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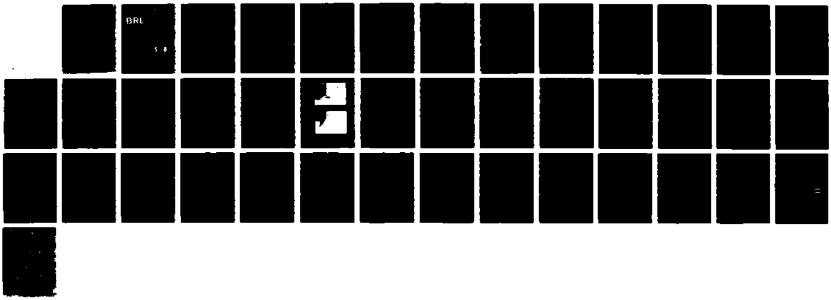

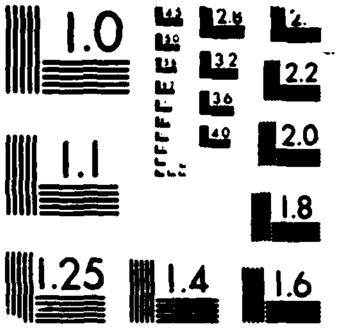

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COMBUSTION STUDIES OF ACOUSTICALLY SUSPENDED LIQUID DROPLETS

DEPT. OF MECHANICAL ENGINEERING
CORVALLIS, OR 97331

MARCH 1988

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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Richard B. Peterson

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A piezoelectrically driven ultrasonic resonator was developed and tested in this study. The device was used to levitate liquid fuel droplets for evaporation measurements and ignition studies. The final report describes the resonator and its operating characteristics, gives a brief review of the literature, and presents the results of various ignition tests. No successful minimum perturbation ignition method was discovered among the several explored. It is the author's opinion that the acoustic levitation technique may hold some promise for conducting non-combustion related droplet measurements, for example evaporation tests, but without further development of the technique combustion experiments will be difficult to be accomplished. Minimum developmental needs will be for a high temperature, high pressure chamber and a feedback positioning controller. However, even with such additional features there is some doubt whether stable levitation of a burning droplet can occur. Keywords

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SUMMARY

Piezoelectrically driven ultrasonic resonators were found to be simple in design, construction, and testing. Over a dozen resonator configurations were made and tested for their operating characteristics. Two proved to be especially reliable at levitating droplets and were subsequently employed in vaporization and ignition studies on liquid fuels such as ethanol, n-heptane, iso-octane, and decane. These tests were performed at resonant frequencies of approximately 20 kHz and 50 kHz, the former value being a fundamental resonator frequency and the latter value being a first harmonic. Droplet stability in suspension was not as good as desired for accurate determinations of droplet diameters. However, the stability was more than adequate to test various ignition techniques which included use of a) hot wires, b) spark discharges, c) open flames, d) excimer laser produced air breakdown, and e) CO_2 laser heating. All attempts proved unsuccessful. The reason for this is not known at this time but the effect of the acoustic pressure field on ignition is a key area of concern. Vaporization tests conducted on the droplets demonstrated that the suspending force in the acoustic field is equivalent to approximately a 12 cm/s flow across the droplet. The magnitude of this velocity, although small, could have detrimental effects on the droplet ignition mechanisms.

1 INTRODUCTION

Much combustion research consists of characterizing the properties of sprays. Due to their complexity, many fundamental aspects important in characterizing spray combustion are obscure. One example of this involves the study of liquid fuel and liquid propellant droplet combustion. Progress in this area has been accomplished not by studies involving spray combustion, but by investigating the burning of isolated single droplets under various conditions. Many techniques have been developed for such studies involving either freely falling droplets or fiber suspended ones. One technique not previously employed in combustion work is droplet levitation. The work reported on here involves an investigation of the acoustic levitation technique and its possible use in studies of liquid fuel and propellant combustion.

Aerodynamic, acoustic, and electrostatic principles have been exploited in the past to design levitation devices where a single droplet could be suspended almost free of motion.[1-3] For our purpose of suspending a liquid fuel or propellant droplet, aerodynamic and electrostatic techniques have been eliminated for the following reasons. With aerodynamic techniques, it is extremely difficult to maintain a gas flow of sufficient stability to keep small droplets stationary. Furthermore, adapting this technique to a high pressure environment adds much more complexity to the system. Electrostatic devices would be expensive, bulky, and not easily adaptable to the high pressure environment necessary to conduct liquid propellant studies. In addition, it is doubtful whether a burning droplet will retain its charge and hence position in the electrostatic field. An acoustic levitation device, on the other hand, has several attractive features; it is relatively inexpensive, it can be made compact and easily incorporated into high pressure vessels, and it has the capability of suspending small droplets motionless.

The approach taken here is the development of a basic piezoelectric driven resonator designed for useful power output in the frequency range between 20 and 60 kHz. Design constraints include compact construction while maintaining a sufficiently strong acoustic pressure field to levitate droplets. For this purpose, a stable frequency source and power amplifier are required to drive the piezoelectric elements of the resonator. The device is used to suspend droplets of various fuels while tests are performed on the levitated specimen. These tests include evaporation measurements and ignition studies. The objectives of this investigation are:

a) Survey the literature for the various designs of piezoelectrically driven ultrasonic resonators.

b) Construct a compact levitator which is driven by piezoelectric ceramic elements. Overall dimensions not to exceed 2.5 inches in diameter and 7.5 inches in length.

c) Acoustically suspend liquid drops in the diameter range of 0.3 to 1.0 millimeters.

d) Find optimum operating parameters of the acoustic levitator for making drops motionless.

e) Find a minimal perturbation igniter technique for ignition of acoustically suspended combustible liquid drops.

f) Ignite an acoustically levitated combustible droplet and monitor the stability as combustion takes place.

g) Render an evaluation on the practicality of using acoustic levitation to study combustion phenomena of individual liquid drops.

