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ASPECTS OF MICROWAVE-HEATING UNIFORMITY*

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1. INTRODUCTION

A major objective in the design of microwave-heating systems is the achievement of heating uniformity in the irradiated object. The degree of uniformity depends on many parameters including microwave frequency, source characteristics, material geometry and properties (Okress, 1). Many improvisations are used industrially to achieve desired uniformity (Kashyap, 2). Recently, interest has been shown in the field of nuclear reactor safety in the use of microwave heating to simulate the nuclear heat source (Gabor, 3; Koontz, 4). The objective of the investigation reported here was to evaluate the usefulness of microwave dielectric heating as a simulator of the nuclear heat source in experiments which simulate the process of boiling of molten mixtures of nuclear fuel and steel (Farahat, 5). This paper summarizes the results of studies of several aspects of energy deposition in dielectric liquid samples which are exposed to microwave radiation.

Low-frequency (60 Hz) electrical resistive heating has been employed in simulation studies of volume-heated boiling systems (Gabor, 6; Ginsberg, 7; Greene, 8). Electrical heating, which requires liquid continuity between electrodes, has been used to study the fluid boiling and heat transfer characteristics of volume-heated systems at relatively low power densities. At such low power conditions the flow structure is either bubbly or churn-turbulent (Ginsberg, 7) and liquid continuity is maintained between electrodes. At higher power densities, however, the vapor generated would likely lead to liquid breakup into droplets. When this occurs, liquid continuity between

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electrodes cannot be maintained and energy deposition in the droplets would not be possible. Under these conditions electrical heating becomes inappropriate and an alternate form of heating becomes necessary.

Microwave heating of dielectric liquids is potentially useful in the context of simulation of nuclear heating at elevated power densities. This is based upon the expectation that "reasonably uniform" volumetric heating of a fuel simulant liquid can be achieved with a source of microwave electromagnetic power remote from the fluid being heated. Thus, the need for liquid continuity would be eliminated, and droplets would be heated under these conditions. For practical reasons, the boiling flow simulation is specified to be contained in a bounded radiation environment such as a microwave oven. Figure 1 presents a schematic representation of the boiling fluid in a microwave radiation environment. Volume-boiling systems are characterized by a spatially varying flow structure (Ginsberg, 7). The dielectric properties of the system, therefore, are also space-dependent. Ideally, an appropriately designed microwave power source would provide uniform heating per unit volume of liquid, independent of position, void content and liquid-vapor geometric structure. The uniformity of heating of the liquid phase provided by microwave power is the major focus of this paper.

Ideally, we would like to apply Maxwell's equations, with appropriate boundary conditions to calculate the electric field and, hence, the power density distribution, throughout the entire volume-boiling system. If this could be done then we would use parametric studies to define conditions which would achieve optimum heating uniformity conditions. The literature, however, suggests that on one hand, uniform liquid heating is difficult to achieve in microwave irradiation of homogeneous dielectrics - both in unbounded space and in confined systems such as microwave ovens (e.g., Guy, 9; Guy, 10; Johnson, 11). On the other hand, analytical methods do not exist to enable us to evaluate the power density distributions in heterogeneous two-phase dielectrics exposed to microwave cavity radiation fields.

In the absence of the methods to study the general problem outlined above, an alternative approach was adopted. Two-phase boiling fluids are characterized by a spectrum of liquid-vapor geometric structures. Single-phase liquid structures of order centimeters in dimension, bubbles dispersed in a continuous liquid phase, irregular liquid filaments of millimeter or centimeter scale surrounded by vapor, and liquid droplets of millimeter (or less) size dispersed in vapor, all may simultaneously exist in a single microwave enrvironment. The analytical tools necessary for computation of the power density distribution under these conditions do not exist. Consequently, two distinct problems were studied, with the objective of providing estimates of the extent of power density variation under boiling conditions. These are: (i) analysis of the power density distribution of liquid droplets exposed to the same incident microwave radiation field, and (ii) analysis of the power density distribution across slabs of roughly 100 mm in width, exposed to either single-sided or bilateral, normally incident microwave radiation.

For simulation purposes, it is desirable that the fluid be heated at the same power density independent of fluid element dimensions. A study of the interactions of plane-wave electromagnetic radiation with spheres was performed using classical scattering theory (Kerker, 12; Van de Hulst, 13) to determine the heating efficiency as functions of sphere diameter, dielectric properties and microwave frequency. Results are presented in Section 2.1. An experiment to qualitatively evaluate the calculation results and to study the effect of geometry on the power density of liquid samples exposed to microwaves in a cavity field is described in Section 2.2.

In the second part of the analysis reported here, the power density distribution in slab geometry is considered. It is assumed that slabs of single-phase fluids are irradiated by incident plane waves. The power density distribution is computed for various fluid systems, and compared for heating uniformity. The analysis is described in Section 3.1. An experiment designed to measure the magnitude of the power density distribution in a liquid sample is described in Section 3.2.

The implication of the analyses and experiments with respect to uniformity of heating in volume-boiling systems heated by microwave radiation is discussed in Section 4.

