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SOME ASPECTS OF THE EVAPORATION RATES OF LIQUID-FUEL DROPS IN A STANDING WAVE ULTRASONIC FIELD

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FOREWORD

This report was prepared by the Engineering Research Institute of The University of Michigan under U. S. Air Force Contract No. AF 33(616)-2436. The work was administered under the direction of the Power Plant Laboratory, Wright Air Development Center, with Mr. J. W. Fulton acting as project coordinator, and was conducted at the University of Michigan under Projects 1988 and 2253-3.

ABSTRACT

This report describes a new technique being developed for studying the evaporation and, possibly, burning rates of free liquid fuel drops. The technique employs air drag and ultrasonic field forces to freely suspend liquid drops in space.

Experimental data for drops suspended from glass filaments in the present apparatus show that evaporation rate is affected by ultrasonic field intensity and frequency, as well as by relative air velocity. For zero ultrasonic field, results for cumene are well correlated by

$$\left(\frac{D}{100}\right)^{1.63} = \left(\frac{D_o}{100}\right)^{1.63} - \left[0.107(V)^{.485} + 0.117\right] t \quad .$$

Results for freely suspended drops show a linear relationship between drop diameter and elapsed time of evaporation.

Recommendations for further improvements and study are given.

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INTRODUCTION

Interest in the combustion process of liquid-fuel droplets has increased considerably since the introduction of the aircraft gas turbine. As a result, numerous investigations have been conducted to determine the combustion and evaporation rates of fuel droplets under a variety of conditions. Because of the complexity of these processes as they exist in a fuel spray, most investigators chose to study the burning or evaporation of single droplets. Of these, some suspended droplets from fine filaments and photographed the stationary drops as they burned,[4,6] while others used pseudo-drops such as flooded solid spheres[8] and flooded porous spheres.[5] Only a few have investigated the combustion or evaporation process in a spray.[1,2,3]

In an attempt to gather additional information, check existing results, and eliminate some of the difficulties introduced by the different experimental techniques, a program of investigation was carried out at the University of Michigan. Three techniques were selected: the first dealt with the combustion rates of droplets in a spray formed by a spinning-disk atomizer,[1,2,9] the second technique involved the study of the combustion rate of a single droplet falling through a hot furnace atmosphere,[7] while the third was concerned with the evaporation rate of a freely suspended droplet in a standing wave ultrasonic field.[1,2]

This report describes the ultrasonic technique for evaporation studies and gives a summary of results obtained for a pure hydrocarbon, cumene.

GENERAL DISCUSSION

The ultrasonic technique is the outgrowth of an attempt to obtain freely suspended droplets, that is, droplets that maintain a fixed position in space by other than mechanical means. The ultrasonic apparatus is capable of doing this by means of vertical air drag forces which oppose the force of gravity and horizontal forces created by the ultrasonic field which stabilize the drop in a fixed horizontal position. The original apparatus has been described in previous reports.[1,2] More recent modifications are briefly described in the section on experimental apparatus in this report.

The advantages sought by the pursuit of such a technique were aimed principally toward the elimination of the filament used for suspending

drops. It was felt that the filament caused unwanted heat transfer, disturbed the air-flow pattern around the drop, distorted the drop shape, limited the lower size range of drops that could be studied, and might possibly have introduced catalytic action in the combustion process. The free-drop technique would allow a continuous photographic record of the complete evaporation process. In addition, the stationary droplet offers the possibility of a critical examination of such factors as fluid circulation in the drop and air-flow pattern around the drop. Furthermore, the droplet is moving at its terminal velocity with respect to the air stream, a situation approximating more closely the condition existing in a combustion chamber than that offered by a fixed drop in still air.

However, experience with the ultrasonic apparatus soon brought to light other equally serious difficulties. Both sound-field intensity and frequency have an effect on evaporation rate. Furthermore, the apparatus in its present form is not suitable to high temperature or combustion experiments. This arises from the temperature sensitivity of the sound-generating element, the barium titanate tube, and the fact that the stationary field is sensitive to changes in air temperature. The latter is due to the dependence of sonic velocity on air temperature.

In spite of these disadvantages, it is felt that there is a possibility the technique will become quite successful after further development. In addition, it introduces the new phenomenon of being able to either increase or decrease the evaporation rate above or below the normal rate by means of the ultrasonic field.

SUMMARY OF PREVIOUS WORK

Previous evaporation data obtained by the ultrasonic technique and described in Reference 2 indicated that free droplets of single constituent fuels evaporating in the standing-wave ultrasonic field maintain a linear relationship between drop diameter and elapsed time of evaporation. This is illustrated in Figure 1 by curve A, taken from Reference 2, which shows a plot of the data obtained for cumene. Similar data were obtained for 13 other pure hydrocarbons, as well as for acetophenone and kerosene. The result for kerosene (Figure 1, curve B) illustrates the effect of the lighter constituents of kerosene in greatly increasing the evaporation rate at the start of the evaporation process.