This report describes the work accomplished toward fulfilling these objectives during the contract period of 22 May to 30 September 1987. During the course of this work, various resonator designs and clamping techniques were considered and several resonators were built and tested. An evaluation of the most reliable design has been provided in this work.

2 REVIEW

Ultrasonic resonators have been employed for a variety of applications.[4-6] For example, one design based on a piezoelectric driven resonator was used for atomization of fuel oil.[4] The vibration of the resonator end caused a liquid sheet of fuel covering it to break off in the form of droplets with an average diameter of 25 micrometers. A vibrational frequency of 60 kHz was used in this study. Atomized fuel collected at the planes of sound pressure minima when a reflector was used to set up a standing wave pattern in air. Fuel delivery to the end of the resonator was accomplished through a center tube so that liquid could be supplied to the resonator at a vibrational nodal point. Tests on the device demonstrated little wear or fatigue developing after 4×10^{12} cycles at a maximum resonator end stress of 11,000 psi. No clogging was observed with the fuel oil used in the study.

This investigation was note worthy because of the various resonator clamping designs studied. It was shown that clamping techniques were of great importance for obtaining proper acoustic coupling between the piezoelectric drivers and the resonator bulk material. Horn designs were also studied to increase the resonator end displacement amplitude. A stepped horn design proved useful for increasing the acoustic intensity by a factor of 6 to 10 times.

In another study, a high power piezoelectric transducer was designed and tested that generated 10 kW of power at an efficiency of 97.5%.[5] The resonator included a catanary horn design specially developed for the high power application. Testing of the system involved attaching two similar devices together as a motor-generator combination and recording input and output power. At lower power levels, it was recommended that a stepped horn be used to obtain high amplification factors. However, the stepped horn resulted in lower overall efficiency. The catanary type proved most efficient. The entire assembly weighed 22 lbs. and produced a 0.004 inch peak-to-peak vibrational amplitude at the end of the horn. Mild steel was used in the construction of the resonator.

An in depth study of the stability of acoustically suspended liquid droplets demonstrated that droplets move towards planes of minimum sound pressure at resonance.[6] In a resonator/reflector configuration, the first two sound pressure minima where shown to be the best. In the untuned state where the reflector distance was not set to the optimal spacing, the pressure maxima were well below the tuned pressure minima. Using a hot wire to map out the velocity in the acoustic field, the peak velocity positions were identified. Further experiments showed that a radial distribution of sound pressure existed and provided a means of stabilizing droplets in the radial direction. This was demonstrated by showing stable levitation with the resonator rotated through 90 degrees.

Other studies using a spherical resonator geometry have been conducted.[7] The stability of droplets was reported to be influenced by the ratio of viscous drag to radiation pressure. When this ratio was between 0.25 and 0.75, the onset of instability occurred. Experiments demonstrated that droplets below 0.5 mm in diameter were ejected for the pressure well, thus falling out of the acoustic field produced by the resonator and reflector.

Center bolt resonators have been designed and constructed for studies in space borne laboratories as well as in ground based facilities.[8] Designs incorporating stepped horns connected to circular vibrating plates for coupling the ultrasonic vibrations to the environment have shown reliable operation for positioning specimens in laboratory furnaces and high pressure vessels. Applications of the levitation equipment included studies of surface waves on freely suspended liquids, variations of the surface tension with temperature, and optical diffraction properties of transparent substances. The criteria for efficient coupling between the resonator and the acoustic medium is given where it was shown that the resonator end diameter should be larger than the wavelength of the sound frequency.

3 RESONATOR DESIGN

The resonator design employed in this work uses the principle of the piezoelectric effect. A ceramic disk having this property expands and contracts as an AC voltage differential is applied across it. In a typical design, two disks are sandwiched between two metal cylinders. The disks expand and contract in opposite directions simultaneously. When an AC signal is applied to the device whose frequency is f, a resonant wave is set up in the metal cylinders if the overall resonator length is $\lambda/2$ where $\lambda = c/f$. Here c is the speed of sound in the metal and λ is the wavelength. The result of the resonant condition is high amplitude displacement of the two ends of the device causing sound energy to be transmitted into the surrounding environment. If a flat reflector is place an integral number of wavelengths (now in air) from the end of the resonator, an acoustic standing wave pattern can be set.

The basic resonator design employed in this study is shown in Fig. 1. Two piezoelectric ceramic disks, with the same polarity faces together, are sandwiched between two matched aluminum cylinders. A center hole exists in each of the disks so that a bolt can be used to clamp the assembly together. A conductive plate is placed between the two disks to provide an electrode for driving the piezoelectric elements. The