2. HEATING UNIFORMITY OF FLUID SAMPLES AS A FUNCTION OF SAMPLE DIMENSIONS

2.1 Power Density Distribution of Fluid Spheres: Interaction of Microwaves With Spherical Dielectrics

The physics of the absorption and scattering of microwaves by droplets is part of the general theory of scattering of electromagnetic radiation by spherical particles (Kerker, 12). The quantities of interest in a quantitative analysis of microwave absorption is the cross section C_{ABS} and the corresponding efficiency factor Q_{ABS}.

The energy absorption rate is

$$P = \phi_{INC} \cdot C_{ABS} = \phi_{INC} \cdot Q_{ABS} \cdot A \tag{1}$$

and the absorption rate of energy per unit volume (or power density) is

$$Q''' = \frac{P}{V} = \phi_{INC} \cdot Q_{ABS} \cdot \frac{A}{V} \tag{2}$$

To satisfy the objectives of uniform volume heating, independent of liquid geometry, Q''' should be independent of the droplet radius.

The behavior of the quantities Q_{ABS} and Q''' were evaluated as functions of droplet radius for various combinations of wavelengths and materials. The computer code, DILISCA (14), representing a solution to Maxwell's equations in spherical geometry, was used in the study.

The behavior of water as the liquid absorber was investigated over a range of microwave wavelengths and temperatures. Figures 2 and 3 present the results for Q_{ABS} and the dimensionless power density

$$\psi \equiv Q'''(a)/Q'''(a = 5\ \text{cm}) \tag{3}$$

The results indicate that water exhibits a strong dependence of power density on liquid geometry. The power density of water droplets of diameters less than 5 mm is two orders of magnitude lower than for centimeter-scale droplets exposed to the same incident energy flux. In a water system, therefore, uniform heating independent of liquid geometry cannot be achieved in the range of interest.

A series of calculations was performed to determine the range of real and imaginary indices of refraction which would: (i) extend the range of linearity of Q_{ABS} to centimeter-scale radii and (ii) smooth out the resonance region. It was found that smaller real and imaginary indices of refraction than water would lead to these results.

A search for an alternate fluid system was performed. It was found that the dielectric properties of mixtures of polar ethanol and non-polar cyclohexane could be tailored to optimize uniform volume-heating conditions (Westphal, 15). Results for pure ethanol and for a 25-mol percent ethanol solution are presented in Figures 2 and 3. The power density of the ethanol/cyclohexane solution varies by only ±25 percent over a range of droplet radius 10^{-4} cm to 10 cm.

The results suggest that volume-boiling of water by microwave radiation would not provide uniform energy generation per unit volume of liquid, when coexisting liquid structures are widely divergent in dimensions. It is possible, however, to create conditions close to uniform volume heating for dispersed droplet regimes by the appropriate choice of dielectric liquid together with the use of microwaves of a matched wavelength as the heating source.

2.2 Power Density of Simultaneously Irradiated Samples in a Microwave Cavity Field: Experiment

The objective of the experiments was to measure the power density of cylindrical samples of liquid of 10-mm diameter and of variable height, relative to the power density of a fixed geometry volume of liquid. A Litton Model 419 microwave oven, rated at 600 W was used along with two liquid containers. The large container was a thin-walled Pyrex glass beaker of 100-mm diameter. The test liquid was filled to a height of 95 mm in the experiments. The second container was a 10-mm diameter Pyrex cylinder with a flat bottom. This container was filled with test liquid to a height H, which was the primary experimental parameter. The oven and test containers are shown in Figure 4.

An experiment was carried out by first filling the reference beaker with a fixed volume of liquid and the cylindrical tube to a selected height H. The initial liquid levels and temperatures were recorded. The samples were inserted into the oven and the power turned on. The two liquid samples were simultaneously irradiated at constant power for a predetermined time interval. After the power was turned off, the samples were mixed and a final temperature for each of the two containers was recorded. All temperatures were measured with a 1.59-mm (1/16 in.) diameter stainless-steel sheathed, chromel-alumel, grounded-junction thermocouple.

The power densities of the reference and variable-height containers were computed by using an energy balance on the liquid containers together with the measured temperatures and liquid masses. It is assumed that all of the microwave energy was deposited in the liquid and that a negligible fraction was deposited in the glass. It is also assumed that the glass and the water were at the same temperature and that heat losses were negligible. A lumped-parameter energy balance on one of the test containers is

$$Q''' \frac{m_\ell}{\rho_\ell} = \left(m_\ell c_\ell + m_g c_g \right) \frac{\Delta T}{\Delta t} \tag{4}$$

The ratio of the power density of the variable height liquid, Q'''_H, to that of the reference container liquid, Q'''_{REF} is, then,

$$\frac{Q'''_H}{Q'''_{REF}} = \frac{\left[\left(1 + \frac{c_g m_g}{c_\ell m_\ell} \right) \frac{\Delta T}{\Delta t} \right]_H}{\left[\left(1 + \frac{c_g m_g}{c_\ell m_\ell} \right) \frac{\Delta T}{\Delta t} \right]_{REF}} \tag{5}$$

The dimensionless power density given by Eq. (5) was computed from the temperature rise data as a function of H, where H was varied from 1 mm to 95 mm. The variation of power density with H was determined from two test fluids: water and a mixture of cyclohexane and ethyl alcohol of composition 12 mol percent ethyl alcohol.

The results of the experiment are presented in Figure 5. Results are shown for water and for the cyclohexane-ethanol solution. The results closely demonstrate a very strong dependence of the power density on liquid geometry. Order of magnitude variations are observed for water, and an absorption resonance is apparent at approximately H = 40-50 mm.

