

[54] **MICROWAVE CHAMBER HAVING
ENERGY DENSITY CONTROL SYSTEM**

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[58] Field of Search **219/10.55; 324/95, 106;
73/190, 193, 355**

[56] **References Cited**

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[57] **ABSTRACT**

A microwave treating chamber is disclosed which includes a monitor for determining the average energy density of the microwave field within the chamber and a feedback control system which responds to the monitor by maintaining the energy density within the chamber constant. The monitor includes a duct which extends a substantial distance through the chamber and through which water is passed at a constant rate. Thermistors in the duct on opposite sides of the chamber measure the total thermal energy imparted to the water by the radiation within the chamber. This total energy gain provides a precise indication of the average energy density along the path of the duct of the microwave field. An electrical feedback loop from the monitor is included for controlling the intensity of the radiation fed to the chamber in order to maintain the energy density constant.

7 Claims, 3 Drawing Figures

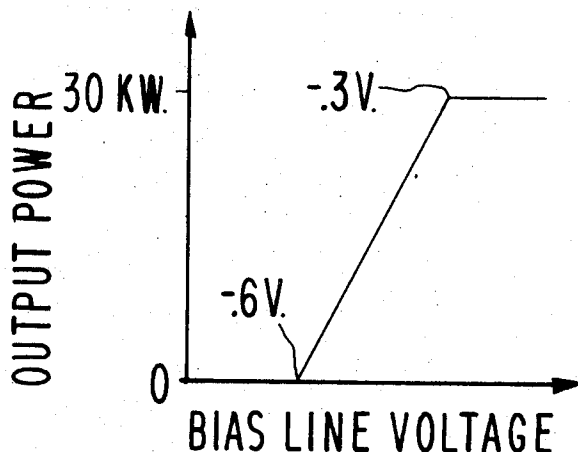


FIG. 1

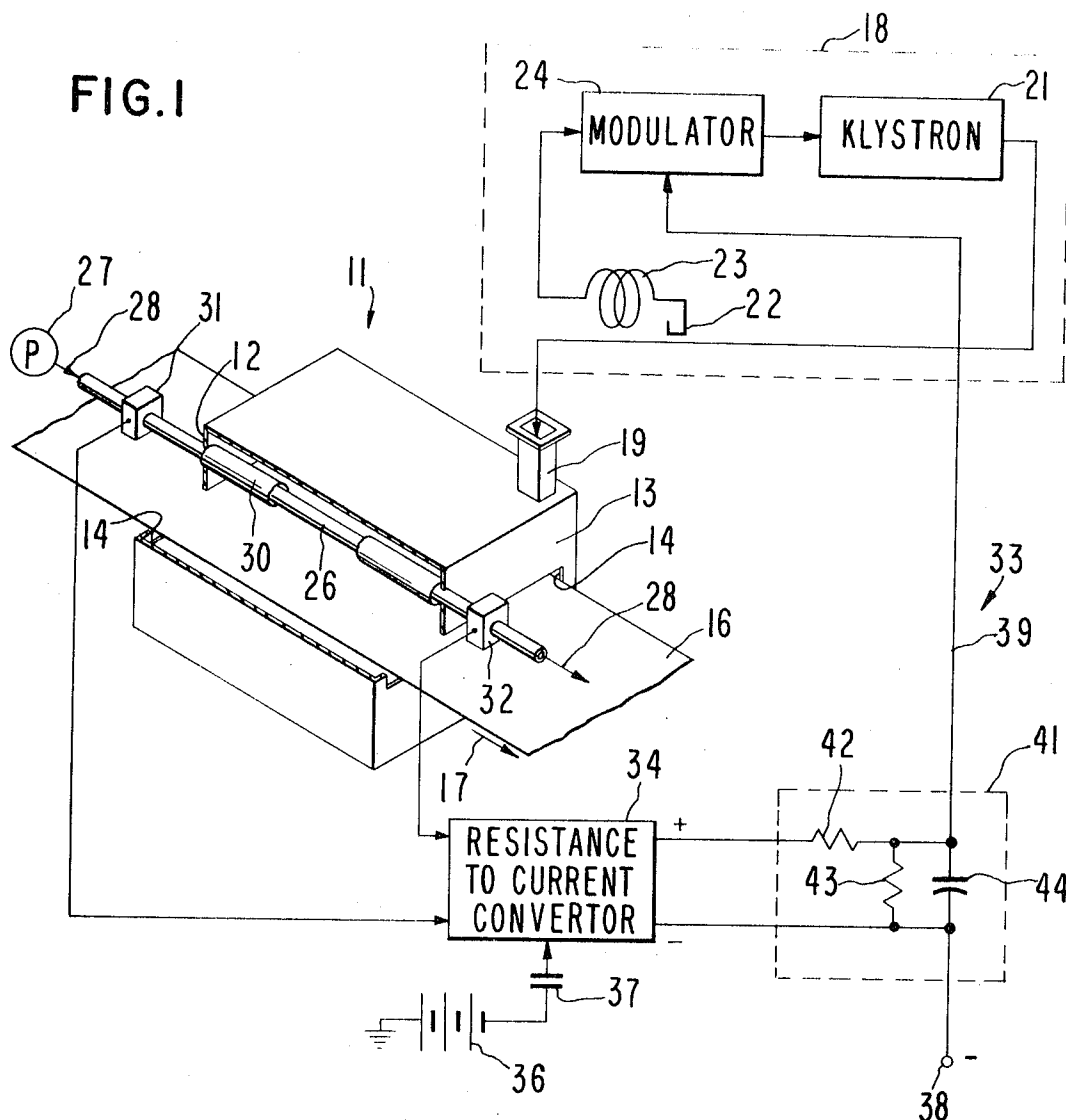


FIG. 2

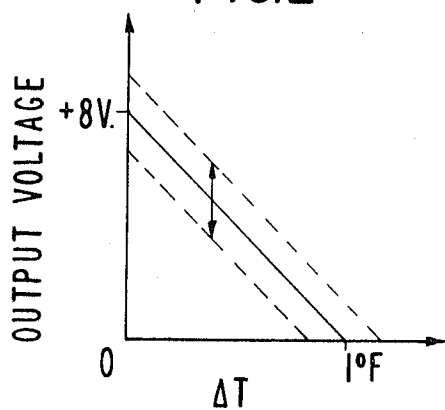
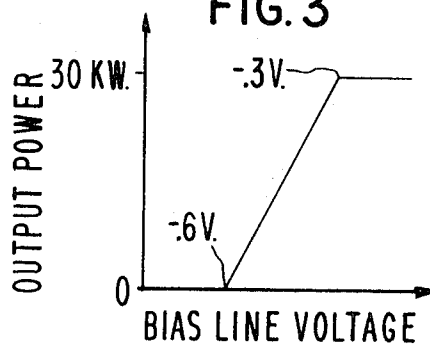


FIG. 3



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MICROWAVE CHAMBER HAVING ENERGY DENSITY CONTROL SYSTEM

BACKGROUND OF THE INVENTION

This invention relates to electromagnetic radiation treating apparatus and, more particularly, to such an apparatus having means for measuring and controlling the average energy density of the radiation in the treating zone.