EXPLODED VIEW OF RESONATOR

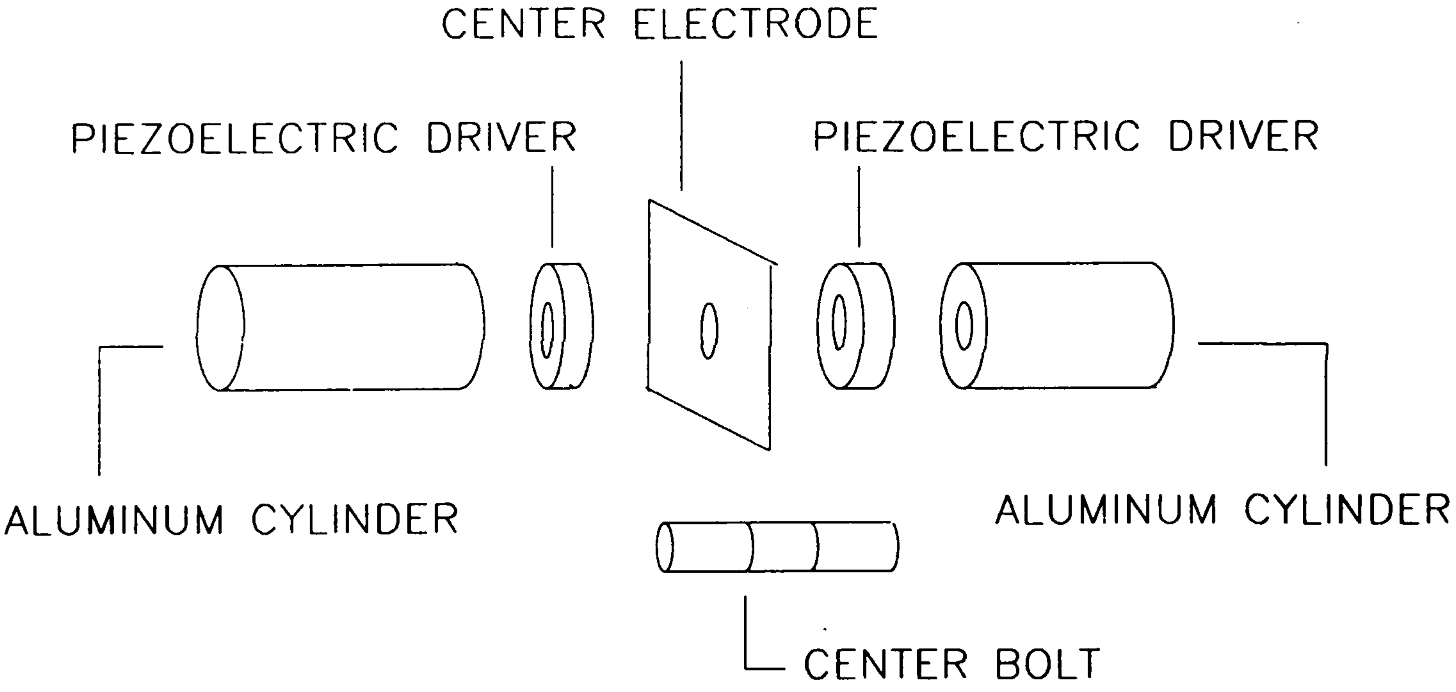

FIGURE 1

non-threaded section of the bolt is sheathed in insulating plastic to prevent the center electrode from shorting out to ground (the cylinders are held at ground potential).

The goal was to produce a resonator that supported fuel droplets at a resonant frequency between 20 and 60 kHz. The resonator developed to achieve this goal had a diameter of 1.06 inches. The aluminum (6061-T6) cylinders on each side of the 0.080 inch thick ceramic drivers were 1.825 inches long. A plate 0.060 inches thick was the center electrode for the design. A center bolt had a length of 1.50 inches, a diameter of 3/8 of an inch and was made out of 304 stainless steel. The threads on the bolt were 3/8 inch NC. A resonant fundamental frequency of slightly below 20 kHz was measured and a first and second harmonic near 50 kHz and between 90 and 100 kHz, respectively, were found. Figure 2 shows the experimentally determined resonant frequencies. A second device having the same length as above and a diameter of 1.465 inches was also constructed and proved to be resonant at approximately the same frequencies (fundamental at 22 kHz). Clamping pressure on the piezoelectric disks had a significant effect on the resonator efficiency, and hence sound intensity level. Figure 3 shows the relationship between the pressure applied to the ceramic disks and the relative increase in detected sound level. The top graph is for ceramic disks 0.080 inches thick while the bottom is for disks 0.125 inches thick. As indicated by the graph, the sound level increased to a point at all three resonant frequencies tested when the clamping pressure increased.

Two different types of resonators were tested. The center bolt type described above was used in all experiments reported on here. Another design, employing flange clamping, was also built and tested. The flange resonator was never successful at supporting droplets and since the center bolt resonator was simple and effective, it was exclusively used in all levitation experiments. Horns were also studied with various designs being

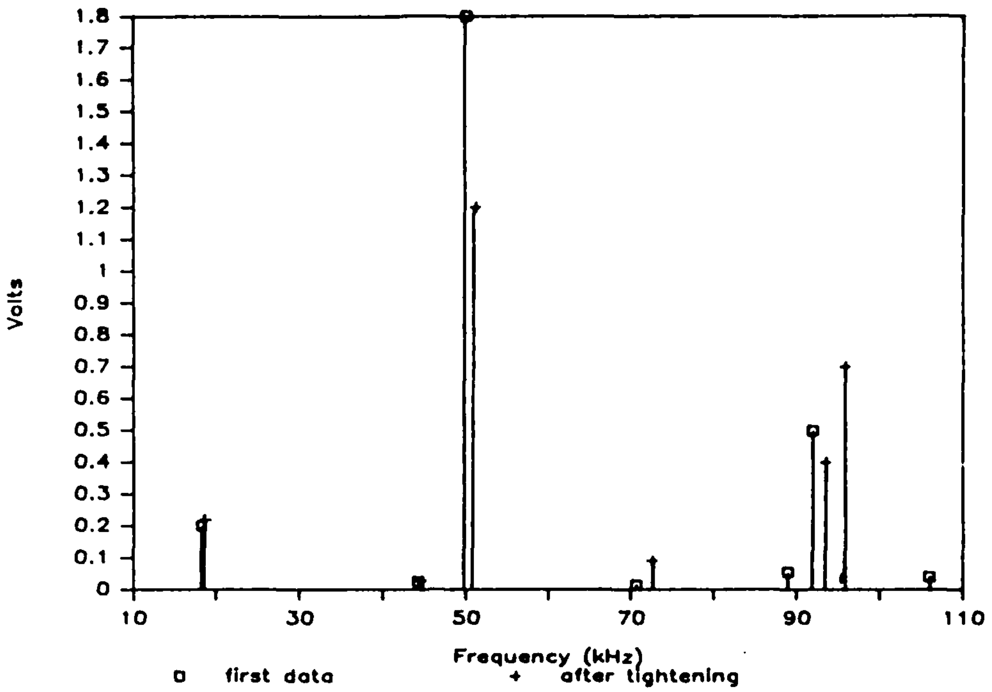
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Volts
10
30
50
70
90
110
Frequency (kHz)
□ first data
+ after tightening

