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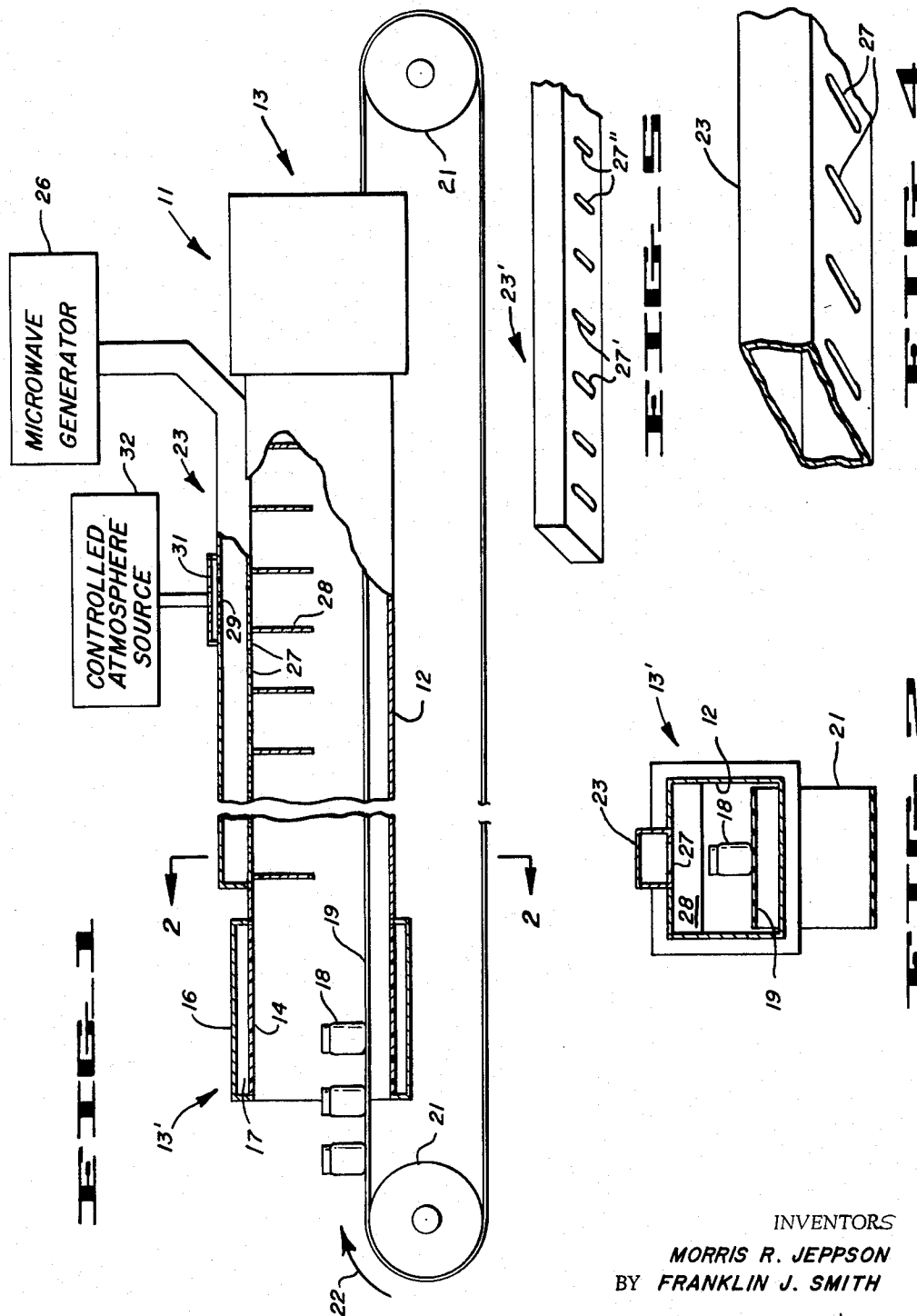
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POWER DISTRIBUTION SYSTEM FOR MICROWAVE PROCESS CHAMBERS

