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THE UNIVERSITY OF MICHIGAN
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Final Report

AN INVESTIGATION ON THE EFFECTS OF ULTRASONIC ENERGY ON COMBUSTION

Jay A. Bolt
David H. Holkeboer
William Mirsky

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ABSTRACT

This report covers an investigation of the effect of high-intensity sound fields, in the frequency range of 20 kc to 50 kc, on combustion of natural gas and kerosene. It follows a previous investigation by Mirsky[1] which showed that the presence of ultrasonic energy increases the evaporation rate of fuel drops. Three transducers were developed, two of which were applied to combustion processes. It was noted that ultrasonic energy decreased smoke and carbon formation, apparently increased the burning rate, and increased the tendency for flames to be quenched or extinguished.

I. INTRODUCTION

The objective of the project was to study the effect of high-intensity ultrasonic fields on combustion of hydrocarbon fuels. Three frequencies of ultrasonic energy were used: 20, 34, and 50 kc. Both single drops and sprays of kerosene were used as fuels. In addition, some tests were made with natural gas flames.

This work follows a previous investigation by Mirsky[1] of the effect of ultrasonic energy on evaporation of liquid drops. The evaporation rates of single drops suspended in an air stream were studied. It was found that the application of ultrasonic energy increased the evaporation rate by more than 50% in some cases. Because evaporation is intimately involved in the combustion of liquid fuels, it was believed that ultrasonic energy might affect the burning rate of liquid fuel drops and sprays.

The following report is divided into three major sections. The first deals with the problem of producing an ultrasonic field in a flame zone. The second section describes three sound sources that were developed. The test work accomplished is outlined in the third section.

II. SUMMARY

A major part of the effort of this project was directed toward developing transducers for converting electrical energy into ultrasonic energy. The transducers consisted of barium titanate driving elements and some type of device to isolate the elements from the flame and hot gases. Considerable difficulty was encountered in devising a cooling and mounting system that would protect the driving element, insulate it electrically, and still pass a large amount of ultrasonic energy to the combustion zone.

A second major problem was that the strength of the field was greatly influenced by whether the air space was resonant at the operating frequency. It was necessary for the air space to be resonant to secure a field of useful strength. The resonant frequency of the air space is determined by its dimensions and the speed of sound, the latter varying with air temperature.

Three types of transducers were developed. The first was a water-cooled hollow cylinder, which operated at a frequency of about 34 kc. The test section was contained within the cylinder. The second transducer was the plate type, having a flat driving element with a thin cooling jacket on one face. It operated at 50kc, and was cooled with castor oil. It was intended that the test section should be surrounded by four of these transducers, which would be operated simultaneously. However, the plate-type transducers did not produce a sufficiently strong field to be useful. The third type of transducer was air-cooled and consisted of a hollow barium titanate cylinder attached to the end of a solid aluminum bar. The aluminum bar was cut to a length which would be resonant at the natural frequency of the barium titanate cylinder, and the face of the bar opposite the point of attachment was used as the source of sound. This device operated at about 20 kc.

No quantitative combustion results were obtained in this investigation, mainly because the transducers were not effective enough in producing a satisfactory field. However, some qualitative results are shown in later sections of the report by means of photographs. A natural gas flame and a small kerosene flame were subjected to a field. In both cases, the flame lost its orange color and smokiness; there was also a tendency for the flame to be extinguished, probably because of the cold surroundings. The flame length was greatly reduced, indicating an increase in the burning rate. When a kerosene spray was burned in the cylindrical transducer, there was no noticeable effect, however. There is some doubt as to the strength of the field in this case, because of the nonresonance of the air due to the elevated temperature in the test section.

III. THE PROBLEM OF SUBJECTING A FLAME TO AN ULTRASONIC FIELD

The source of ultrasonic energy used for subjecting a flame zone to an ultrasonic field is an electro-acoustic transducer which converts electrical energy from a power oscillator into sound. Figure 1 shows several types of transducers. The transducers were arranged to form the walls of a rectangular or cylindrical duct around the flame; the air and combustion gases pass through this duct. Cylindrical test sections have an advantage for studying single-drop phenomena in that the sound field is focused on the axis of the cylinder permitting a strong field to be attained rather easily. This kind of focusing does not take place in rectangular fields.