FIGURE 2

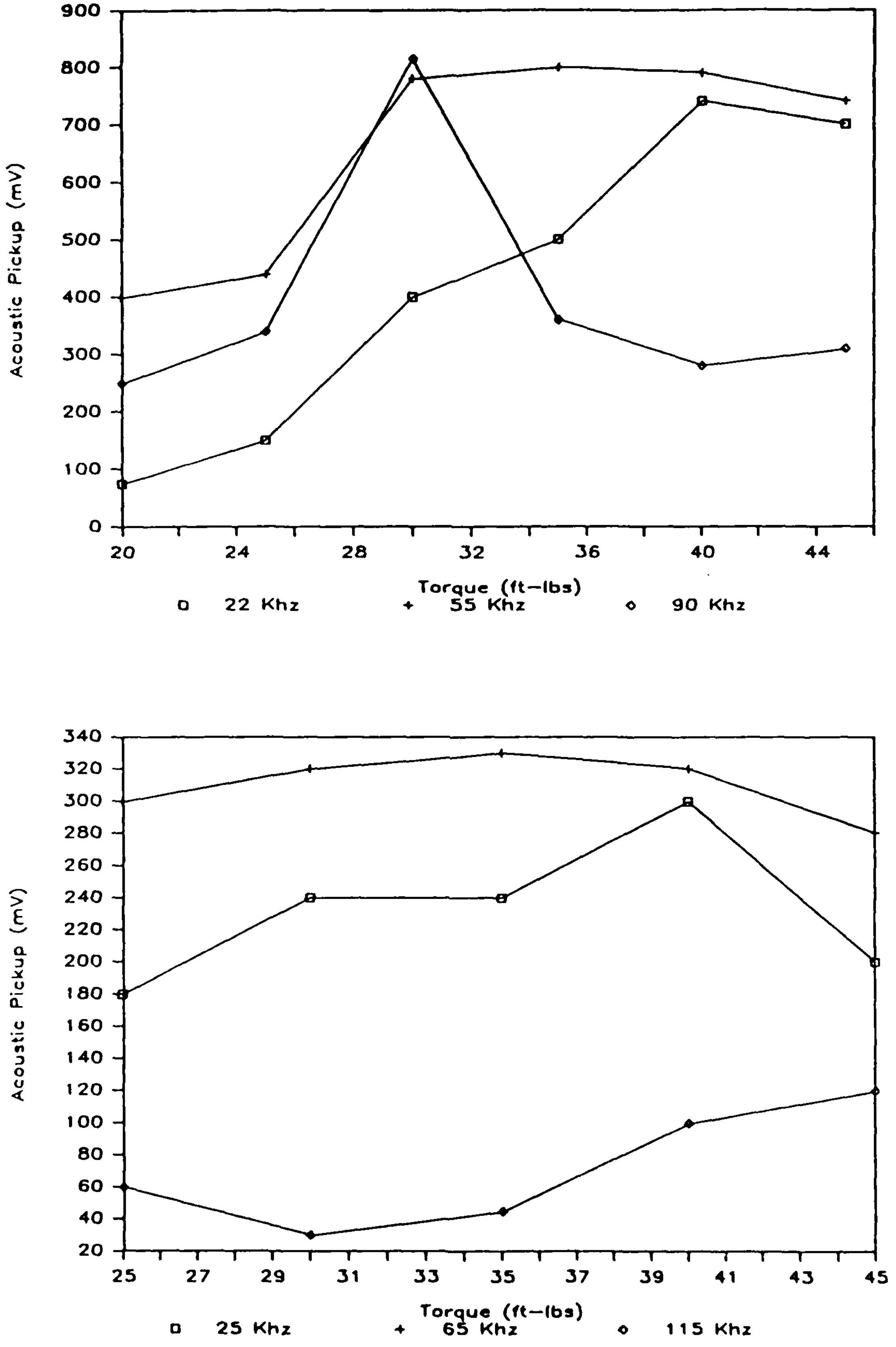
900
800
700
600
500
400
300
200
100
0
Acoustic Pickup (mV)
20
24
28
32
36
40
44
Torque (ft-lbs)
□ 22 Khz
+ 55 Khz
◇ 90 Khz
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
Acoustic Pickup (mV)
25
27
29
31
33
35
37
39
41
43
45
Torque (ft-lbs)
□ 25 Khz
+ 65 Khz
◇ 115 Khz

FIGURE 3

constructed. None appeared to be useful for amplifying the acoustic sound pressure levels, and so they were not pursued further in this study.

The experimental apparatus used to conduct the frequency, sound level, and levitation measurements is shown in Fig. 4. A sine wave generator produced the required signal which was first routed to a counter/timer to obtain an accurate reading of the output frequency, and then to a 10 Watt amplifier for boosting the voltage and power levels of the signal supplied to the resonator. An oscilloscope was used to monitor both the voltage supplied to the resonator and the acoustic signal detected by another ceramic disk which doubled as an effective flat plate reflector. The resonator was mounted in a translator that provided accurate adjustment of the distance between the resonator and the reflector.