Filed Sept. 11, 1963

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

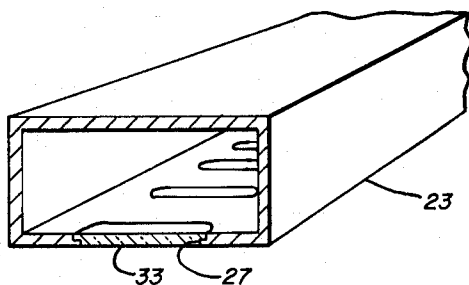


FIG. 3

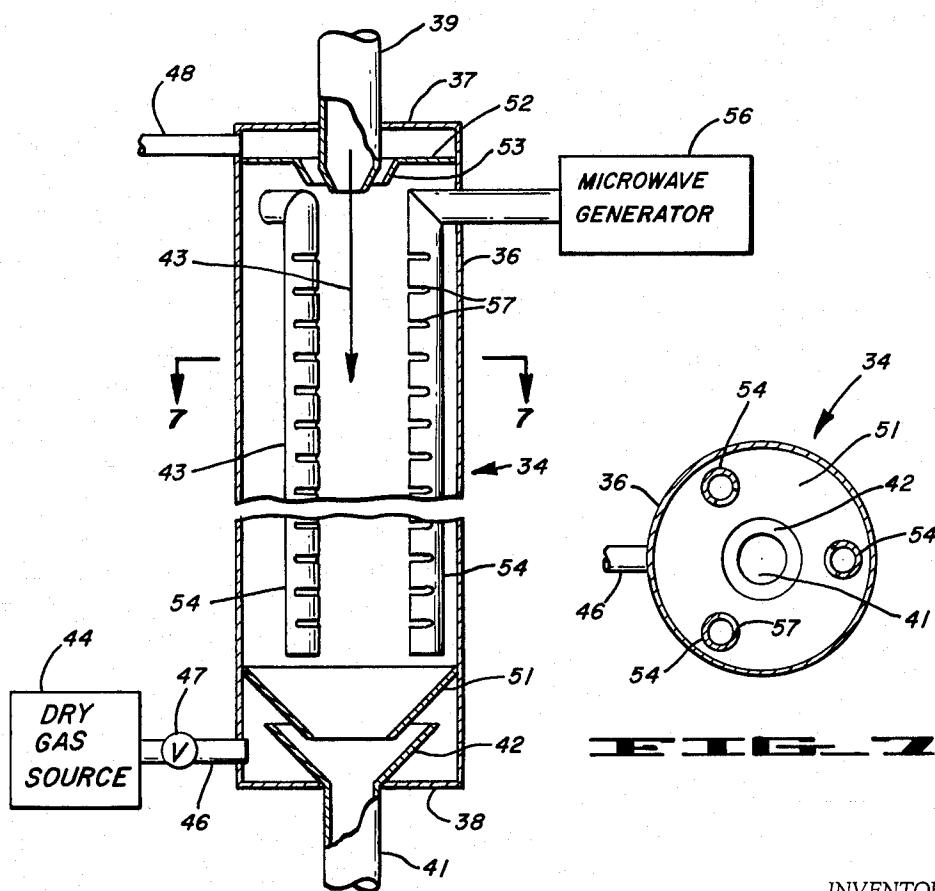


FIG. 6

FIG. 7

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POWER DISTRIBUTION SYSTEM FOR MICROWAVE PROCESS CHAMBERS

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The present invention relates to apparatus for treating products with microwave energy and more particularly to a microwave energy distributing system for processing chambers.

Microwave energy has recently been applied to the processing of substances for a variety of purposes. As such energy penetrates dielectric materials and readily heats any water contained therein, microwave irradiation provides a very rapid and efficient means for cooking foods, freeze drying foods, and for drying or heat treating many other products such as paper, wood, and a variety of industrial chemicals. A representative process involving the treatment of substances by microwave irradiation is disclosed in copending application Serial No. 274,648, filed April 22, 1963, now abandoned, by Morris R. Jeppson and entitled, Process for Sterilizing Food Products.

Processes of the type discussed above generally require a heating chamber in which the product is disposed for irradiation. By means of a waveguide or other transmission means, microwave energy is injected into the chamber which has conducting walls so that the energy is reflected and repeatedly passes through the product. The detailed structure and mode of operation of a heating chamber of this class is disclosed in copending application Serial No. 245,010, filed December 17, 1962, now abandoned, by Morris R. Jeppson and entitled, Continuous Process Microwave Heating Chamber.

In order to process substances rapidly and to obtain other advantageous results, it is generally desirable to provide for a high intensity of microwave irradiation. However, the rate at which such energy can be injected into the chamber through a single ordinary waveguide is generally limited to a value which is much less than the optimum from the process standpoint. This limitation arises from voltage breakdown at the region where the waveguide opens into the chamber and is primarily due to the concentration of power at this point. Breakdown, in the form of arcing or other types of electrical discharge, must be prevented as it consumes power and may severely damage the equipment.