At the time of the above experiments, some results showed indications that the evaporation rate was being affected appreciably by the ultrasonic field. These results, again taken from Reference 2, are shown in Figure 2. To investigate this phenomenon, additional tests were carried out in an attempt to evaluate these effects. The outcome of these experiments are given in the following sections.

EXPERIMENTAL RESULTS

In order to isolate the effects of the ultrasonic field on evaporation from those due to other sources, it was necessary to obtain the evaporation rate at zero-field intensity. Under this condition the drop could not be freely suspended. Therefore, it was decided to conduct the experiments with droplets suspended on a fine glass filament. This made it possible to vary field intensity and relative air velocity through the range of values used in the tests on freely suspended drops.

EFFECT OF RELATIVE AIR VELOCITY

The first case considered was the evaporation rate at zero sound-field intensity and various relative air velocities. The results are interesting in that they offer a direct comparison with the results of other investigators using the suspended-drop technique.

Drops of cumene were suspended on a glass filament approximately 100 microns in diameter, and these were placed in a vertical air stream of known fixed velocity. During evaporation, photographs were taken at known time intervals to get drop diameter as a function of elapsed time of evaporation. Runs were taken at 11 air velocities ranging from about 0.8 to 8.6 feet per second, as well as at zero velocity. The higher value is the terminal velocity of a 750-micron drop of cumene.

An empirical relationship, given below, was derived from the resulting data and gives close agreement with the experimental results throughout the velocity range.

$$\left(\frac{D}{100}\right)^{1.63} = \left(\frac{D_o}{100}\right)^{1.63} - \left[.107(V)^{.485} + .117\right]t,$$

where

D = drop diameter at time t (microns)
D_o = initial drop diameter (microns)
V = relative air velocity (feet per second)
t = elapsed time of evaporation (seconds) .

Curves from the equation and the corresponding experimental results are shown in Figure 3 for three different velocities. A close check of the curves indicates that the values of the exponent in the above equation may possibly vary slightly with velocity, increasing with a decrease in velocity.

Figure 4 shows the effect of relative air velocity on the evaporation constant λ, where λ is the slope of the linear curve of $(D/100)^{1.63}$ versus elapsed time t. It shows that the greatest increase in effect on evaporation

occurs at the very low air velocities.

EFFECT OF ULTRASONIC FIELD FREQUENCY

The rates of evaporation of drops suspended on a filament were measured as a function of field frequency. Tests were made at a fixed applied voltage and at a range of frequencies on both sides of the critical frequency. Two different relative air velocities were used. The results, plotted in Figure 5, show a large increase in evaporation rate as the frequency approaches a critical value. It is believed that at this frequency the barium titanate tube and the air column within the tube are critically tuned. On either side of the critical frequency the evaporation rate drops quite rapidly and soon reaches values that are lower than those obtained with no sound field present, an effect that was quite unexpected.

Additional tests, the results of which are plotted in Figure 6, show that the critical frequency is a function of relative air velocity. (A hysteresis effect believed due to lack of thermal equilibrium in the barium titanate tube can be noticed.) It is this dependence on air velocity that is presently limiting the usefulness of this technique, since it causes the effect of the ultrasonic field on evaporation to change with relative air velocity and, therefore, with the size of freely suspended drops.

EFFECT OF ULTRASONIC FIELD INTENSITY

By taking evaporation data at critical frequencies, a series of tests was made to obtain the effect of field intensity on evaporation rate of fixed drops. Runs at several field intensities, measured in terms of voltage applied to the barium titanate tube, were made at a fixed air velocity to obtain a series of values for the evaporation constant. Similar tests were repeated for the full range of air velocities. The results show that an increase in field intensity increases the evaporation rate and that the effect is practically constant throughout the velocity range. Figure 7 shows the average increase in λ caused by an increase in applied voltage. The effect is of the same order of magnitude as the effect on evaporation rate caused by changes in frequency.

EVAPORATION RATES - FREE AND FIXED DROPS

Because of the very complex nature of the manner in which the sound field affects evaporation rate, no satisfactory correlation has yet been established between the rates for fixed and freely suspended drops. This

is due largely to the fact that critical frequency varies with relative air velocity (Figure 6). Because of this, and the effect caused by changes in $(f - f_{crit})$, Figure 5, the resultant effect on evaporation rate changes continuously during the tests with freely suspended droplets.

Figure 8 illustrates the manner in which the sound-field effects on evaporation rate vary as a freely suspended drop evaporates. Since the test is made at a fixed frequency, the evaporating drop follows the fixed frequency line a-b. Initially, the drop is at point 1 where $(f - f_{crit})$ is large. Figure 5 indicates that the evaporation rate under this circumstance would be lower than the normal rate (no sound field). As evaporation proceeds, the frequency gradually approaches the critical frequency at point 3 where the rate of evaporation is at maximum. Thereafter, the value of $(f - f_{crit})$ again increases with the resulting decrease in evaporation rate.