4 RESULTS

Droplets were supported at both 20 and 60 kHz with the 1.06 inch diameter resonator. The 1.465 inch diameter resonator only supported drops at a resonant frequency of 22 kHz but proved useful in stability tests and was employed in all evaporation tests with liquid fuels. This resonator closely approach the condition of rendering motionless the suspended droplets hence diameter measurements for evaporation tests were easier to perform with this device. Typical driving signals were between 25 and 75 volts peak-to-peak.

Size, stability, and how the droplets were placed on the sound planes were important considerations in this study. Theoretically, the largest droplet diameter that could be levitated in air at 60 kHz, based on the consideration that a droplet cannot cross two sound pressure minima, is 0.4 cm. Experimentally, the largest droplet suspended was ellipsoidal in shape having a mean diameter of 0.2 cm, roughly one half the theoretical limit. Attempts to suspend larger droplets produced

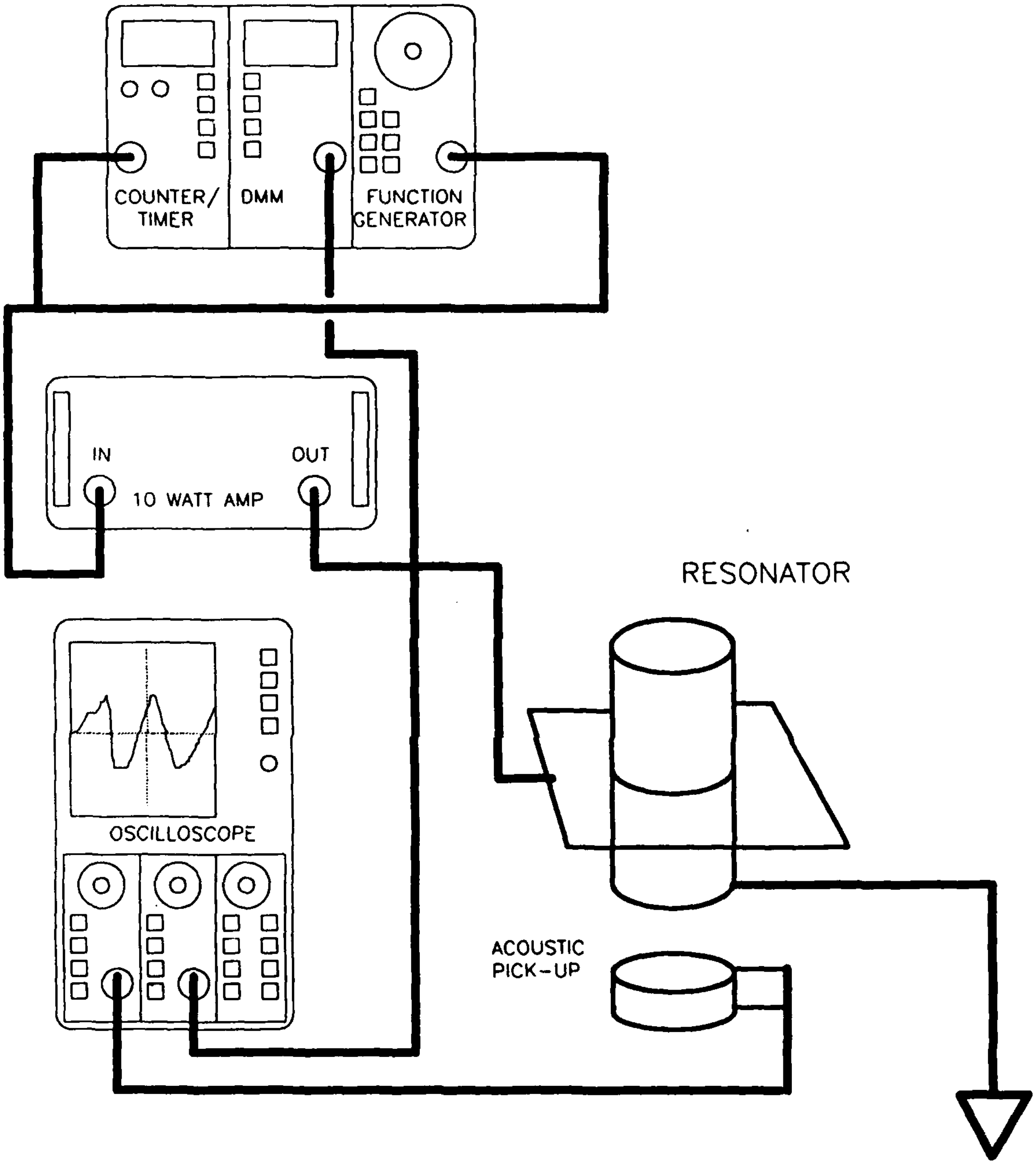
COUNTER/ TIMER
DMM
FUNCTION GENERATOR
IN
OUT
10 WATT AMP
RESONATOR
OSCILLOSCOPE
ACOUSTIC PICK-UP

FIGURE 4

a disk shaped specimen as seen in Fig. 5 (top). This disk was 0.1 cm thick and 0.5 cm in diameter. As these disks evaporated, they became spherical and smaller. The smaller spherical droplets tended to oscillate about a fixed point in the acoustic field. The amplitude of oscillation was approximately 0.005 inches. Different fuels oscillated at different rates. For example, methanol vibrated so rapidly that no accurate diameter measurements could be obtained. A droplet was deposited within the acoustic field with a hypodermic syringe and needle. It was important to have a very small tip in order to minimized the surface tension effects keeping the droplet attached to the needle. In some cases, a metal needle was used. In other cases, it proved useful to outfit the syringe with a glass tube that had been drawn down to a fine capillary (100 micrometers in diameter). It was observed that high sound intensity levels permitted easy droplet depositing within the resonant field.