Although this limitation on power injection is present in varying degrees in most types of microwave chamber process, it is particularly severe where microwaves are used to accelerate the freeze drying of foods. In this process heat is supplied to a frozen food product within a vacuum environment. The water content of the food is thereby caused to sublime directly from the frozen phase to vapor in which form it is withdrawn from the product. Microwaves provide a particularly efficient means for supplying heat to the product as such energy penetrates the product and preferentially heats the ice crystals therein. A difficulty in using microwave energy for this purpose results from the fact that the vacuum within the heating chamber promotes breakdown and sparking, near the point of injection, at very low power levels.

At the microwave frequencies most useful for freeze drying, 400 to 10,000 megacycles, discharges tend to occur at power levels of less than one kilowatt where a single conventional feed is employed. The most efficient application of microwave energy to freeze drying requires

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the injection of tens to hundreds of kilowatts into the heating chamber.

In other microwave irradiation processes, which do not require a vacuum in the heating chamber, different factors tend to promote electric field breakdown at less than optimum power levels. Where such energy is used to accelerate the drying of foods, chemicals, wood or the like at atmospheric or higher pressures, the presence of water vapor near a single high power microwave injection opening leads to sparking.

The difficulties discussed above are overcome in this invention by dividing the total power input into many small separate increments which are injected into the heating chamber at a plurality of spaced apart points. In addition to overcoming the limitation on power input, a distributed injection of microwaves has the further advantage of providing for a more uniform or controlled heating of the product throughout the volume of the heating chamber. This effect is particularly desirable where the heating chamber is a long tunnel through which products are continuously carried by a conveyor as described in the previously identified copending applications.

While it is possible to obtain a distributed input of power by coupling a large number of small microwave sources to the heating chamber through an equal number of spaced apart waveguides or the like, several practical difficulties are involved. Such a heating chamber is complex, costly and subject to considerable maintenance requirements relative to one which is coupled to a single high power microwave generator or to a small number of such sources. A very pronounced difficulty is that of interaction between the several power sources. Power from one source may be coupled back into another with possible severe damage thereto.

The present invention overcomes the several problems discussed above by providing a simple and efficient system in which the output of a high power microwave source is divided into many small increments and injected into a heating chamber at a plurality of spaced apart points.

In accordance with the present invention, energy from a high power source is coupled to a microwave chamber through a very long waveguide or transmission line means which extends along the product irradiation region. The waveguide may itself form a portion of the chamber wall where this construction is convenient. To provide for a distributed injection of energy into the chamber, the wall of the waveguide which faces the product irradiation region of the chamber is open at a plurality of points along the length thereof. The waveguide wall may, for example, be provided with a large number of spaced apart slots which are directed transverse to the axis of the guide or may have openings with other configurations as will hereinafter be discussed.

The openings interrupt the systematically varying current sheet which exists in the wall of an excited waveguide. Owing to the interruption of the current, a time varying electrical field and accompanying perpendicular magnetic field exists across each opening causing a portion of the microwave energy to be radiated therethrough toward the product region of the chamber. The emission of energy through the openings in the above described arrangement does not conform to that predicted by antenna theory for radiation into free space. Where the energy is injected into a process chamber, the size of the openings should be greater than that determined by theory.

While the waveguide has been described as having openings in a wall thereof, it should be understood that these need be openings in the electrical sense only, i.e., the electrical conductor of the waveguide wall is absent at the opening area. If necessary, where energy is to be in-

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jected into a vacuum or pressurized chamber, for example, the openings may be physically closed by windows of dielectric material such as glass, ceramic or plastic.

In other applications, no closure is provided and the waveguide is utilized as a highly efficient means for injecting or withdrawing gases at the chamber. This function need not interfere with the electrical operations. Where the waveguide is utilized for gas injection, the flow acts to prevent water vapor from approaching the injection region and thus further inhibits sparking.

The above described energy injection structure may be used with virtually any type of microwave chamber and serves to maximize the rate at which energy can be injected without field breakdown. By an appropriate variation in the size and spacing of the openings along the waveguide, the relative amounts of energy injected into different portions of the chamber may be controlled. By substituting different waveguides on a given chamber, the distribution of power therein may be modified as is sometimes desirable where the chamber operates on a continuous process basis and is used for treating different products.

As a further advantage, two or more such energy distributing waveguides may be employed on a single chamber without any significant interference between the two microwave sources.

Accordingly, it is an object of this invention to facilitate the processing of substances by exposure to microwave energy.

It is another object of the invention to provide a more efficient means for injecting microwave energy into a processing chamber.

It is another object of the invention to minimize the difficulties and limitations which arise from electrical field breakdown in a microwave processing chamber.

It is still another object of the invention to provide means for increasing the amount of microwave power which can be fed into a processing chamber.