The results for cyclohexane-ethanol are distinctly different than for water. In general the power density of the 10 mm cylindrical diameter samples are less than for the reference liquid container. The variation in power density is much smaller than for the case of water.

Also shown in Figure 5 are power density ratios computed on the basis of two simplified models. The first is based upon the assumption that the power density is independent of geometry. This is represented by the "uniform power density" curve. This assumption, as shown in Figure 5, is clearly inaccurate. It should be noted, however, that the cyclohexane-ethanol data is more closely characterized by this assumption than is water.

A second model of energy absorption in a microwave oven is based upon two assumptions: (i) the rate of energy absorbed is proportional to the surface area of the sample, and (ii) the incident energy flux is uniform across the surface of the samples under irradiation. Under these assumptions, the ratio of power densities is

$$\frac{Q'''_H}{Q'''_{REF}} = \left(\frac{A_{REF}}{A_H}\right) \left(\frac{V_H}{V_{REF}}\right) \tag{6}$$

Equation (6) is plotted in Figure 5 as the "uniform energy flux" model. This model also clearly does not adequately characterize the data.

The experimental results presented here demonstrate that the power density of samples of liquid irradiated in a microwave oven is not adequately characterized by either the assumption of uniform power density or the assumption of uniform incident energy flux. Rather, the results show that the power density of multiple water samples exposed in a microwave oven is a strong function of sample geometry. The power density of cyclohexane-ethanol solutions is considerably less dependent on sample geometry than is water. These results support the analytical findings of Section 2.1, albeit for a different geometry and for a different radiation environment.

3. POWER DENSITY DISTRIBUTIONS IN SINGLE SAMPLES

3.1 Theoretical Results for Slabs in Plane-Wave Radiation Fields

Electric field distributions were computed for semi-infinite slabs of water and cyclohexane-ethanol solution exposed to microwave radiation at normal incidence, as shown schematically in Figure 6.

Figures 7 and 8 show, respectively, the field intensities (proportional to power density) for single-sided and bilateral irradiation of 100-mm slabs of the two fluids using a microwave wavelength of 100 mm. Strong spatial variations in power density are computed. These are attributed to (i) attenuation across the media, (ii) interference of the incident wave with the internally reflected wave, and (iii) interference, in the bilateral case, of the two incident waves.

Analysis of the problem of bilateral irradiation of a slab with sources of slightly different frequency leads to the conclusion that these standing waves do not develop as a result of interference of the transmitted waves (Ginsberg, 16). If, in addition, the internal reflection at the dielectric boundaries is neglected, then the resulting expression for power density is equivalent to the sum of two decaying exponentials, representing the attenuation of two waves transmitted into the slab from opposite directions, i.e.,

$$\frac{Q'''(x)}{Q'''(0)} = \cosh(2\alpha x) \qquad (7)$$

for $-\frac{1}{2}\ell < x < +\frac{1}{2}\ell$

Figure 9 presents the maximum to minimum power density ratio for irradiation of both water and cyclohexane-ethanol with microwaves of wavelengths $\lambda = 100$ mm and $\lambda = 300$ mm. A range of slab thicknesses up to 300 mm is considered. Both materials are considered to be at their normal boiling points. The results indicate that the attenuation of power density across a slab due to dielectric losses is quite significant for water. The attenuation is, however, significantly smaller for cyclohexane-ethanol.

3.2 Experimental Results for Water in Microwave Cavity Field

An experiment was carried out to measure the spatial variation of power density in a sample of liquid exposed in a microwave oven. A container of liquid was inserted into an oven and irradiated for a fixed period of time. The sample was subsequently quickly removed and a thermocouple rake was inserted into the liquid. The temperatures at several locations in the liquid were measured simultaneously. The power densities at these locations were calculated from the temperature rise of the liquid. It was assumed that heat losses and liquid motion in the test container were negligible. The power density is given by

$$Q''' = \rho_\ell c_\ell \frac{\Delta T}{\Delta t} \qquad (8)$$

where ΔT is the recorded temperature rise for an irradiation period of Δt.

Figure 10 shows the microwave oven, together with the test container, a thin-walled glass beaker, and the thermocouple rake and support rig. Six chromel-alumel, steel-sheathed, grounded-junction thermocouples were used. They are shown in Figure 10 in a staggered array. Most of the experiments, however, were carried out with the thermocouples at the same elevation. The glass beaker was 100 mm in diameter and 100 mm long. It was filled with liquid to a height of 90 mm. Water was used exclusively in this experiment.

An experiment was performed by first filling the beaker with water. The water was irradiated for 30 seconds and was subsequently removed from the oven and placed on the support rig. The thermocouple rake was positioned at the desired location. Temperatures at the six radial locations for a fixed distance below the free surface were recorded. This procedure was repeated for various levels below the free surface.

The experimental data showed variations of temperatures with radial position of, generally, less than 0.5 K. As a result, the radial variation of temperature rise is not considered here. Figure 11 presents the measured temperature rise of the liquid as a function of depth below the free surface. This temperature rise is proportional to the local power density, and is also represented as such in Figure 11. The measured temperature rise varies from approximately 10 K at the bottom of the beaker to approximately 14-18 K near the surface. A sharp temperature gradient is observed in the vicinity of the free surface, and much experimental scatter is also observed.