The driving elements of the transducers used in this investigation were cylinders and plates of barium titanate, a ceramic material. When properly treated during manufacture, this ceramic becomes electrostrictive, that is, it expands or contracts when subjected to an electric voltage. Because of permanent loss of the electrostrictive property of the ceramic at temperatures above 200°F, it was necessary to cool the ceramic element, both to protect it from the flame and to absorb the internally generated heat of high power levels. Two surfaces of each ceramic element have silver coatings fired on them to serve as electrodes, to which electrical contact was made either by pressure or by soldering. The design of the mount and cooling jacket must be such that these surfaces are electrically insulated from each other to withstand about 200 volts. In addition, the silver coatings erode rapidly when in contact with a liquid coolant because of the effects of cavitation during operation, and therefore must be protected. Considerable effort was expended in developing a cooling system that would satisfy these requirements and still pass a sufficient amount of energy to the flame zone.

The operating frequencies that were used were dictated by the ceramic elements, since it was necessary to operate at one of the resonant frequencies of the elements to secure a reasonably large amplitude of vibration. The transfer of energy from the transducer to air was found to be greatly enhanced if the air space was made resonant to the frequency of the transducer, because under some conditions the acoustic impedance of a resonant air space more nearly matches that of the transducer than does that of free air. The acoustic impedance of the ceramic material is quite high, which means that at a given energy level the amplitude is small. The acoustic impedance of free air, on the other hand, is very much lower. Thus even if the energy level in the ceramic is quite high, the relatively small amplitude of vibration in the ceramic represents a low energy level in the surrounding air. In practice, it was found that the spacing of the transducers was rather critical and had to be almost exactly a whole number of wavelengths to secure resonance and a suitably intense field. Because the wavelength depends on the speed of sound in air, the field intensity was markedly affected by the temperature and hence by the presence of a flame. The cylindrical transducer, incidentally, is so proportioned that the ceramic tube and the air inside of it both resonate at about 34 kc at room temperature; this transducer loses much of its effectiveness at elevated temperatures, where the air space is "out of tune."

IV. TRANSDUCERS

Three types of transducers were developed: cylindrical, plate, and resonant bar types. All these incorporated barium titanate driving elements and were designed to provide a high-intensity sound field in a flame zone. The first two were liquid-cooled and the last was air-cooled. The electrical power source for the transducers was a 400-watt power oscillator.*

A. CYLINDRICAL TRANSDUCER

The cylindrical transducer, shown in Fig. 1, is a modification of the device used by Mirsky[1] in studies on the evaporation of fuel drops. The driving

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*GU 400 Ultrasonic Generator, General Ultrasonics Corp.

element is a barium titanate* cylinder 1-1/2-in. ID by 4-in. long. A sheet of .010-in. brass shim stock was glued to the inner face of the cylinder with "Pliobond" cement to protect it agains erosion.

An annular water passage was formed between the inner face of the cylinder and a 1-1/8-in.-diameter thin-walled copper tube. The ends were closed by caps and sealed with "O-rings." Cold tap water was circulated through the annular space between the cylinder and the tube to act as a coolant. This cooling system was effective enough to permit continuous operation at power levels of 400 watts without damage to the ceramic element. The resonant frequency of this transducer is about 34 kc.

While the cylindrical transducer was quite effective at room temperature, the field obtained at elevated temperatures was rather weak. The decrease in field strength was due to the air space becoming nonresonant because of a change in the speed of sound in air.

Two techniques were used for detecting the presence of a strong sound field. The simpler technique was to suspend a needle on a length of thread in the center of the cylinder; when a field was present, the needle was "grasped" and held in position with noticeable force. The strength of the field may be estimated by noting how strongly the needle is held in place. The second technique was to put a black paper disk dusted with lycopodium powder in the area of the sound field. The powder showed the pattern of nodes when a strong field was present.

The transducer was mounted on a stand (see Fig. 2). A small electric furnace was built for heating the air supplied to the combustion zone, and a "wind tunnel" with fine screens for controlling turbulence was provided.

B. PLATE TRANSDUCER

The plate-transducer apparatus, consisting of four identical plate transducers mounted on a base, is shown in Fig. 3. It was developed to overcome some of the limitations of the cylindrical transducer which preceded it. Specifically, provision was made for varying the spacing of the transducers to permit the air space in the test section to be made resonant at any temperature, which is necessary for a strong field. In addition, it was designed to have a larger test section and to incorporate observation windows which the cylindrical apparatus did not have.

Figure 1 shows two of the transducers. The driving element is a barium titanate* plate approximately 2-1/4 in. by 2-1/4 in. by 1/2 in. and operates at a frequency of about 50 kc. It is cemented to a cooling jacket consisting

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*Ceramic "B," Brush Development Co.

of two 1/16-in. brass plates with a 1/16-in. space between them for coolant. Several cements were tried for this purpose; "Weldwood Contact Glue" was found to be the most satisfactory. This glue joint also acts as an electrical contact for one of the faces of the transducer. Castor oil was found to transmit sound better than water in this transducer and was used as the coolant. A small pump and heat exchanger were assembled to circulate and cool the castor oil.