It is still another object of this invention to provide a means for obtaining a desired distribution of energy within a microwave chamber.

It is a further object of the invention to provide a system with which microwave energy from a plurality of sources can be injected into a process chamber without significant interaction between the sources.

It is a further object of the invention to provide a means for dividing the output of a microwave power source for injection into a processing chamber at a plurality of spaced apart regions thereof.

The invention, together with further objects and advantages thereof, will be better understood by reference to the following specification taken in conjunction with the accompanying drawings of which:

FIGURE 1 is a broken out elevation view of a continuous process microwave chamber having the present invention embodied therein,

FIGURE 2 is a cross-section view of the chamber of FIGURE 1 taken along line 2—2 thereof,

FIGURE 3 is a perspective view showing a modification of the waveguide for use with a chamber which must be hermetically sealed from the waveguide,

FIGURE 4 is a perspective view of a section of the waveguide structure which supplies power to the chamber of FIGURES 1 and 2,

FIGURE 5 is a perspective view showing a second modification of the waveguide for varying the power density along the chamber,

FIGURE 6 is an elevation section view of a second form of microwave processing chamber embodying the invention, and

FIGURE 7 is a cross section view taken along line 7—7 of FIGURE 6.

Referring now to the drawing and more particularly to FIGURES 1 and 2 thereof, there is shown a microwave heating chamber 11 of the general type described in the

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hereinbefore identified copending application Serial No. 245,010, the chamber being suitable for treating substances on a continuous process basis.

The primary heating region of chamber 11 is formed by a long horizontal tunnel 12 which is of rectangular cross section and which has electrically conducting walls. Tunnel 12 is extended at each end by terminating sections 13 and 13' which function to suppress the escape of microwave energy from the ends of the chamber 11. As described in detail in copending application Serial No. 245,010, each termination 13 has an inner wall 14 which is of rectangular cross section and which forms an extension of the through passage of tunnel 12. Spaced outwardly from the dielectric wall 14 is a conducting outer wall 16 and a volume of water 17 or other lossy liquid is contained therebetween. As the microwave energy is injected at right angles to the axis of tunnel 12, it tends to propagate toward the ends of the tunnel by repeated reflections between opposite walls thereof. Upon reaching the terminating sections 13, such energy must repeatedly pass through the lossy liquid 17 and is therefore attenuated rather than being emitted from the tunnel.

The product to be treated, which may be containers of food 18 to be heated, for example, is carried through tunnel 12 by a continuous belt conveyor 19 formed of dielectric material. Conveyer 19 may be mounted on rotating drums 21 disposed one at each end of the tunnel with drive being applied to one of the drums in the direction indicated by arrow 22.

Considering now the means by which microwave energy is injected into the chamber, a long waveguide 23, of rectangular cross-section in this instance, extends along the upper surface of tunnel 12. The waveguide 23 may form an integral part of the wall of tunnel 12 by being fitted in a matching slot formed in the wall thereof.

Waveguide 23 receives power from a suitable conventional source 26 coupled to one end thereof, the opposite end of the waveguide being closed.

A series of openings, such as transverse slots 27, are spaced along the wall of waveguide 23 that faces the interior of tunnel 12 to provide for the distributed injection of energy from generator 26 into the tunnel. Factors affecting the selection of a suitable configuration and spacing for the slots 27 will be hereinafter discussed in greater detail, the general effect of the slots being to divide the microwave energy from source 26 into increments which are directed downwardly into tunnel 11 at spaced points along the length thereof. The energy is repeatedly reflected between the opposing walls of the tunnel 12 and thus the contents of the containers 18 is continually penetrated by the microwaves. In passing through the contents of the containers, a portion of the energy is absorbed with consequent heating thereof.

As will be discussed in greater detail, the injected energy will usually, to some extent, be directed obliquely with respect to the axis of tunnel 11. It is desirable to counteract this tendency as such energy propagates rapidly toward the ends of the tunnel with a reduced number of passages through the product. Accordingly, a series of sheet reflectors 28, formed of electrically conducting material, are mounted transversely in tunnel 12 at intervals along the length thereof. The reflectors 28 in this example extend downwardly from the top wall of tunnel 11 to a level just above the tops of the containers 18. Other reflector orientations and configurations may be employed where it is desirable to concentrate the energy at some particular region of the tunnel or to overcome an undesired intensity pattern.

In some microwave chamber operations, it is necessary to provide means for preventing the migration of water vapor from the product to the microwave input as such vapor will promote sparking with consequent energy dissipation and possible damage to electrical components. In addition, some processes may call for the maintenance of a controlled atmosphere with the heating chamber. It

may, for example, be desirable to pass a flow of warm dry air through tunnel 12 to further promote rapid drying of a product.