The power density in the liquid varies by 60% across the height of liquid in the test container. This variation is probably due to the design of the oven, in which the microwave energy is ducted into the cavity through the top surface of the oven. The free surface of the test liquid is directly below the porthole which supplies the microwave energy flux.

4. CONCLUSIONS AND IMPLICATIONS

This section discusses the implications of the prior sections from the point of view of heating uniformity of boiling two-phase mixtures which are heated by a microwave power source.

The two-phase boiling configuration under conditions of microwave heating is expected to be characterized by a spectrum of liquid-vapor geometric structures. Single-phase liquid structure of order centimeters in dimension, spherical bubbles dispersed in a continuous liquid phase, irregular liquid filaments of millimeter or centimeter scale surrounded by vapor, and liquid droplets of millimeter (or less) size dispersed in vapor, all would simultaneously exist in a single microwave environment. The analytical tools necessary for computation of the power density distribution under these complex conditions do not exist. Consequently, two distinct problems were studied with the objective of providing estimates of the extent of power density variation under boiling conditions. First, the effect of liquid geometry on power density was studied in order to determine whether millimeter-size droplets can be heated as efficiently as centimeter-scale liquid masses which are exposed to the same source of radiation. Both analyses and experiments were performed in this portion of the study. Second, the spatial distribution of power density across liquid slabs was studied, in order to determine whether wave interference effects, which lead to severe power density gradients, can be minimized by choice of suitable dielectric liquids. The above analyses were carried out for a variety of wavelengths within the microwave radiation band, for several dielectric liquids and for a range of temperature. Plane wave irradiation was assumed in all casses.

The studies characterized above led to the following conclusions:

(i) Water droplets in the millimeter size range absorb 1-2 orders-of-magnitude less energy per unit volume than centimeter-scale droplets exposed to the same source of radiation. The reason for this behavior is that the Rayleigh scattering regime extends only out to millimeter droplets. Laboratory experiments were performed which qualitatively support this conclusion.

(ii) Mixtures of polar and non-polar liquids, such as cyclohexane-ethanol solutions, extend the Rayleigh regime to centimeter radii, and provide reasonably uniform droplet power density over the range of interest. A 25 mol percent ethanol solution is a suitable dielectric liquid from the standpoint of uniform droplet heating.

(iii) Standing waves are generated within slabs due to interference of transmitted waves and of internally reflected waves. These standing waves are partially responsible for the power density distributions computed across the slabs. The choice of fluids does not significantly alter this conclusion.

(iv) Laboratory tests in a microwave oven did not demonstrate the effects of standing waves. They did, however, reveal a substantial variation in power density across a volume of water.

It is concluded that the use of microwave heating for simulation of uniform nuclear heating in a two-phase boiling fluid is not straightforward. The results of the study, however, suggest that it may be possible to choose a test fluid with a smaller index of refraction than water together with a microwave source of matched frequency which will lead to reasonably uniform heating of dispersed droplets, independent of droplet size. Elimination of standing waves within the boiling fluid may also be possible using impedance matching principles.