In developing this transducer, a new means of detecting the sound output was needed because the methods used with the cylindrical transducer were not sensitive enough. It was found that a ceramic plate could be connected directly to an oscilloscope and serve as a microphone provided it was electrically shielded. This "microphone" was used to evaluate the sound-transmitting capabilities of several types of cooling jackets and different cooling media. The sound distribution pattern of a plate transducer is shown in Fig. 4.

In spite of considerable effort, it was not found possible to develop a sound field of sufficient intensity with this transducer. No pattern of nodes could be detected with lycopodium powder, although the bare ceramic plates could be used to produce such a pattern. Consequently, this apparatus was not used for test work.

C. RESONANT BAR TRANSDUCER

The resonant bar transducer was developed as a substitute for the plate transducer. Two of the transducers are shown in Fig. 1. The driving element was a ceramic cylinder identical to that used in the cylindrical transducer; in this case, however, it was used to produce longitudinal vibrations in a solid aluminum cylinder 2 in. in diameter and 5.8 in. long; one end of the aluminum cylinder then served as the source of sound. "Poxy-Weld"* epoxy resin was used for attaching the ceramic to the aluminum. The unit was operated at 20 kc, which was the resonant frequency for both the ceramic element and the aluminum bar. It was supported at a nodal point midway along the length of the aluminum bar.

It was unnecessary to cool the ceramic element, provided a good bond to the aluminum bar was maintained so that efficient energy transfer took place. This apparatus gave a rather strong field initially but the ceramic elements soon lost their activity, probably from being driven too hard, and some of them even fractured during operation. However, some test work was done with this apparatus.

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*Swiss Laboratories, Cleveland, Ohio.

V. FLAME TESTS

Three experiments were carried out in which combustion processes were subjected to an ultrasonic field. In all cases the results are only qualitative, but there are some pronounced differences in the appearance of the flame when a strong field is present.

A small natural gas flame was subjected to the field developed by a pair of resonant bar transducers. The equipment for this experiment is shown in Fig. 5. The spacing between the transducers was adjusted to provide the strongest node pattern in lycopodium powder. The flame, about 1-1/2 in. long, was then introduced; in some cases it was necessary to change the spacing or frequency slightly to obtain a strong field. It was noted that the flame was changed from orange to blue in the region of the ultrasonic field, and tended to blow off from the supply pipe. In some cases the flame lifted from the supply pipe completely and burned at the upper edge of the ultrasonic field. A comparison of the flames with and without the field is shown in Figs. 6 and 7.

Tests were also made using kerosene in the cylindrical transducer. In this case, a simulated liquid drop was made by using a small ball of steel wool on the end of a hypodermic needle. By feeding the kerosene through the needle from below the flame, continuous burning was achieved. When the field was applied, the flame lost its smokiness and turned white, as well as being shortened considerably. In intense fields the flame was extinguished immediately. Figures 8 and 9 show this flame, both with and without the ultrasonic field.

In both of these tests, the flame was sometimes unstable. If the apparatus is adjusted to be resonant with a large flame present, it is not resonant after the field is applied and the flame has shrunk to a small size. That is, the change in the size of the flame changes the temperature of the gases in the test section and therefore the speed of sound, throwing the air space "out of tune." With the air space made nonresonant by the shrinkage of the flame, the field is much weaker and the flame therefore grows to its original size again, whereupon the process repeats itself. The result of this factor is a fluttering of the flame. It can usually be eliminated by a slight change in tuning.

An attempt was made to subject a small burning spray to the field in the cylindrical apparatus. An air-atomizing nozzle from a throat sprayer was used to spray kerosene continuously into the cylindrical transducer where it was burned. The flame was rather large for the purpose, completely filling the test section of the transducer and extending some 6 in. beyond it. No effect of the field was observed. However, it should be pointed out that because of the temperature, the air space was probably nonresonant and the field, therefore, very weak. There was no way to estimate the strength of this field under actual combustion conditions. In addition, the strong portion of the field is confined to a small area near the axis of the cylinder, and thus would affect only a small part of the flame in this situation. Consequently, the negative result that was obtained may well reflect the unsuitable characteristics of the cylindrical transducer, rather than the absence of the influence of ultrasonic energy.

Because all these tests were carried out at room temperature, there was a tendency for the flames to be quenched by the cold surroundings. It is believed that the mixing of cold air into the flame region accounts for the tendency of flames to blow out when the field is turned on.