If the frequency were set at f_2, the droplet would follow path c-d and would not pass through the critical frequency. In this case, the evaporation rate would decrease throughout the evaporation process.

DESCRIPTION OF APPARATUS

The experimental apparatus, shown in Figures 9 and 10, consists of an air supply, ultrasonic frequency generator and amplifier, camera, camera timer, EPUT (events per unit time) meter, time interval meter, and a small wind tunnel with a barium titanate tube mounted over the exit. A detailed description can be found in Reference 2.

Briefly, the apparatus operates in the following manner. A controlled amount of air is allowed to flow through the wind tunnel and barium titanate tube. The drag force on the drop created by this flow is just enough to balance out the gravitational force. To stabilize the drop laterally, a standing sound field with concentric cylindrical nodes is created within the tube. This is accomplished by impressing a high-frequency voltage across the wall of the barium titanate tube, causing it to vibrate at the impressed frequency. When the impressed frequency matches the resonant frequency of the tube and air column, a standing sound field is generated in the air, within the tube. The droplet becomes stabilized in one of the sound nodes.

With the drop thus stabilized, photographs are taken at fixed time intervals, the timing being controlled by an Air Force Intervalometer, type B-5A. Accurate frequency measurements were made by applying the oscillator signal, used to drive the barium titanate tube, to the input of a Berkley

EPUT meter. This instrument counts the events (in this case, the voltage oscillations) in a given time interval. However, the time interval used in the meter is based on 60-cycle line frequency and was not accurate enough for use in this case. Therefore, the pulses of both the first and six-thousandth oscillations were fed from the EPUT meter to the Start and Stop connections, respectively, of a Berkley time-interval meter. This instrument measures the time interval between two events to within one one-millionth second, the timing being based on an accurately controlled crystal oscillator. The time required for the 5999 oscillations is easily converted to frequency in cycles per second.

CONCLUSIONS

Experimental results with fixed drops in a moving air stream indicate that elapsed time of evaporation is a linear function of $D.^{1.63}$ There is some indication that the exponent increases slightly with decreasing velocity and may approach two for the limiting case of a stationary drop in still air.

Results obtained with drops evaporating in an ultrasonic field indicate that the evaporation rate is affected by the field, the effect being dependent on both field frequency and intensity. The combined action of the ultrasonic field and relative air velocity on the evaporation of freely suspended drops is such as to make elapsed time a linear function of drop diameter.

A correlation between normal evaporation and evaporation within a sound field has not yet been established because of the complex nature by which the sound-field effects are dependent upon such parameters as relative air velocity, field frequency and intensity, and temperature of the barium titanate tube.

It is felt that only a start has been made on a new technique for studying, and possibly controlling, evaporation and combustion of liquid-fuel droplets. Further development is required to gather additional information on the exact mechanism by which the ultrasonic field affects evaporation and to improve the apparatus. Suggestions for possible improvements are:

1. Elimination of the dependence of critical frequency on relative air velocity. It appears that the change in critical frequency is brought about by a change in the temperature of the barium titanate tube which, in turn, is caused by variations in the cooling effect of the air stream at different relative velocities. Insulation from the air stream and temperature control offers a possible solu-

tion. With critical frequency independent of velocity, it appears that the field effect on evaporation would be constant throughout the evaporation process of a freely suspended drop (Figure 7). This would make the task of accounting for the field much easier in the evaluation of the normal evaporation rate at no sound field.

2. Modification of the apparatus to permit operation at higher temperatures. This would involve changes in the configuration of the barium-titanate sound transducer and insulation from the hot-air stream.

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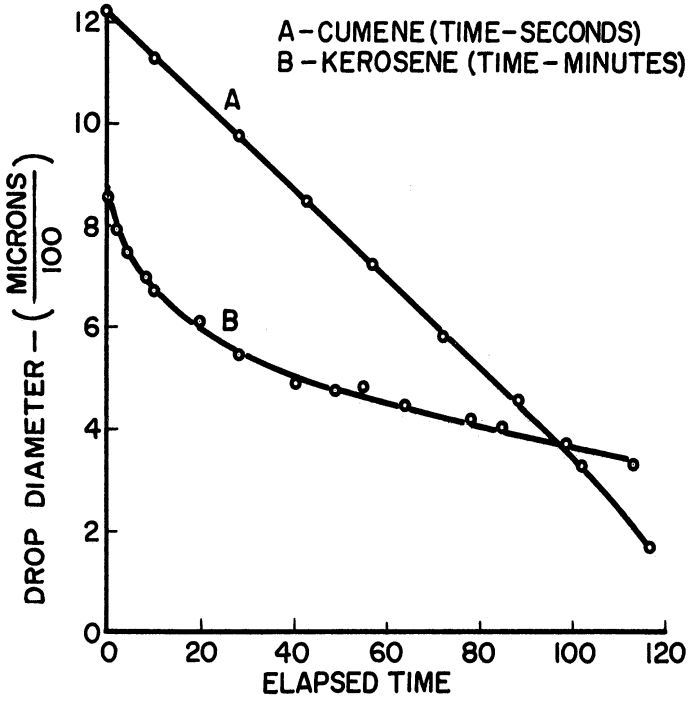

Figure 1. Evaporation of free drops in an ultrasonic field.