5 VAPORIZATION TESTS

The vaporization tests were performed with the apparatus described above. To observe the size of droplets as a function of time, a binocular microscope was employed having a reticle with a resolution of 0.001 inches. Data from a series of measurements on various liquid fuels can be found in Appendix A. Note that in these measurements the drops oscillated about their equilibrium positions, thus rendering measurements of their diameters difficult. Five runs were averaged together to minimize the errors associated with these measurements.

Theoretical considerations of droplet evaporation in a quiescent environment leads to a linear plot of the droplet diameter squared as a function of time. The linear plot is characterized by a slope of $-\lambda$ calculated by,[9]

$$\lambda = \frac{4\,\mathrm{Nu}\,\rho_g \alpha_g}{\rho_l} \ln(B+1)$$

FIGURE 5

B is a nondimensional constant relating diffusion and convection. The Nusselt number is represented by Nu and the density is ρ. α is the thermal diffusivity. Subscripts g and l refer to the gas and liquid phases, respectively. The thermal diffusivity and density can be found in the CRC handbook. When there is no flow by the droplet the Nusselt number is equal to two. For cases of nonzero flow rate where the flow velocity is u, the droplet diameter is d, the kinematic viscosity is ν, and the thermal diffusivity is α, the Nusselt number equals:

$$\mathrm{Nu} = 2 + 0.6\left(\frac{ud}{\nu_g}\right)^{\frac{1}{2}}\left(\frac{\nu_g}{\alpha_g}\right)^{\frac{1}{3}}$$

Figure 6 (bottom) shows the results of evaporation tests on ethanol, n-heptane, and iso-octane. The dashed line shows the theoretical results when a flow of 12 cm/s is assumed to pass across a droplet having an initial diameter of 0.03 inches. These comparisons show that a flow is developed by the acoustic field that supports the droplets.

6 DROPLET IGNITION STUDIES

Table I lists the techniques that were tried for igniting fuel droplets in this study. The first, and simplest, method was the use of a pre-ignited match. A series of attempts to ignite a levitated droplet resulted in a disruption of the acoustic field causing the droplet to fall out of suspension. The second technique used was a hot tungsten wire. Although repeated use of a glowing tungsten filament ended with eventual failure of the wire due to oxidation, the filament lasted long enough to observe the same results as those occurring with the lighted match.

The next technique employed a spark generator to pass a discharge through the suspended droplet. A spark gap 0.5 cm wide was created with two electrodes having diameters of approximately 0.05 cm. The electrodes were moved into a position where the gap

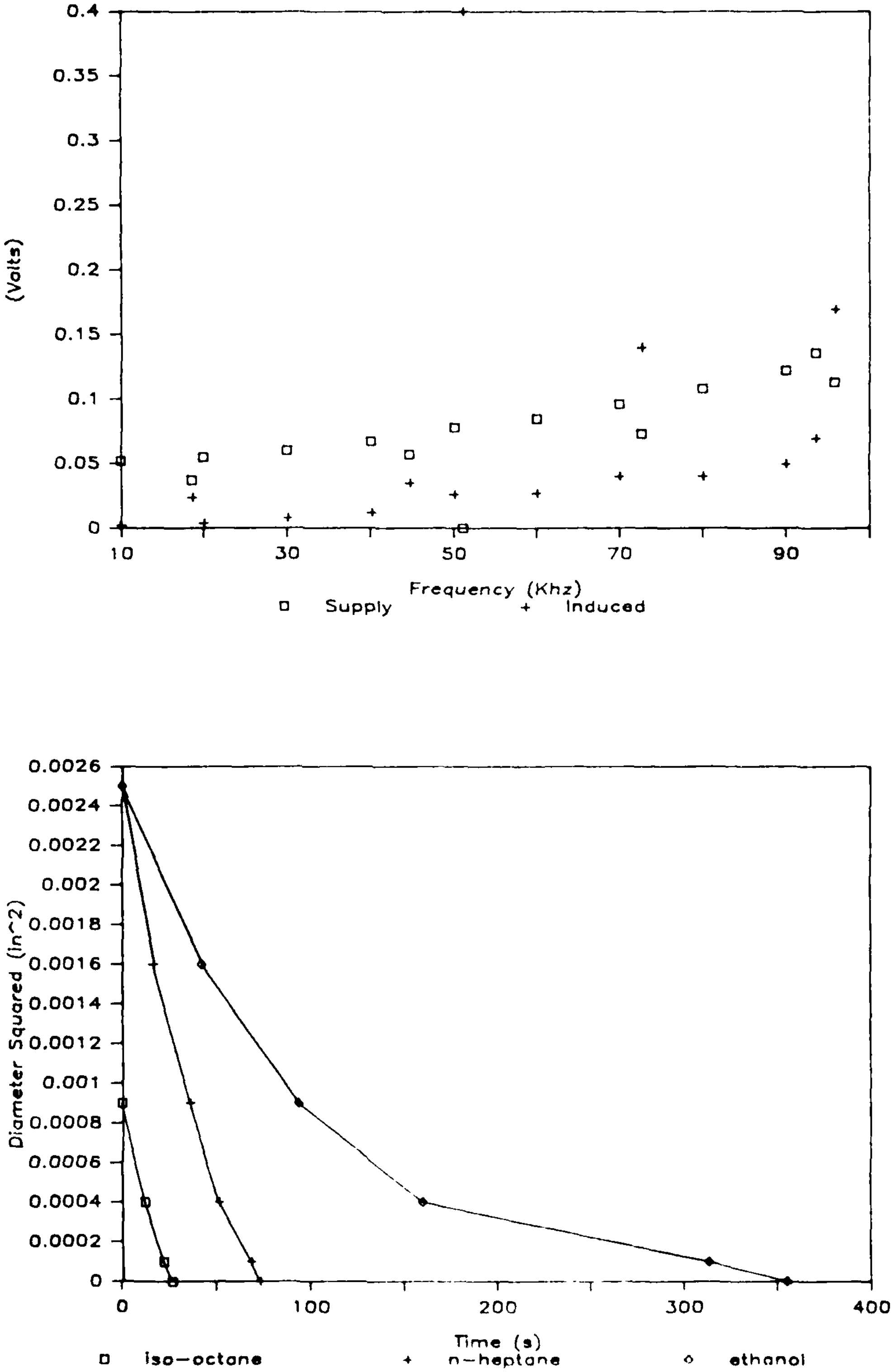
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
(Volts)
10
30
50
70
90
Frequency (Khz)
□ Supply
+ Induced
0.0026
0.0024
0.0022
0.002
0.0018
0.0016
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
0
Diameter Squared (in^2)
0
100
200
300
400
Time (s)
□ iso-octane
+ n-heptane
◇ ethanol