VI. CONCLUSIONS

Ultrasonic energy has a pronounced qualitative effect on combustion under some conditions. Its effect appears to be similar to that of turbulence, and is characterized by a reduction in flame length, the elimination of smoke, and a change in flame color from orange to white.

It is very difficult to subject a flame zone to an ultrasonic field of high intensity for two main reasons. First, the amount of ultrasonic energy which can be transmitted through a water jacket is limited. It depends on the coolant, the coolant pressure, and the surface; castor oil was the best coolant found. Second, with present techniques, it is required that the air space be resonant at the frequency of the ultrasonic field in order for the field to be suitably intense. However, the flame affects the resonant frequency so much that the desired condition is difficult to produce and maintain.

Barium titanate driving elements were not found suitable for producing high-intensity sound fields in air unless some means of focusing is used as in the cylindrical transducer.

Ultrasonic energy has a definite beneficial effect on combustion, and this phenomenon should be investigated further. The immediate need is for a more effective transducer so that high-intensity fields can be readily generated. A second need is a means of measuring the intensity level of the sound field under test conditions.

VII. SELECTED BIBLIOGRAPHY

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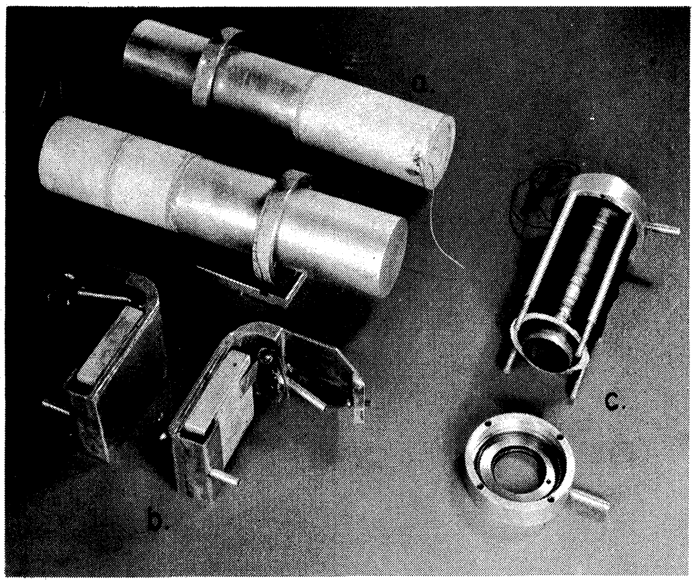

Fig. 1. Ultrasonic transducers developed for use in combustion tests; (a) resonant bar transducers, (b) plate transducers, (c) cylindrical transducer.

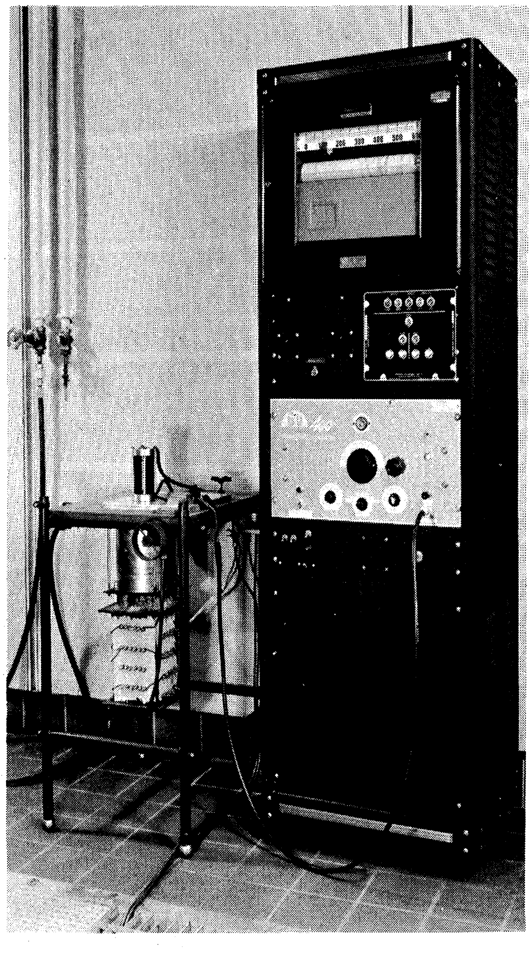

Fig. 2. Experimental setup for tests with cylindrical transducer.