In electromagnetic radiation treating apparatus, such as microwave cooking equipment, it is often desirable to be able to determine with accuracy the average energy density of the electromagnetic field in the treating chamber or zone. Such density provides a measure of the degree of cooking or heating to which a product in the zone is subjected by the radiation field. One measure of this average density is provided by the average of the absolute value or square of the intensity of the field in the zone. In the past, to determine this density, it has been the practice to locate one or more microwave probes at selected positions within the chamber. However, as is known, the energy density within an electromagnetic treating chamber or zone is generally not uniform. That is, because of the presence of standing waves and because of mode mixing, the energy density may vary with both space and non-harmonically with time throughout the zone. Because of this, the reading obtained from a microwave probe is only instantaneously representative of the energy density and only at the one particular location at which the probe is positioned. The reading obtained from it, therefore, does not represent the average energy density throughout the zone.

In attempting to provide a better reading, those skilled in the art have placed a plurality of microwave probes at selected locations within the zone and then averaged the various readings. While this procedure will provide better results than that obtained with one probe, it still does not provide a truly accurate measure of the average density throughout the zone. This is so because the error of any one probe may often only be compounded by like errors at other probes. An inordinate number of probes would have to be located throughout the full zone before a statistical average reading of all of them would provide a usefully accurate measurement of the average energy density in the zone. Besides such an arrangement being quite expensive, it is impractical.