FIGURE 6

TABLE I

Ignition Techniques Studied

Technique	Fuel	Results
Open Flame	n-Hexane	Loss of Suspension
	iso-Octane	Loss of Suspension
		(all ignited on fiber)
Hot Wire	n-Hexane	Loss of Suspension
(Chromel wire)	Ethanol	Loss of Suspension
	Methanol	Loss of Suspension
Hot Wire	n-Hexane	Ignition on Fiber Only
(Tungsten)	Methanol	Ignition on Fiber Only
Spark Discharge	Decane	No Ignition
	n-Hexane	Ignition on Fiber Only
	Ethanol	No Ignition
	Methanol	No Ignition
Excimer Laser	Ethanol	No Ignition
	n-Hexane	No Ignition
CO_2 Laser	Ethanol	Loss of Suspension
	n-Hexane	Loss of Suspension
	Decane	Rapid Evaporation

contained the levitated droplet. A short duration, 25 kV spark discharge was made to jump the gap. A large number of attempts to ignite the droplets were made. Discharges appeared to pass very close to, or even through the droplet with no apparent effect other than to occasionally eject the droplet out of the acoustic field. The reason for the failure of this technique is speculative, but apparently the resonator sound energy inhibits the ignition mechanisms associated with droplet combustion. This problem does not occur with fiber suspended droplets which can be ignited with a discharge.

A fourth technique employed an excimer laser (ArF) to induce a breakdown of the air next to the droplet. The setup is shown in Fig. 7. Sufficient energy was available to disintegrate the droplet when it was in the beam path, or eject the droplet from the acoustic field by shock wave disturbances. At lower energy settings, a laser induced plasma could be observed at the beam focus (a 10 cm focal length lens was used). Using both hexane and ethanol droplets, the location of the plasma was moved to positions above, below, and to the side of the droplet with no apparent effect other than to set the droplet into oscillation. The plasma was even caused to impinge slightly on the droplet which caused violent oscillations or ejected the droplet from the field. No ignition was observed.

The last technique tried was ignition using a CO_2 laser emitting at 10.6 micrometers. The total available power for this experiment was 50 watts, however, much reduced power levels were necessary in order to conduct the experiment. Unfocussed radiation from the laser was used to fully illuminate the droplet from one side. From wavelength considerations, it was anticipated that rapid heating would be available for the experiment. Droplets attached to capillary tubes were first studied. Rapid evaporation could be induced in the attached droplets with some evidence of pyrolysis occurring from smoke generated during the process. No ignition was observed in these