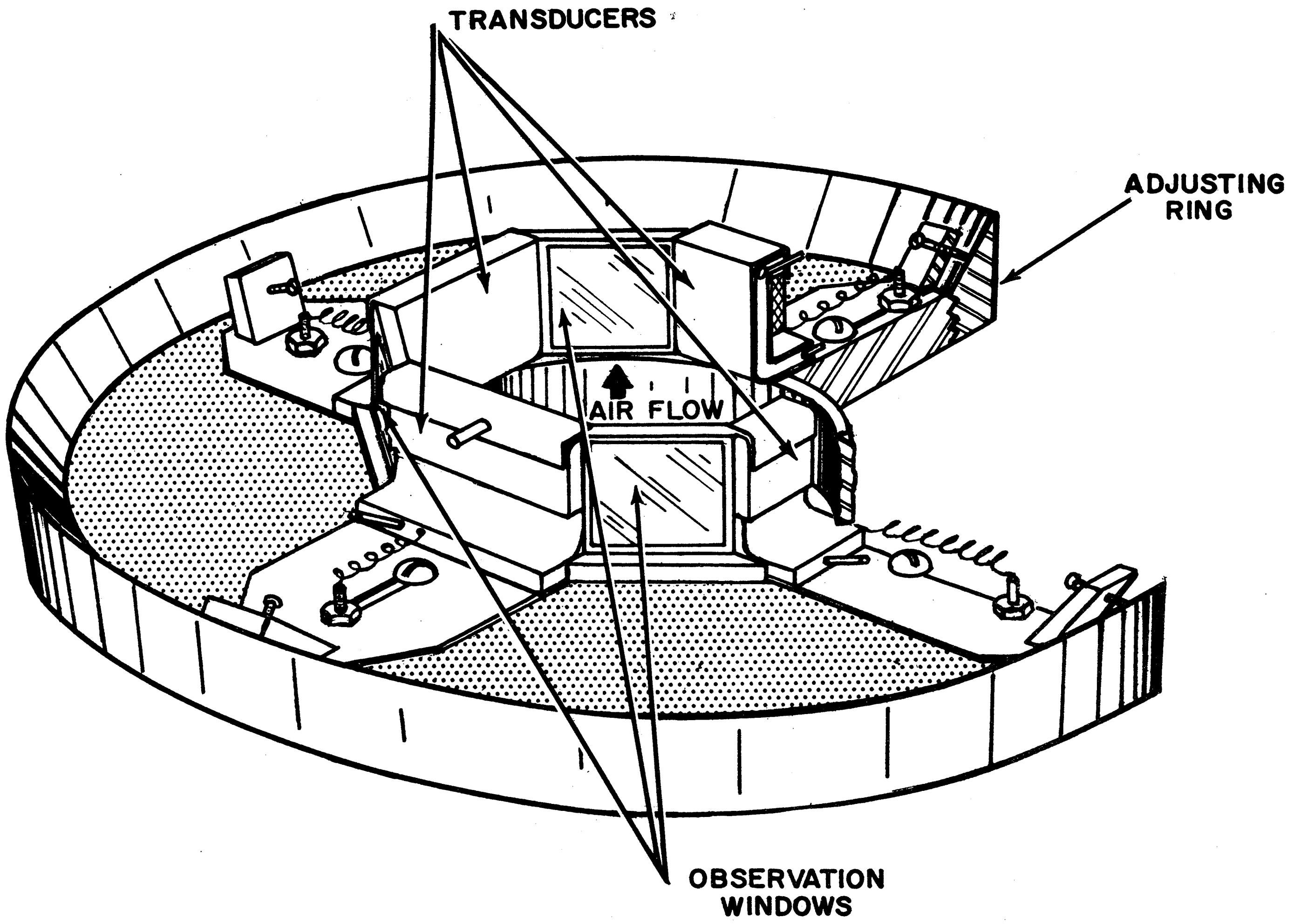

Fig. 3. Plate-transducer assembly.