The inability to obtain an accurate measure of the average energy density within a microwave treating zone has precluded the commercial use of microwave processing in many instances. For example, in the continuous cooking of food pieces such as chicken parts by passing the same on a conveyor through a cooking chamber, it is often necessary before a cooking process will be acceptable from a commercial standpoint that all of the food pieces be subjected to the same amount of cooking to within a degree or two of temperature. Since those in the microwave cooking art have been incapable of even determining the energy density with the accuracy needed, they have not been able to provide this required cooking control. This problem has been compounded by the fact that the energy density of a microwave field within a chamber depends largely on the amount of absorptive material to be treated which is present in the chamber at any one time. That is, as more product is added to the chamber, more energy will be absorbed with a consequent lowering of the energy density in the chamber assuming, of course, that the input power is maintained constant. Thus, the inability to obtain an accurate measure of the density so that the power source can be controlled to provide the desired heating rate has prevented the use of microwave heating or treating in many possible applications.

SUMMARY OF THE INVENTION

The present invention provides an electromagnetic radiation treating apparatus and a heating rate monitor for the same which is quite simple and yet provides the necessary accurate measurement of the average energy density within the treatment zone. The invention also provides a control system

which is based upon the monitor and which assures that the energy density within the treatment zone is maintained at a desired level irrespective of the amount of absorptive product within such zone. In its basic aspects, the monitor of the invention includes sensing means responsive to the electromagnetic radiation within the treatment zone by generating a representation, such as an electrical signal or a thermal gain, of the energy density of the field thereof. Such means extends a substantial distance through the electromagnetic field and senses the energy density along its path through the field. This provides an integration of the energy density over the path of the sensing means, and a measurement or sensing of such integration will provide an accurate indication of the average energy density along such path. If the field along the path of the sensing means is representative of the field in the full treatment zone, the measurement obtained is representative of the average energy density in such zone. In those instances in which the treating zone is a heating zone, the sensing means most desirably provides the desired representation as a thermal gain. Then the sensed representation is proportional to the true heating rate along the path, as well as to the average energy density. In a preferred embodiment, such means responsive to the electromagnetic radiation includes a duct which is transparent to the radiation within and which passes a substantial distance through the chamber. Means are provided for passing at a predetermined rate through the duct a flowable material which is heatable by radiation in the zone. Measurement of the gain of thermal energy imparted to the flowable material by the radiation as it passes through the chamber is a simple matter of obtaining the desired accurate measurement of the average energy density of the field along the path of the material. That is, the thermal energy gained by the material is directly related to the energy density of the radiation causing the gain and measurement of the total gain in energy imparted to the material as it passes through the zone provides an energy density measurement which takes into account both time and space fluctuations in the energy along such path, i.e., the average energy density.

The invention also provides means which responds to changes in the energy density by changing the power output of the radiation source to control such energy density, e.g., maintain the same constant. When it is maintained constant, one is assured that all pieces of product exposed to radiation within the zone for a given time will be subjected to the same radiation energy, irrespective of those factors which will normally cause field variations.

BRIEF DESCRIPTION OF THE FIGURES

With reference to the accompanying drawing, FIG. 1 is a schematic illustration of a preferred embodiment of the invention;

FIG. 2 is a graphical representation of the transfer characteristics of a portion of the control system of the invention; and

FIG. 3 is a graphical representation of the transfer characteristics of the radiation power source of the preferred embodiment.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

With reference to FIG. 1 of the accompanying drawing, a microwave treatment zone is defined by a radiation confining chamber schematically illustrated at 11. Insofar as the instant invention is concerned, chamber 11 can be designed to confine or support microwave radiation in any suitable manner. For example, the chamber can be either a standing wave resonant cavity or a travelling wave guide.

Means are provided for supporting within the chamber one or more objects to be treated. For this purpose, opposite end walls 12 and 13 of the chamber are provided with registering feedthrough slots 14 through which pass a conveyor belt 16. A conventional belt drive (not shown) is provided to continu-

ously move belt 16 through the slots 14 in the direction of arrow 17. The belt 16 acts as means for moving a plurality of objects to be treated, such as chicken parts to be cooked, through chamber 11 in a continuous treating process.