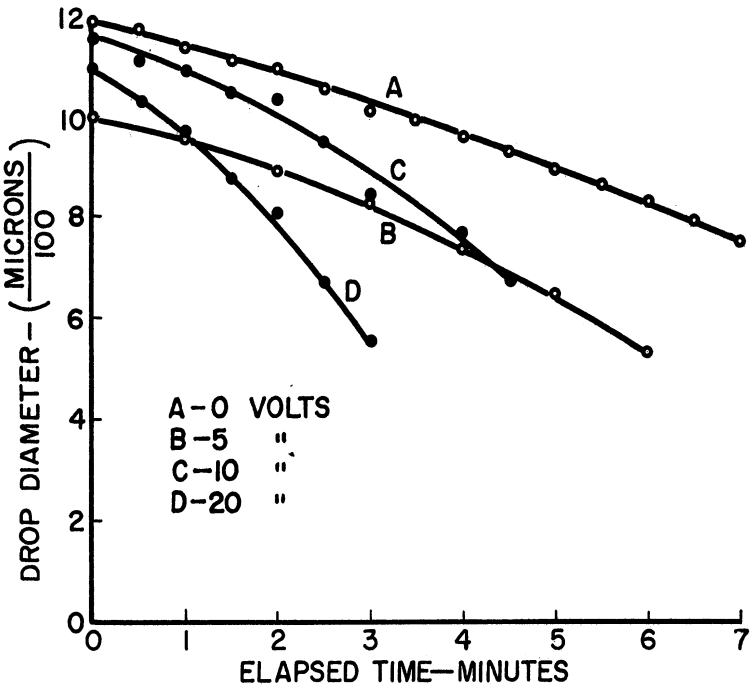

Figure 2. Effect of ultrasonic-field intensity on evaporation of fixed drops (tert-butylbenzene).

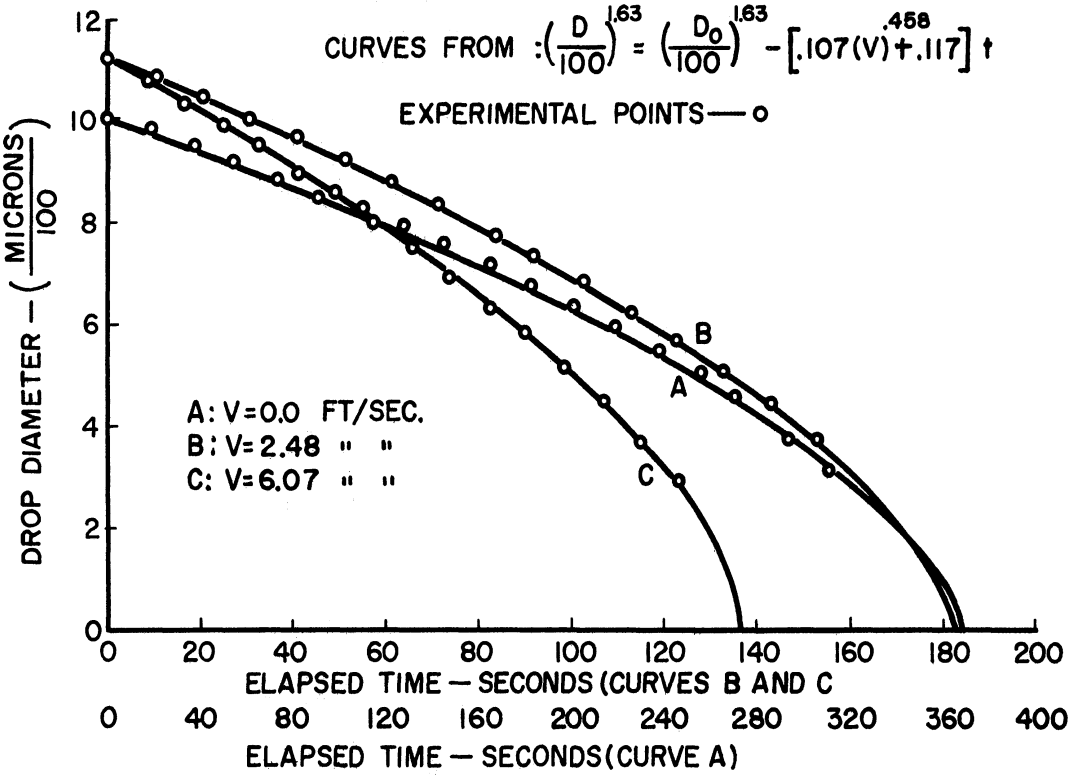

Figure 3. Check of evaporation equation for fixed drops of cumene at three velocities (no sound field).