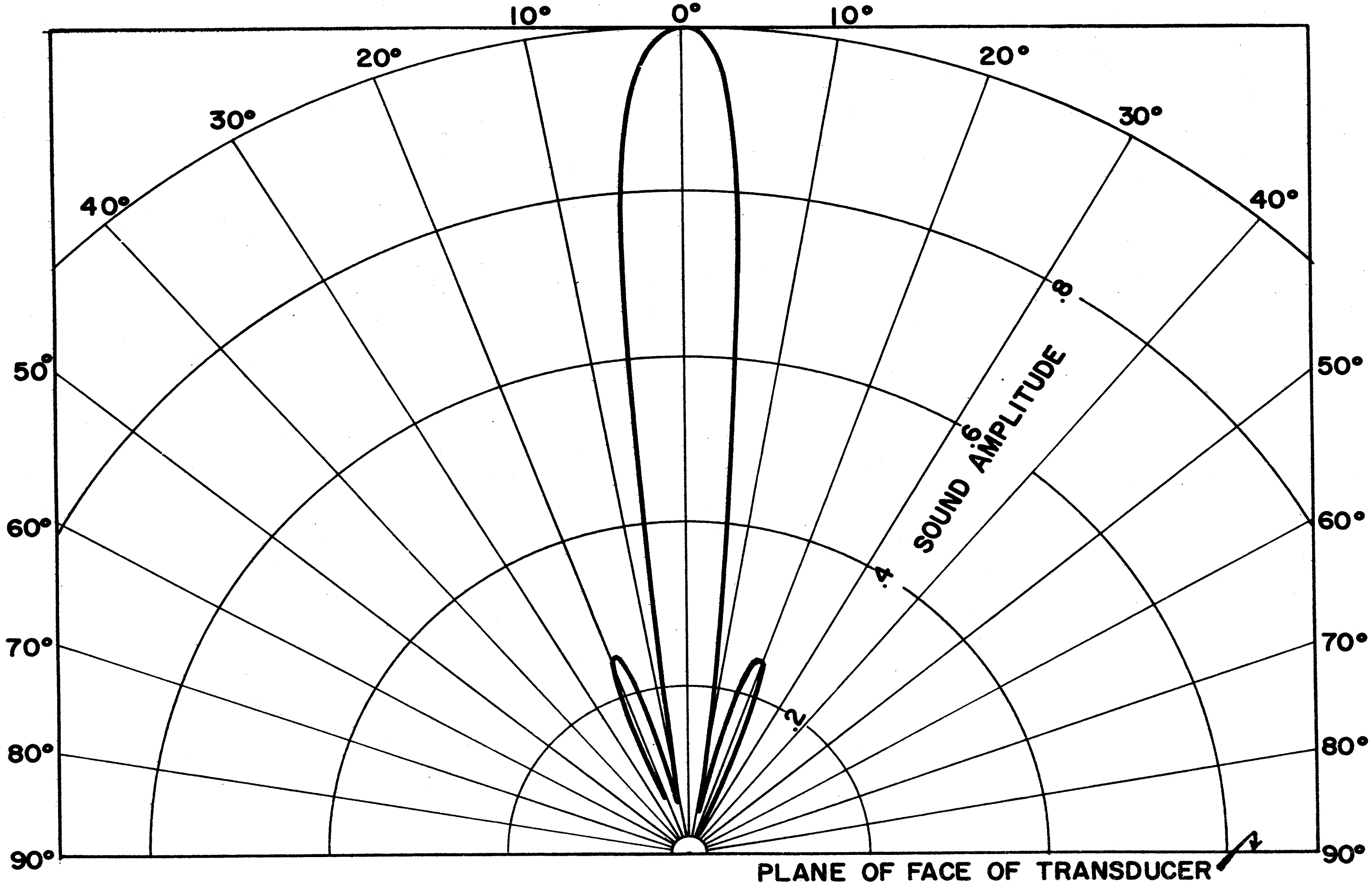

Fig. 4. Field distribution pattern of plate transducer.