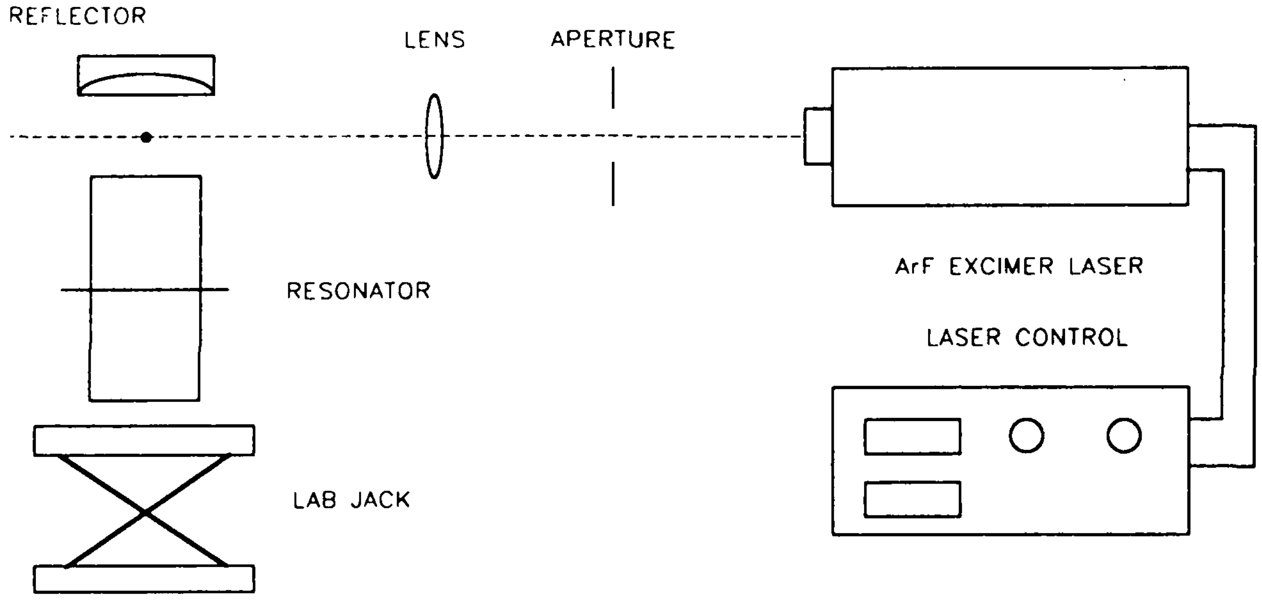
REFLECTOR
LENS
APERTURE
RESONATOR
LAB JACK
ArF EXCIMER LASER
LASER CONTROL

FIGURE 7

preliminary experiments. During droplet levitation, decane remained stable during irradiation. Rapid evaporation was observed with the CO_2 laser output at approximately 2 to 3 watts. Again, some evidence of pyrolysis was observed in the form of smoke. Other liquids such as hexane and ethanol became unstable upon irradiation and fell out of suspension. No ignition was observed during these experiments. Focussing the laser beam was not attempted, neither was use made of CO_2 laser breakdown as a potential ignition source. It was believed that such attempts would not be productive because of the violent nature accompanying plasma formation at a wavelength of 10.6 micrometers.

The final results of the ignition experiments were negative. Although many techniques were explored for their usefulness, no minimum perturbation ignition method was found in this study.

7 CONCLUSION

Piezoelectrically driven ultrasonic resonators were found to be simple in design, construction, and testing. Over a dozen resonator configurations were made and tested for their operating characteristics. Two proved to be especially reliable at levitating droplets and were subsequently employed in vaporization and ignition studies on liquid fuels such as ethanol, n-heptane, iso-octane, and decane. These tests were performed at resonant frequencies of approximately 20 kHz and 50 kHz, the former value being a fundamental resonator frequency and the latter value being a first harmonic. Droplet stability in suspension was not as good as desired for accurate determinations of droplet diameters. However, the stability was more than adequate to test various ignition techniques which included use of a) hot wires, b) spark discharges, c) open flames, d) excimer laser produced air breakdown, and e) CO_2 laser heating. All attempts proved unsuccessful. The reason for this is not known at this time but the effect of the acoustic pressure field on ignition is a key area of concern. Vaporization tests conducted on the droplets demonstrated that the suspending force in the acoustic field is equivalent to approximately a 12 cm/s flow across the droplet. The magnitude of this velocity, although small, could have detrimental effects on the droplet ignition mechanisms.

REFERENCES

1) W.A. Oran and L.H. Berge, Rev. Sci. Instrum., **53**, 851 (1982).

2) A.R. Hanson, E.G. Domich, H.S. Adams, Rev. Sci.Instrum., **35**, 1031 (1964).

3) E.J. Davis, Aerosol Science and Technology, **2**, 121 (1983).

4) R.R. Perron, IEEE Trans. Sonics and Ultrasonics, **SU-14**, 149 (1967).

5) H. Minchenko, IEEE Trans. Sonics and Ultrasonics, **SU-16**, 126 (1969).

6) R.R. Wymark, Ultrasonics, **13**, 251 (1975).

7) M.C. Lee and I. Feng, Rev. Sci. Instrum., **53**, 854 (1982).

8) E.H. Trinh, Rev. Sci. Instrum., **56**, 2059 (1985).

9) A.M. Kanury, "Combustion Phenomena," (Gordon and Breach Science Publishers, New York, 1975), p. 166.

APPENDIX A

VAPORIZATION DATA

1 1/2" RESONATOR tightened to 80 ft-lb
35 volts driving at 20.7 kHz
160 mV acoustic pickup
76.6 F

n-heptane

TIME (s)	DIA (in)
0	0.05
15	0.04
35	0.03
55	0.015
67	0.01
70	0.000

TIME (s)	DIA (in)
-20	0.07
-5	0.06
0	0.05
10	0.04
40	0.025
50	0.02
65	0.01
70	0.000

TIME (s)	DIA (in)
-40	0.08
-23	0.07
-14	0.06
0	0.05
10	0.04
21	0.035
47	0.02
60	0.015
67	0.01

TIME (s)	DIA (in)
-30	0.08
-20	0.07
-10	0.06
0	0.05
31	0.04
49	0.03
69	0.02
80	0.01
88	0.000

TIME (s)	DIA (in)
-15	0.06
0	0.05
18	0.04
36	0.03
45	0.02
65	0.01
67	0.000

AVERAGE VALUES

TIME (s)	DIA (in)
0	0.05
16.8	0.04
36.4	0.03
51.9	0.02
68.8	0.01
73.3	0.000

ethonol

TIME [s]	DIA [in]
-40	0.06
0	0.05
40	0.04
86	0.03
152	0.02
350	0.01
406	0.000

TIME [s]	DIA [in]
0	0.03
45	0.04
130	0.025
209	0.02
318	0.01
345	0.000

AVERAGE VALUES

TIME [s]	DIA [in]
0	0.05
42.5	0.04
94.0	0.03
180.5	0.02
334.0	0.01
375.5	0.000

iso-octane

TIME (s)	DIA (in)
-8	0.04
0	0.03
15	0.02
21	0.01
27	0.000

TIME (s)	DIA (in)
0	0.03
11	0.02
19	0.015
24	0.01

TIME (s)	DIA (in)
-9	0.04
0	0.03
10	0.02
16	0.015
20	0.01
23	0.000

TIME (s)	DIA (in)
0	0.03
14	0.02
24	0.01
28	0.000

AVERAGE VALUES

TIME (s)	DIA (in)
0	0.03
12.5	0.02
22.3	0.01
26.6	0.000

methanol

TIME (s)	DIA (in)
0	0.04
245	0.000

To unstable to make any further measurements

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