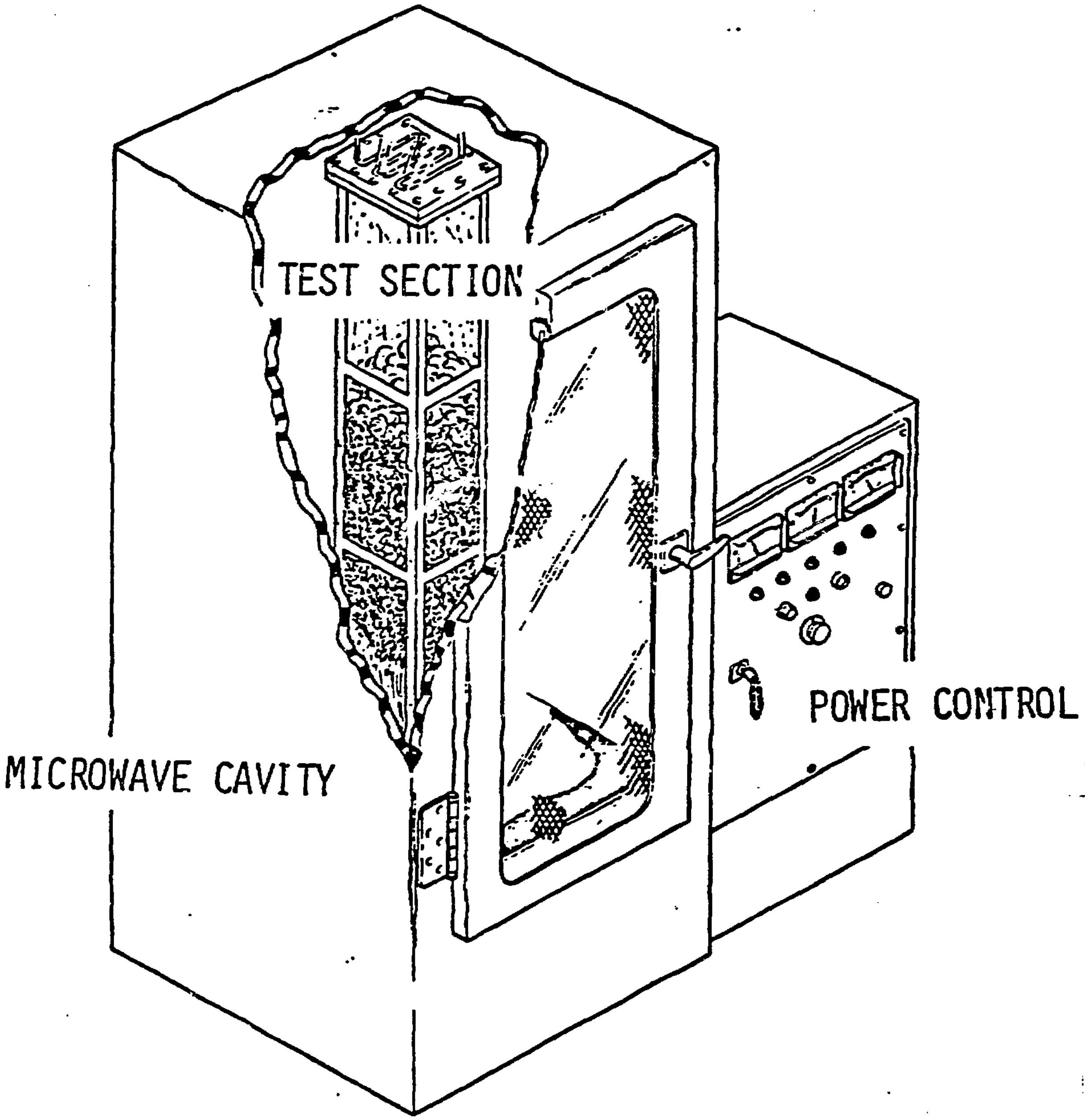


Figure 1 Schematic of boiling fluid in microwave cavity field.

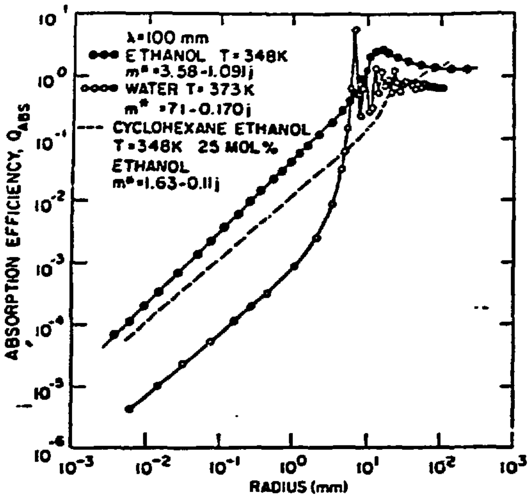


Figure 2 Absorption efficiency for pure ethanol and for 25 mol% ethanol spheres compared with water spheres.

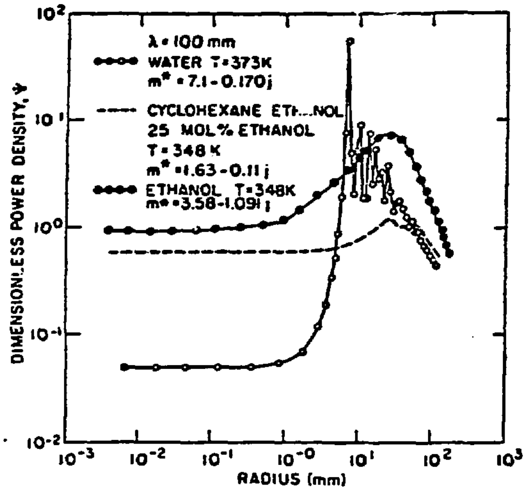


Figure 3 Power density for pure ethanol and for 25 mol% ethanol spheres compared with water spheres.

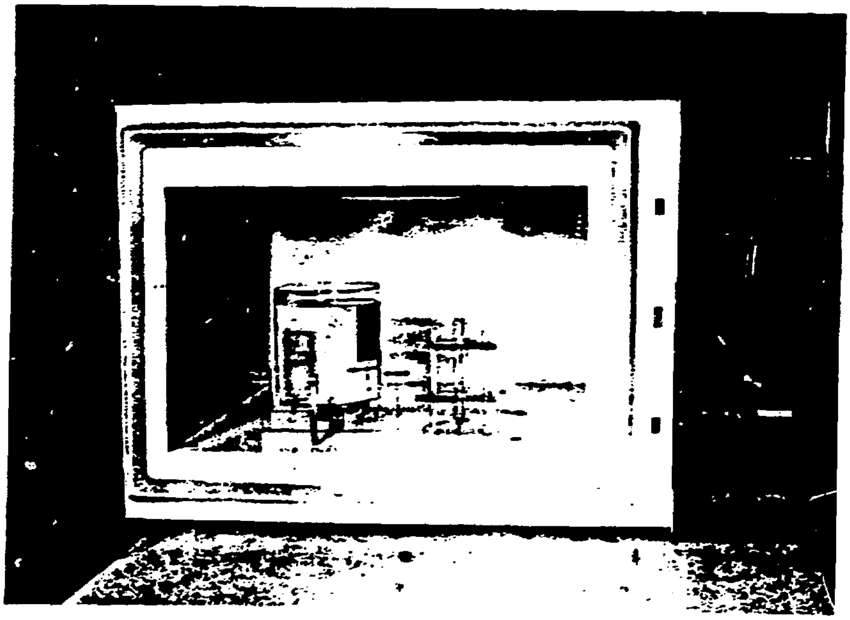


Figure 4 Photograph of microwave oven and sample test containers. (BNL Neg. No. 12-606-80)