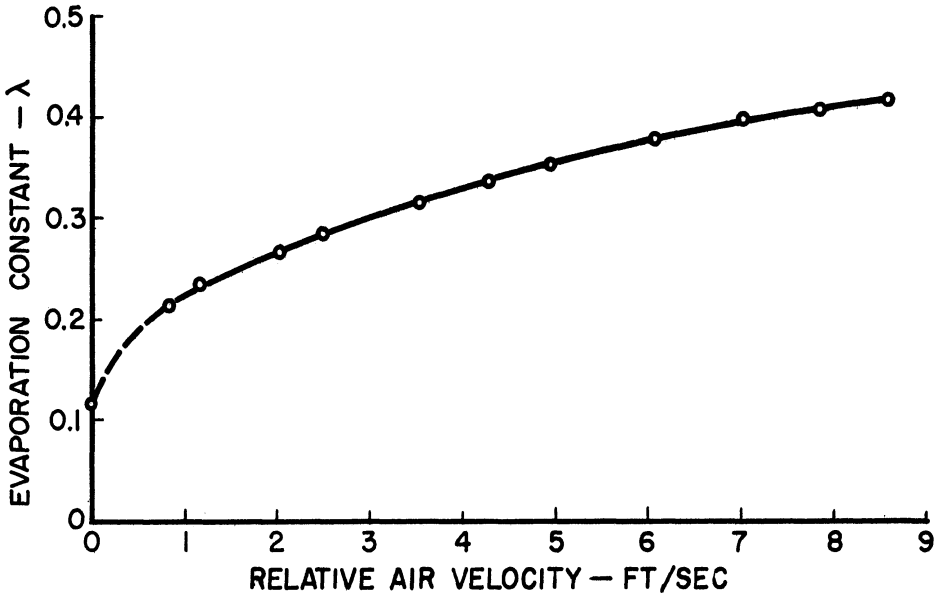

Figure 4. Effect of relative air velocity on evaporation constant for cumene (fixed drop-no sound field).

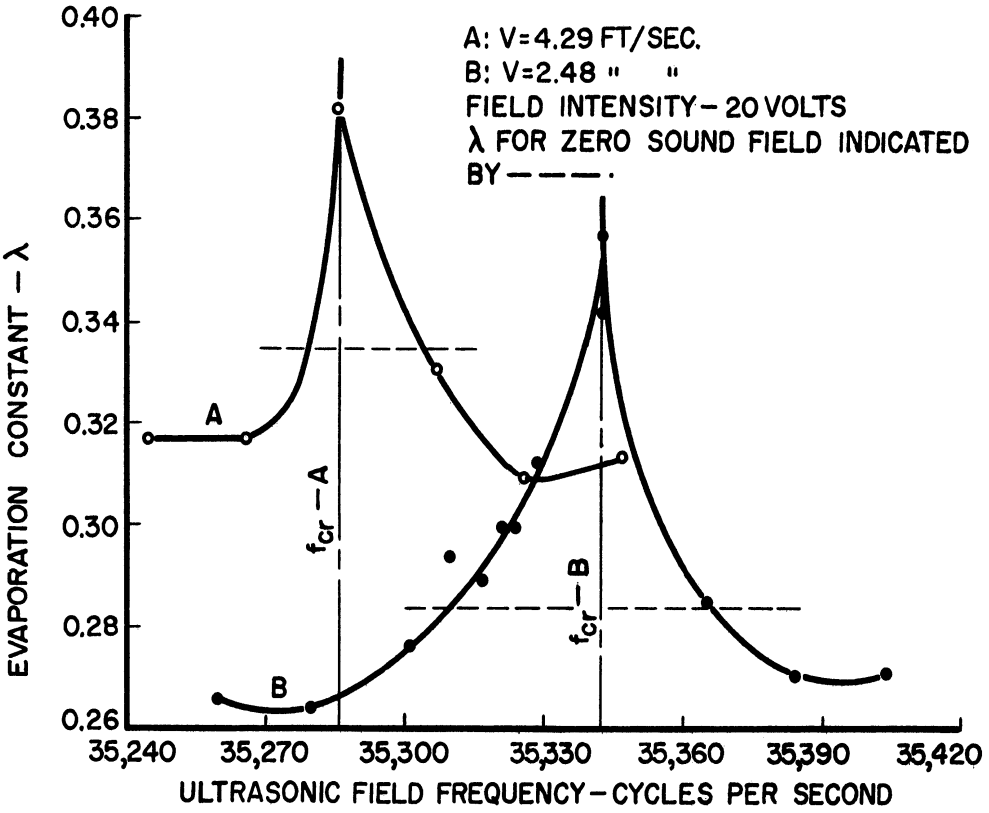

Figure 5. Effect of ultrasonic-field frequency on evaporation constant for cumene (fixed drop).