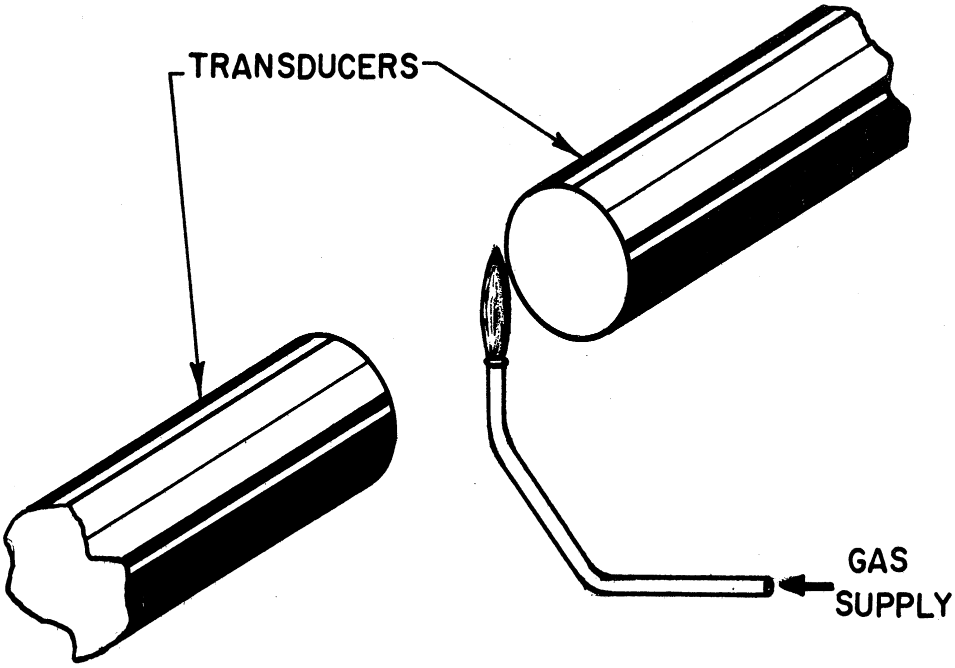

Fig. 5. Experimental setup for gas-flame tests with resonant bar transducers.

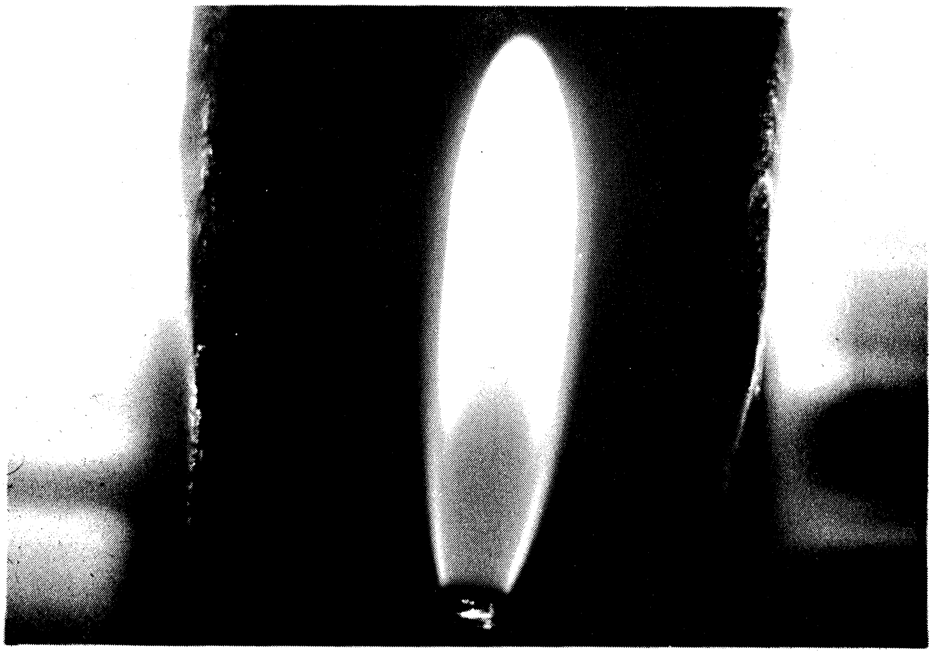

Fig. 6. Natural gas flame.

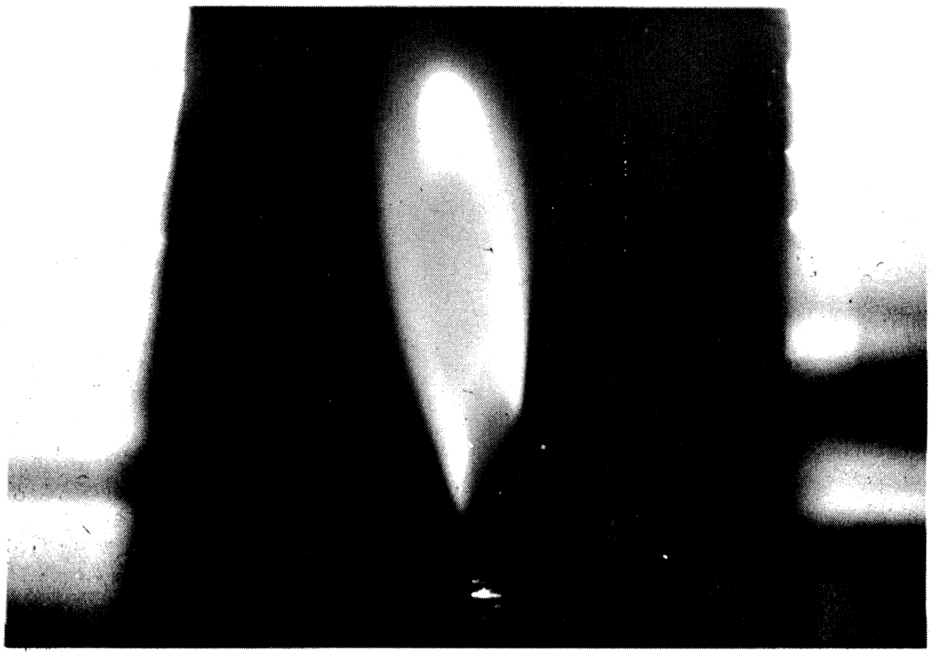

Fig. 7. Natural gas flame in ultrasonic field (resonant bar transducer).