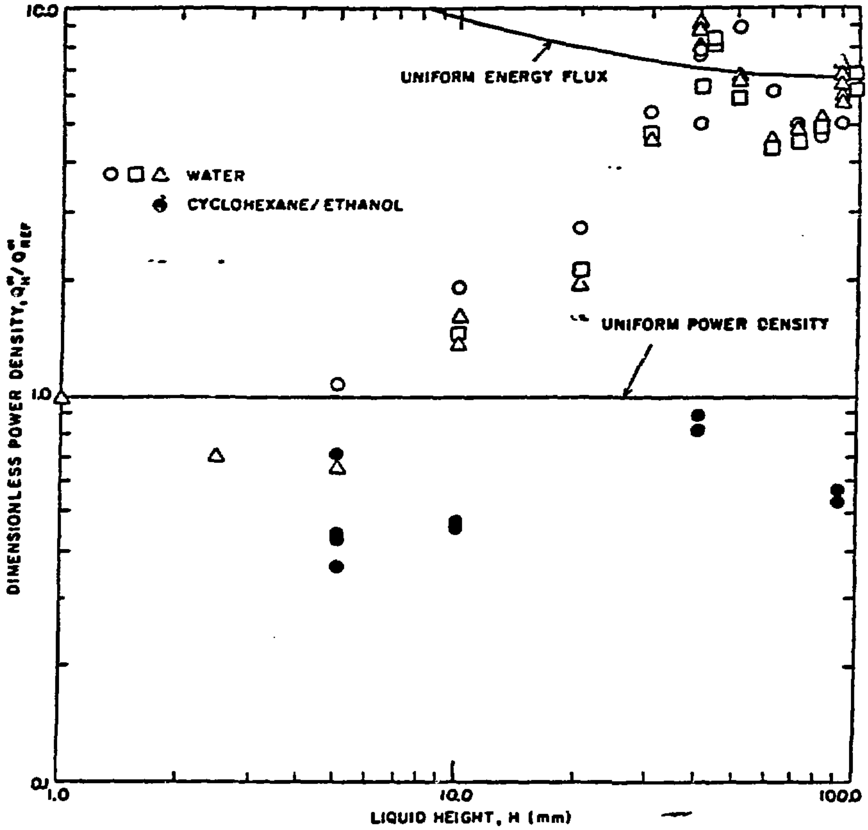


Figure 5 Dimensionless power density of liquid samples vs liquid height. (BNL Neg. No. 12-810-80)

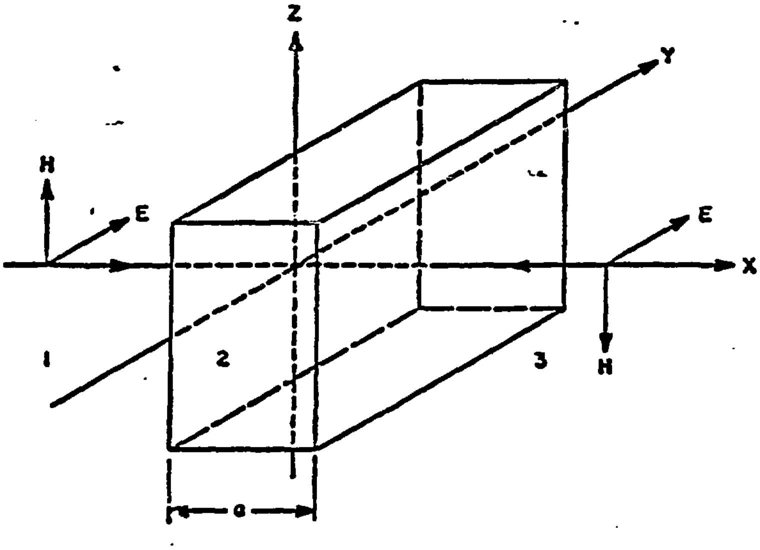


Figure 6 Schematic of slab exposed to plane wave normally incident radiation. (BNL Neg. No. 11-533-79)