Means are provided for delivering microwave energy to the treatment zone defined by chamber 11. That is, a microwave generator 18 feeds microwave energy through waveguide coupling 19 into the chamber 11. Generator 18 can be of any suitable type. In the preferred embodiment being described, it is of the self-oscillating type disclosed and claimed in U.S. Pat. No. 3,461,401, the disclosure of which is hereby incorporated herein by reference. More particularly, the microwave generator 18 includes a klystron amplifier 21 which has a portion of its power output fed back to its input via a coupler 22 and an electrically long transmission line feedback path, schematically represented at 23, having a length equal to or greater than Q wavelengths long where Q is the inverse of the fractional bandwidth of the amplifier and feedback path over which the loop gain is greater than unity. An electronically variable attenuator in the form of a PIN diode modulator 24 is included in the feedback path to permit regulation of the power level of the oscillator for a purpose to be described subsequently.

As has been mentioned previously, the energy density of the microwave radiation fed to chamber 11 by generator 18 will not be uniform throughout the chamber. That is, due to mode mixing and the presence of standing waves within the chamber, the uniformity of the field throughout the chamber will vary both spatially and with time. This has made it difficult to obtain an accurate reading of the average energy density within the chamber. Such a reading is necessary in order to provide a measure of the amount of radiation treatment to which the objects being treated are exposed, and also to permit control of such amount. The problem becomes especially acute when it is desired to treat materials on a continuous process, i.e., when it is desired to continuously pass a plurality of objects through the chamber at a predetermined rate to treat the same equally with microwave energy. This is because the energy density of the microwave field will vary depending upon the amount of product within the chamber. That is, as more product enters the chamber, more of the energy will be absorbed, thus lowering the energy density. However, to assure that all of the product receives the same heating or amount of cooking, the density should be maintained constant. Before such can be done, though, an accurate measurement of the average energy density throughout the chamber must be obtainable.

The instant invention provides a heating rate monitoring arrangement capable of obtaining the desired accurate measurement. To this end, a duct in the form of a tube 26 extends through chamber 11 between end walls 12 and 13. (Chamber 11 is shown cut away to better illustrate the location of such tube). Means are provided for passing at a predetermined rate through the tube a flowable material which will be heated by radiation in the chamber. Most desirably, the flowable material is a liquid such as water which is passed through the duct at a constant rate for simplicity. Such means is graphically represented as a pump 27 which forces the flowable material through the tube 26 in the direction of arrows 28. Means are provided for measuring the gain in thermal energy imparted to the material in its passage through the chamber. For this purpose, a pair of temperature-to-signal type transducers in the form of resistance bulb thermometers or thermistors 31 and 32 are provided in tube 26 respectively upstream and downstream of chamber 11. Thermistor 31 measures the temperature of the water or other flowable material prior to its entry into chamber 11, and thermistor 32 provides its temperature after it has passed through such chamber. The difference between the entrance and exit temperatures of the liquid will provide a precise indication of the total gain in thermal energy imparted to the flowable material by the radiation within the chamber. This total gain in thermal energy will be directly related to the average energy density of the field along

the path of the flowable material during its transit time through the chamber. That is, fluctuations in the energy density along such path will cause corresponding fluctuations in the thermal energy imparted to the flowable material.

The length of the path or distance within the chamber that must be traversed by the duct before the thermal energy gained by the material flowing therethrough will be representative of the average energy density throughout the chamber, rather than just along such path, will depend upon the particular treatment chamber and radiation frequency being used. As will be apparent, this distance should be at least as long as several wavelengths of the radiation and for most applications at least five wavelengths long before the density measurement will be representative. Whenever it is stated herein and in the claims that the density measuring means or duct extends a "substantial" distance through the treatment zone, it is meant that the duct extends a sufficient distance through the chamber to provide an average energy density of the accuracy desired for the particular application.