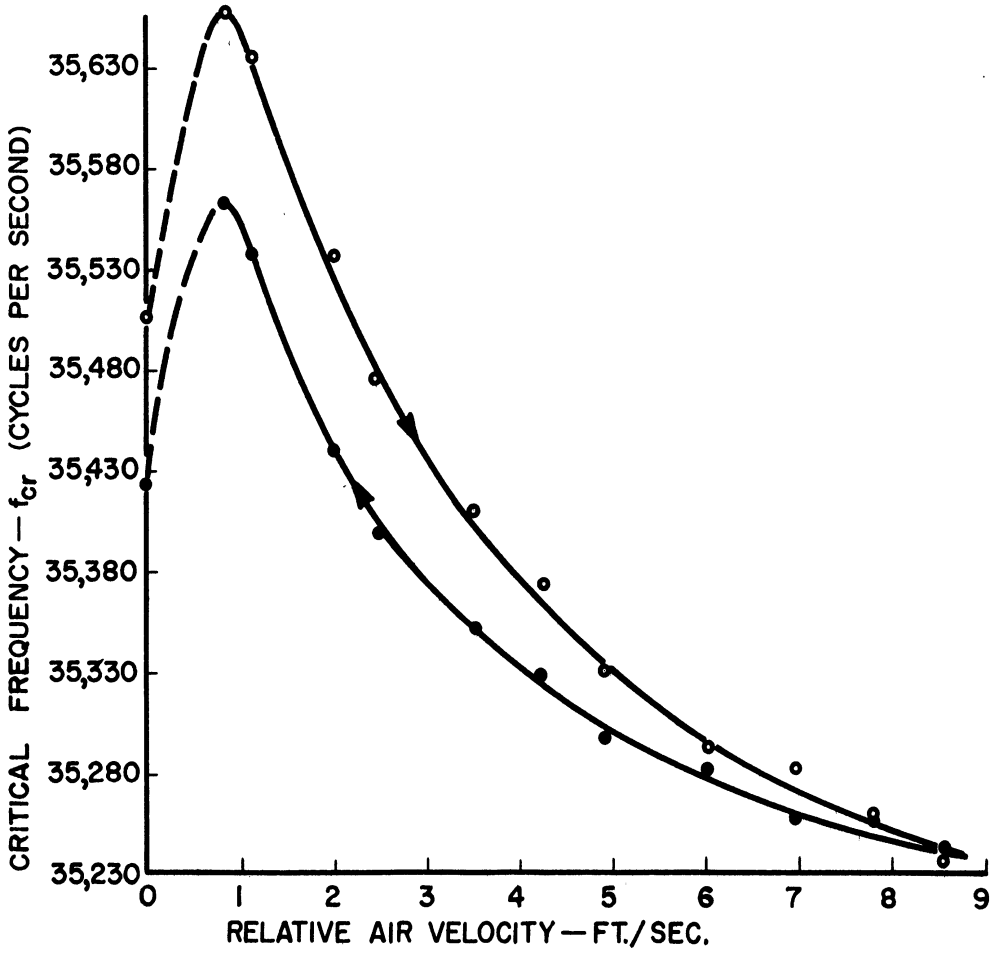

Figure 6. Effect of relative air velocity on critical frequency.

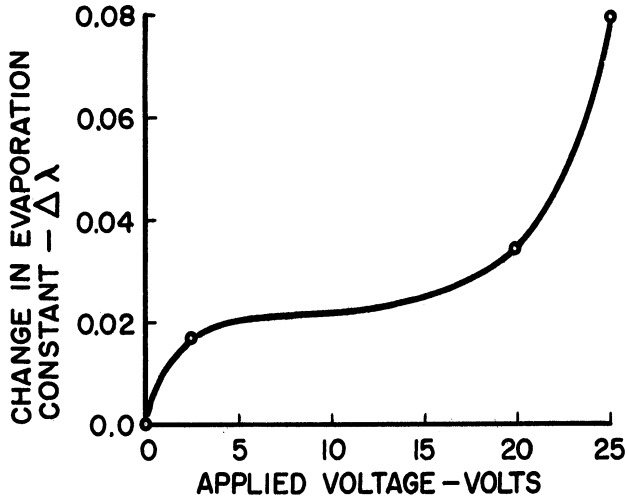

Figure 7. Effect of field intensity (volts) on evaporation constant for cumene (at critical frequency).