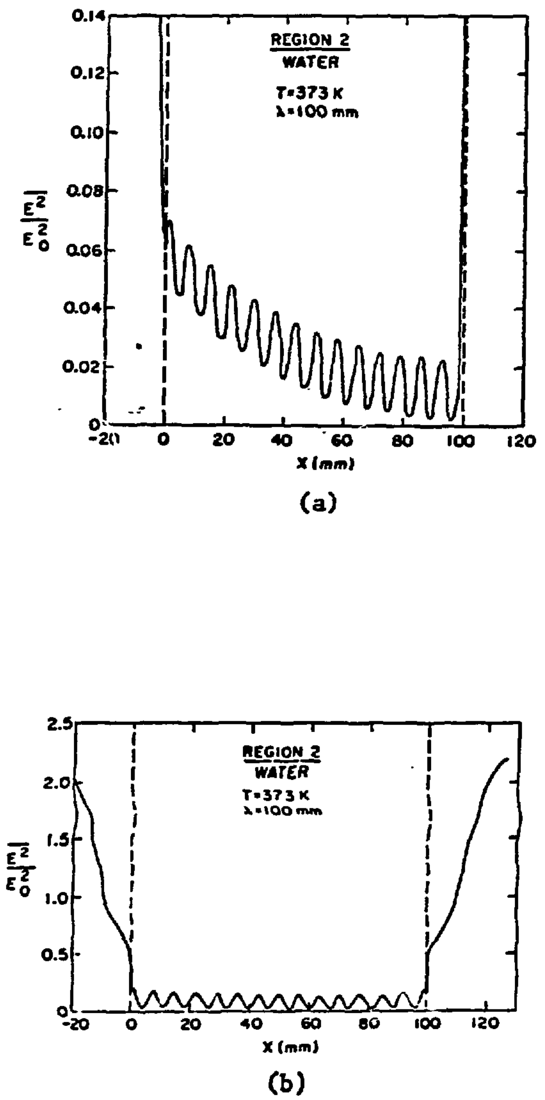
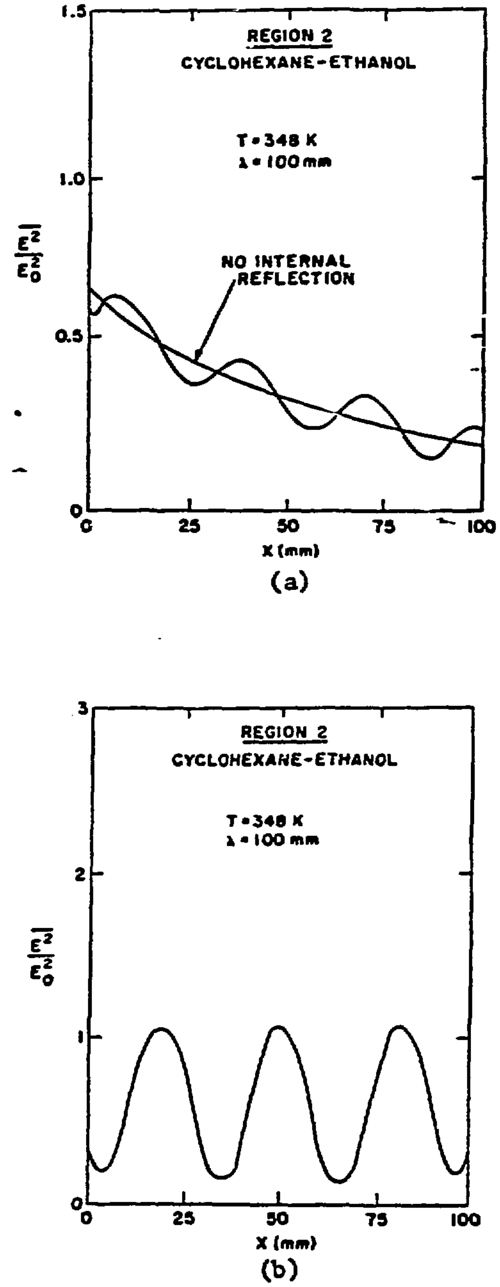


Figure 7 Electric field distribution in 100-mm water slab with single-sided (a) and bilateral (b) incident radiation: λ = 100 mm. (BNL Neg. No. 12-826-80)



(a)

(b)

Figure 8 Electric field distribution in 100-mm cyclohexane-ethanol slab with single-sided (a) and bilateral (b) incident radiation: λ = 100 mm. (BNL Neg. No. 12-830-80; 12-834-80).

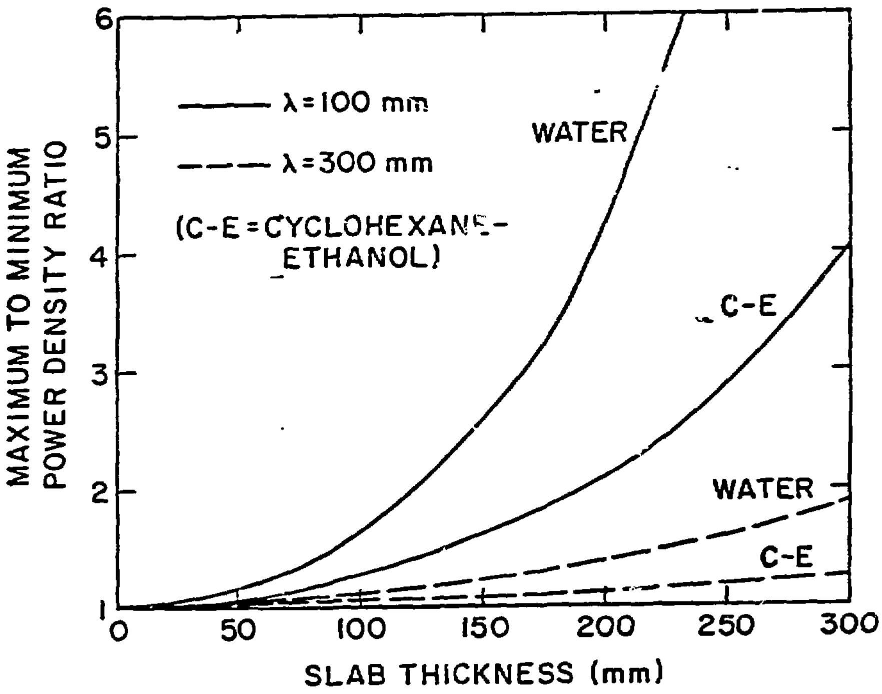


Figure 9 Maximum-to-minimum power density ratios for water and cyclohexane-ethanol slabs with no internal reflections: λ = 100 and 300 mm. (BNL Neg. No. 12-813-80)