As is illustrated in FIG. 1, the duct 26 through the chamber in generally the same direction as the objects or product being treated are moved therethrough. It will be appreciated that with this arrangement the duct is subjected to substantially the same fluctuations in energy density that the product being treated is subjected to. Thus, the average energy density or heating rate provided by the thermal gain of the flowable material is closely allied to the energy density or heating rate to which the product is subjected, irrespective of whether or not the thermal gain provides an accurate indication of the average energy density throughout the full chamber. For best results, the duct should be spaced from the walls of the chamber in order to prevent perturbations, etc. at such walls from affecting the measurement. Also, as is illustrated, the duct 26 is surrounded within the treatment chamber 11 with a closed heat insulation jacket 30. Jacket 30 is transparent to the radiation within the chamber, and the dead air space between it and duct 26 prevents any thermal energy within the chamber, other than that imparted to the duct 26 and fluid flowing therethrough by electromagnetic radiation, from being sensed by the fluid and affecting the measurement provided by it. The use of such an insulation means can be quite important if the product is being treated within the chamber with a heating medium such as steam in addition to the electromagnetic radiation. The jacket 30 and the dead air space will prevent thermal energy from the additional heating medium from reaching duct 26 while not affecting the thermal energy imparted to it by the radiation since the jacket is transparent to such radiation.

In many instances, it is desirable to be able to control the energy density of the radiation within a treatment zone. For example, in the microwave cooking of food pieces in a continuous process by passing the same through the chamber, it is necessary that each of the pieces be subjected to the same amount of cooking. However, the energy density and thus cooling rate within a chamber will vary depending on many factors, including the number of food pieces which are in the chamber at one time. The instant invention includes a control feedback loop, generally referred to by the reference numeral 33, which is responsive to a change in the average energy density or heating rate, i.e., in the amount of gain in thermal energy of the flowable material, by causing a corresponding inverse change to the intensity of the radiation delivered to the chamber so that the average energy density of the radiation field within the chamber is maintained substantially constant. More particularly, the output from the thermistors 31 and 32 is fed to a resistance-to-current converter 34. Converter 34 can be of the self-balancing bridge type such as that marketed by the Foxboro Co., Foxboro, Massachusetts, under Model 694A. Converter 34 is conventionally powered by a power source 36 which supplies 110 volt alternating current. Such power source 36 is connected to the converter 34 through a contactor or relay 37, the purpose of which will be described hereinafter.

The output of resistance-to-current converter 34 is inversely related to the temperature differential between thermistors 31 and 32 as is illustrated by the converter transfer characteristics shown in FIG. 2. Such output is used to control the bias on PIN diode modulator 24 and, hence, the output of klystron 21. More particularly, modulator 24 is normally biased off by the application of a negative potential such as one volt to terminal 38 on the end of bias line 39. The output of converter 34 is connected through a time lag circuit in the form of low pass filter 41 to line 39 in order to selectively overcome such bias. As is shown in FIG. 2, converter 34 has a high positive output current when there is no temperature difference between thermistors 31 and 32, i.e., when there is little or no microwave intensity within the chamber, in order to turn modulator 24 and hence klystron 21 full on. The output voltage of converter 34 decreases as the temperature difference between thermistor 31 and 32 increases, thus reducing the power on klystron 21. FIG. 3 illustrates the transfer characteristics of a suitable klystron amplifier, such as Model No. PPS-30A available from Varian Associates, Palo Alto, California, having a power output variable between 0 and 30 kilowatts.

The contactor 37 in the power circuit of converter 34 is connected with the on-off switch of the power source 18 in a manner assuring that the converter is rendered inoperable whenever the power source is off, i.e., not delivering energy to the chamber. This will assure that when the power source 18 is initially turned on that the converter 34 does not immediately cause the source to go to full power and possibly produce initial overvoltages in the chamber due to the lack of temperature differential between the input and output thermistors 31 and 32. Time lag circuit 41 further assures the stable operation of the circuit by delaying the response of the power source to changes in the thermal energy to a time which is long, compared to the time in which it takes the flowable material to pass between the thermistors 31 and 32. The control changes fed to the power source will therefore be representative of the actual conditions within the chamber at the time such changes are made.

EXAMPLE

An embodiment of the invention has been incorporated into a microwave resonant cavity designed to uniformly cook up to three-fourths ton of chicken pieces in 1 hour by continuously passing the same through the cavity. The cavity has dimensions of 4 ft. by 5 ft. by 38 ft. with the chicken being passed through the chamber along the 38 ft. dimension. The chamber is powered by two PPS-30A microwave amplifiers available from Varian Associates, Palo Alto, California which together provide 0-60 Kw of power at 2,450 MHz. The cavity is fed by the power packs to set up standing wave resonance in all dimensions of the cavity.