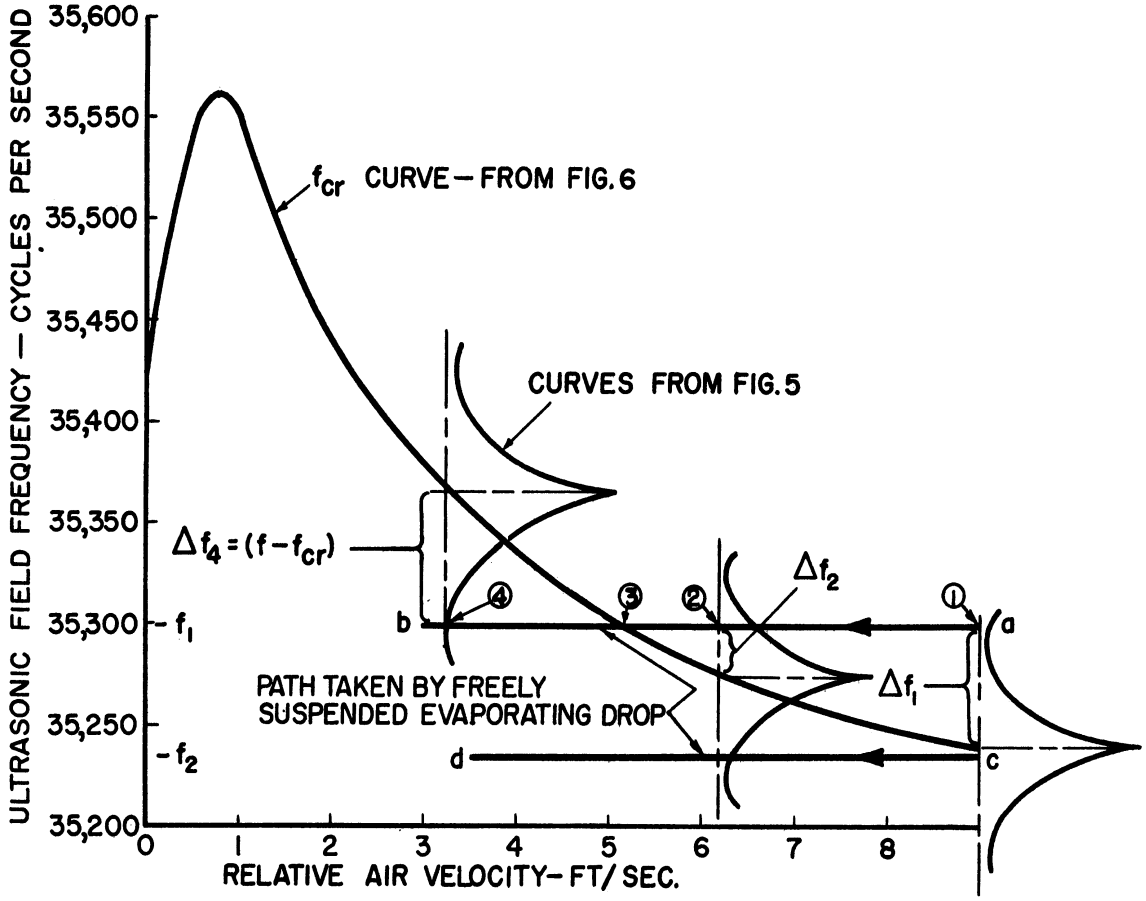

Figure 8. Variations of sound-field effect on evaporation of freely suspended drop at its terminal velocity.