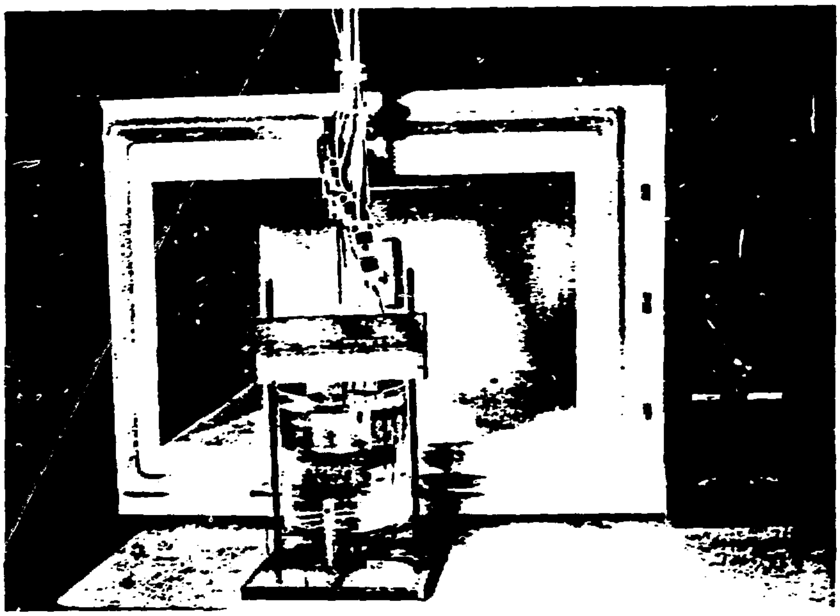


Figure 10 Photograph of oven, test container and temperature rake used in power density experiments. (BNL Neg. No. 12-609-80)

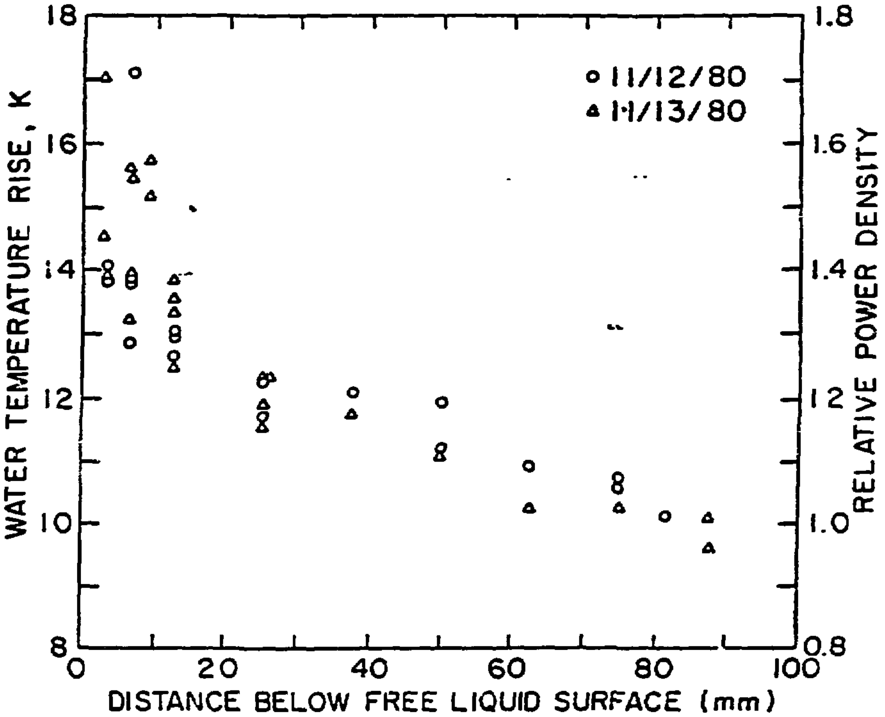


Figure 11 Measured spatial variaton of power density in test container. (BNL Neg. No. 12-817-80)

NOMENCLATURE

a = droplet radius
A = droplet frontal area
A_H = surface area of variable-height container
A_{REF} = surface area of reference container
c_g = specific heat of glass
c_ℓ = specific heat of liquid
C_{ABS} = absorption cross section
ℓ = slab thickness
m_g = mass of glass
m_ℓ = mass of liquid sample
P = energy absorption rate
Q_{ABS} = absorption efficiency factor
Q''' = volumetric absorption rate
Q'''_H = power density of liquid in variable-height container
Q'''_{REF} = power density of liquid in reference container
t = time
T = temperature
V = volume
V_H = volume of liquid in variable-height container
V_{REF} = volume of liquid in reference container
x = coordinate in slab geometry

α = electric field attenuation coefficient
λ = electromagnetic wave length
ρ_ℓ = liquid density
ϕ_{INC} = incident energy flux
ψ = dimensionless power density

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