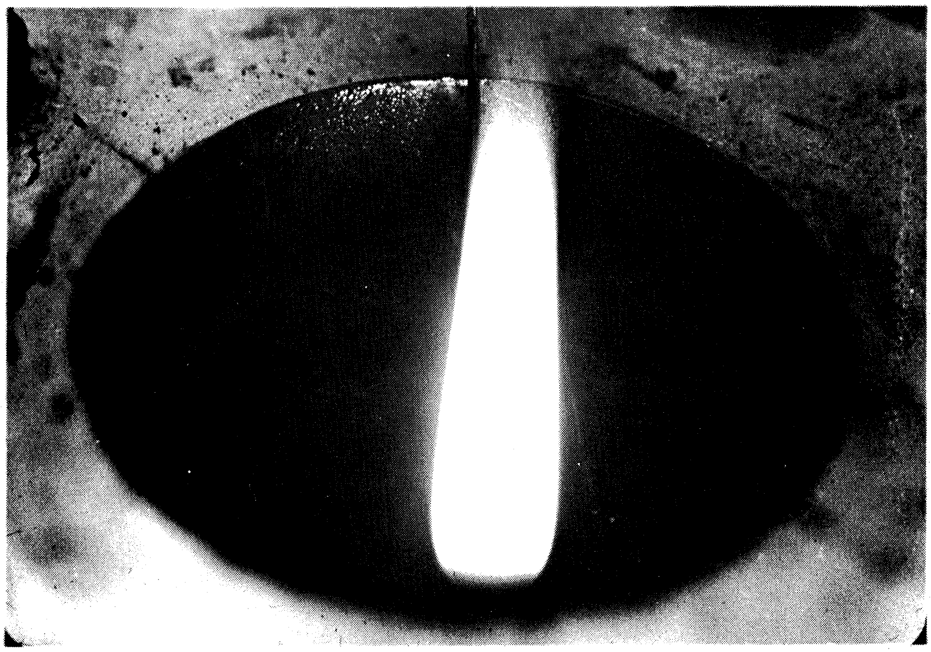

Fig. 8. Kerosene drop flame.

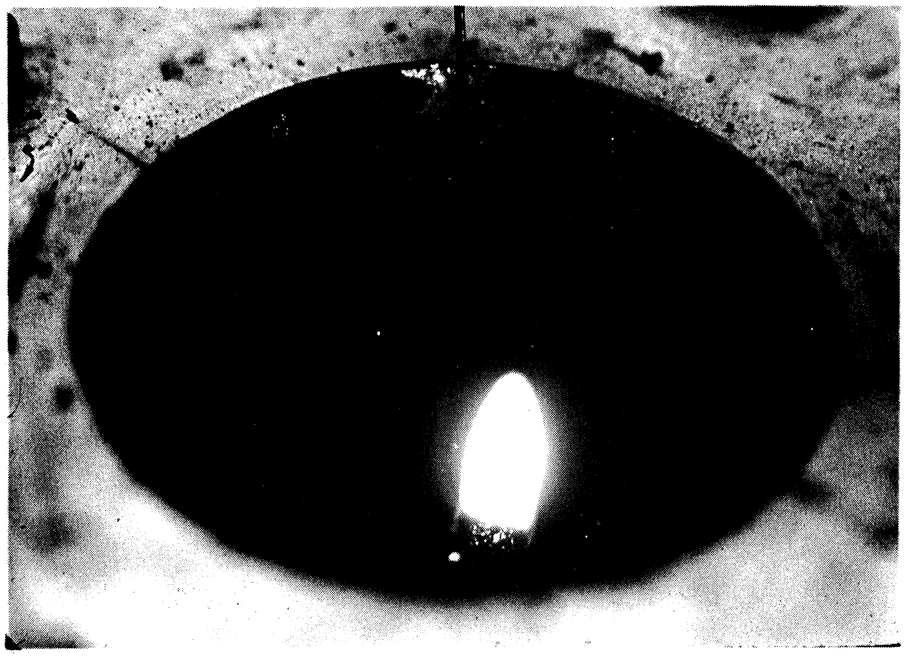

Fig. 9. Kerosene drop flame in ultrasonic field (cylindrical transducer).