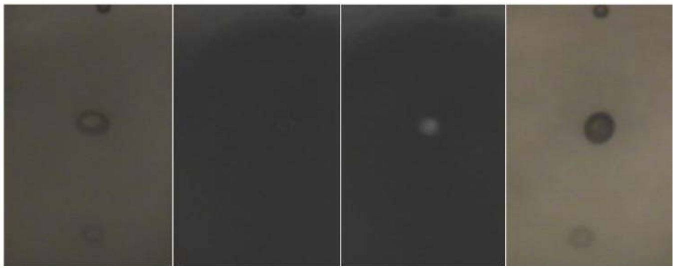

Fig. 10. Acoustic stimulation of drop causing nucleation in the resonator. The top and bottom drops did not freeze during the acoustic pulse. The top of each image is up, and the time sequence is left to right.

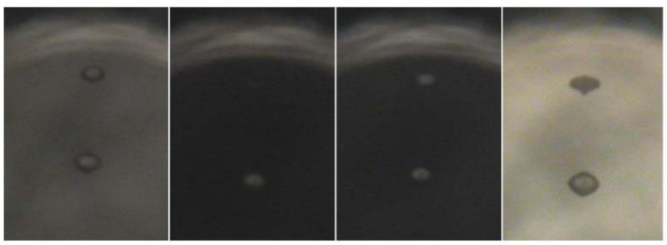

Fig. 11. The bottom drop froze without acoustic stimulation shortly after being injected into the resonator. The upper drop nucleated during the acoustic pulse. The top of each image is up, and the time sequence is left to right.

Parkins and Parkins [20] developed the resonator in response to the inconsistency of the oscillation experiments. It is evident that the resonator, which is designed to optimally stimulate drops at their resonance frequency and cause, according to theory, cavitation and nucleation provided some additional control over the nucleation process. Though we conducted only six documented resonator experiments that caused drop nucleation, each experiment did cause nucleation when drops were pulsed with a high intensity signal. However, drops that were not centered in the axis of the resonator displayed inconsistent behavior. Occasionally, off-axis drops did freeze when acoustically pulsed, as observed in Fig. 11. But in three of the experiments supercooled liquid drops that were not in the center of the resonator did not freeze even after multiple acoustic pulses. This behavior might be related to the less-than-optimum insonification that the off-axis drops experienced.

Though acoustic resonation did appear to cause nucleation in our experiments, many more repetitions are required with greater experimental control to obtain statistical validity. In addition, several factors may have confounded the results that we did obtain. We do not know whether ice crystals or other freezing nuclei could have been carried through the chamber by the cooling air, impacted the drops, and caused nucleation. We also do not know if impurities in the water may have encourage nucleation – we used ordinary tap water in the experiments. However, since drops did freeze primarily when pulsed by the acoustic signal in the resonator experiments, we believe with some certainty that the acoustic signal, and perhaps cavitation, initiated the nucleation.

In addition to a need for more repetitive, controlled experiments, there is still a need to answer questions we established at the beginning of the work. Though we did obtain some control over the freezing process, additional work is necessary to demonstrate effectiveness of control. Evaluation is still necessary of the effects of supercool temperature, drop size, drop water purity, the potential for nucleation by air borne freezing nuclei, the intensity of acoustic energy, and frequency effects on nucleation efficiency – especially with regard to drop size.

VI. Conclusions

Our initial goal was to determine the feasibility of intentionally freezing drops using acoustic excitation. Though not accomplished with statistical rigor, we have demonstrated that it is possible to perturb supercooled drops sufficiently with acoustic energy to freeze them. We have also demonstrated that we can control the process when the drops are levitated within a resonator tuned for the drop sizes to be used, and using a frequency and power level tuned to that droplet size.

At this time the phenomenon is still only a laboratory curiosity; using the process in the operational environment has additional challenges. Operationally, the process must operate in a wide range of supercooled temperatures, with a wide range of drop sizes. It must also operate in many air speeds, all less than Mach. Fortunately, most icing problems do occur at lower air speeds, both on slower moving aircraft and on stationary structures at the Earth's surface.

We believe that there is promise in continuing this work and answering the many questions necessary to evaluate it for operational use. It should not be dismissed as a potential ice protection technology without additional research investment.

VII. Acknowledgment

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