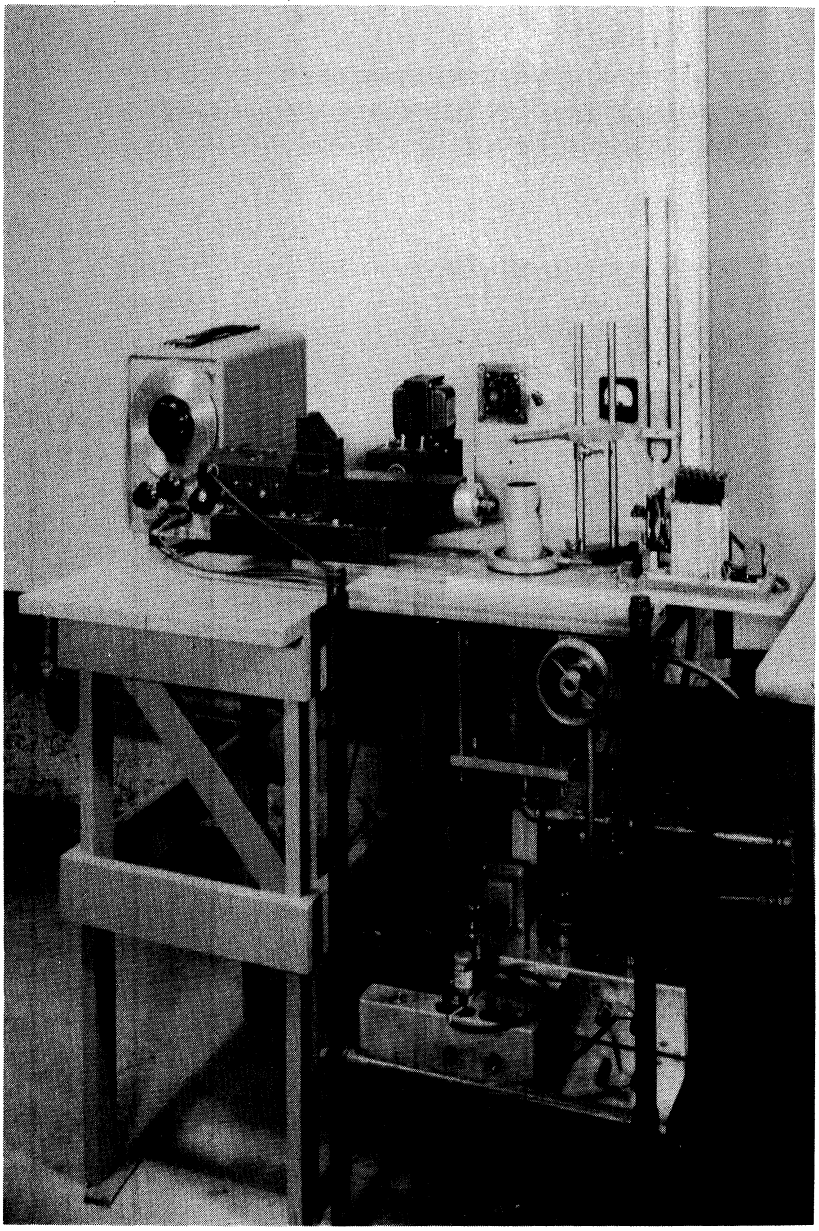

Figure 9. Experimental apparatus.

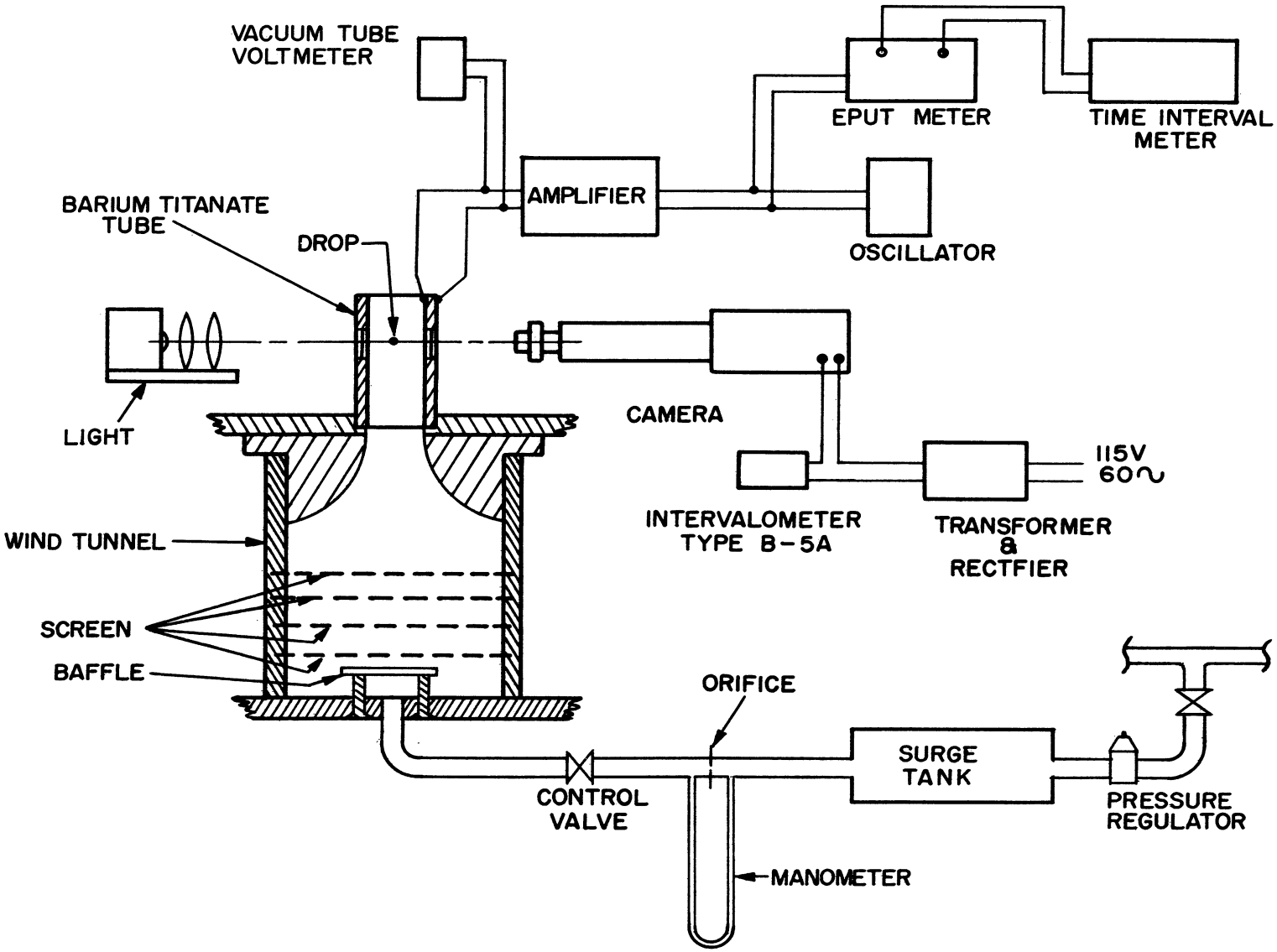

Figure 10. Schematic diagram of experimental apparatus.