The duct for the flowable material is extended 5 feet through the chamber along the 38 ft. dimension. The flowable material is water and is fed through the duct at a constant rate of 1 gallon per minute. In order to assure that each piece of chicken received the same amount of cooking, the average field intensity throughout the chamber had to be very precisely controlled. Therefore, the resistance to current converter was adjusted to provide a full 8V power differential for a difference in temperature of only 1° between the inlet and outlet thermistors, as is indicated in FIG. 2. The converter 34 also included means for adjusting the field intensity at which it tended to maintain the cavity 11. This is represented by the dotted lines on each side of the characteristic plot line in FIG. 2. The negative bias applied to terminal 38 was minus 1 volt DC, and the low pass filter was designed to overcome this by converting the 8V output of converter 34 to about a 0.6 volt output with approximately a 100 second time lag. More particularly, resistor 42 had a value of 2,200 ohms, resistor 43 a value of 500 ohms, and capacitor 44 a value of 0.25 farads. PIN diode modulator 24 was a model 8732A PIN diode marketed by Hewlett-Packard, Inc. of Palo Alto, California.

With this arrangement, the average microwave field intensity was held to within ± 1.5 percent, resulting in each piece of the chicken being cooked to the same extent as the other pieces, irrespective of the number of pieces within the chamber. The instant invention therefore makes the chicken-cooking process usable for cooking chicken at any desired rate up to three-fourths ton per hour.

While the invention has been described with respect to the continuous processing of individual pieces of food or the like, it will be appreciated that it is useful in batch processing, and in general, any situation in which it is desirable to obtain an accurate determination of the average energy density within a radiation-treatment zone or to control such density. And while a preferred feedback control arrangement has been described, from the broad viewpoint any standard feedback or control arrangement, such as one which controls the on-off state of the power source rather than continuously varies its power output, is usable with the invention. The duct could also be incorporated into a self-balancing bridge or an arm thereof to provide the desired indication of changes in energy density. It is therefore intended that the scope of the invention be limited only by the terms of the claims and equivalents thereof.

I claim:

1. Electromagnetic radiation treating apparatus comprising a treating chamber capable of confining an electromagnetic radiation field, means for supporting within said chamber at least one object to be treated with electromagnetic radiation, said object extending over a distance in one direction in said chamber, means for delivering electromagnetic radiation to the object within said chamber to generate an electromagnetic field in the vicinity of said object, means including a duct transparent to said electromagnetic radiation extending within said chamber and through said field along said one direction a substantial distance at least equal to several wavelengths of the electromagnetic radiation, means for flowing a heatable material in said duct at a controlled rate of flow over said distance, the gain in thermal energy of said material along said substantial distance of duct being a measure of the average energy density of said field along the path of said duct, temperature insensitive means for measuring said gain in thermal energy along said duct, and means responsive to said measured gain in thermal energy for controlling the intensity of the electromagnetic radiation delivered to said object to maintain the energy density of said radiation along said path substantially constant.

2. The electromagnetic treating apparatus of claim 1 wherein said means for supporting within said chamber at least one object to be treated with electromagnetic radiation includes means for moving said object through said chamber in said one direction.

3. The electromagnetic treating apparatus according to claim 1 wherein said means responsive to said measured gain in thermal energy of said flowable material is a feedback control loop connecting said means for measuring the gain in thermal energy imparted to said flowable material with said means for delivering electromagnetic radiation to said object.

4. The electromagnetic treating apparatus of claim 3 wherein said feedback control loop includes an electrical time lag circuit which delays the response of the means for delivering the electromagnetic radiation to changes in said thermal energy for a time which is long comparable to the time of passage of said flowable material through the portion of said duct within said field.

5. The electromagnetic treating apparatus of claim 3 further including means for rendering said feedback control loop inoperable whenever said means for delivering electromagnetic radiation to said energy.

6. The electromagnetic treating apparatus of claim 1 wherein said means for delivering electromagnetic radiation to said chamber delivers microwave radiation thereto, and thermal insulation transparent to said microwave radiation is provided around said duct within said chamber.

7. The electromagnetic treating apparatus of claim 2 wherein said duct extends substantially from end to end of said treatment chamber.