Both of the above discussed objectives may be accomplished by providing very small perforations 29 in a wall of waveguide 23 which communicate with a housing 31 formed on the outer side of the waveguide. Housing 31 is in turn connected to a source 32 of the gas, such as dry air, which is to be introduced into tunnel 12. The apertures 27 of the waveguide 23 distribute the gas along the length of the tunnel 12 and the flow of such gas through the apertures prevents water vapor from entering the microwave source and distribution system. Provided that the perforations 29 are of sufficiently small dimensions relative to the wavelength of the microwave energy, no significant amount of power is released into the housing 31.

In operations where it is unnecessary to provide a controlled flow of gas through tunnel 12, other means may be employed to seal off the microwave supply. As shown in FIGURE 3, inserts 33 may be disposed in the apertures 27 of waveguide 23. Provided the inserts 33 are formed of a suitable dielectric material such as glass, ceramic or insulative plastic, no significant interference with microwave injection occurs.

Referring now to FIGURE 4, the slotted waveguide 23 may be considered as a form of antenna coupled to the conductor walled chamber defined by the tunnel 12. Under this condition the slots or apertures 27 will not function precisely as would be predicted by antenna theory for radiation into free space but, in general, must be somewhat enlarged. As a rigorous mathematical computation of the optimum aperture configuration for a specific chamber would be unduly complex, a suitable arrangement is best determined empirically, using antenna theory criteria as a starting point. A trial waveguide may be constructed and appropriate changes made according to the observed density and distribution of energy within the chamber. This may readily be done by taking into account certain general properties of the apertured waveguide.

A slot cut in a conducting wall of a waveguide becomes a radiator when it is energized by a magnetic field parallel with its length. The slot is the magnetic counterpart of the electric dipole, and resonance and dipole radiations occur when the slot has a length near $\lambda/2$ where λ is the wavelength of the microwave.

Aperture configurations other than that shown in FIGURE 4 will function to radiate energy from the waveguide. For example, a shunt inclined slot may be cut obliquely in the narrower wall of the waveguide or a shunt displaced slot may be provided in the broad wall thereof asymmetrically with respect to the axis of the waveguide. The power radiated by a slot is proportional to its conductance which in turn is controlled by the inclination of the slot in the shunt inclined case and by the displacement from the center of waveguide wall in the shunt displaced case. Still another aperture variation is a series inclined slot which is cut in the broadwall of the waveguide at an angle to the axis thereof.

Slot configurations which are in effect combinations of the foregoing cases may be employed to obtain specialized properties. Cross shaped apertures or circular apertures in the broad wall of the waveguide for example will radiate an elliptically polarized wave.

A series of $\lambda/2$ slots spaced at $\lambda g/2$ intervals is a resonant array with the slots effectively in parallel. This arrangement produces a radiation pattern which is normal to the waveguide or at right angles to the axis of the associated chamber. This characteristic is desirable in microwave chamber operations. However, the resonant array requires precision tuning of the system as frequency variations from the design value cause rapid changes in the input admittance.

Spacing the slots at other than $\lambda g/2$ produces a non-resonant array which is less sensitive to minor changes in

electrical parameters. Such an arrangement remains well matched over large frequency changes and the attenuation and phase change coefficients can be controlled with considerable arbitrariness by changing the waveguide and slot dimensions and slot spacing. Although this arrangement results in the injection of energy at an angle with respect to the axis of the associated tunnel, this effect can be largely compensated for by the use of the reflectors as hereinbefore described and can be minimized by using waveguide dimensions close to cut-off.

The waveguide may also be constructed with a single longitudinal slot which will radiate energy. Such a slot will generally be in the narrow wall of the waveguide but may be in the broadwall, and still radiate, if there is a volume of dielectric material adjacent the slot. The dielectric material may be the hermetic closure hereinbefore discussed. The amount of radiation from different sections of the uniform slot may be controlled by varying the width thereof.

As an example, a rectangular waveguide of the transverse slot form shown in FIGURE 4 has been successfully employed in conjunction with a chamber for heating foods by microwave irradiation. The chamber was eight feet long, twelve inches high and eighteen inches wide. The active length of the associated waveguide, arranged as shown in FIGURES 1 and 2, was five feet. The slots 27 were $3/16$ inch wide and spaced $15/32$ inch apart. At one end of the waveguide the slots were 1.2 inches in length and increased to a length of 2.2 inches at the opposite end thereof.

By varying the length, or other dimensions, of the apertures 27 along the length of the waveguide as discussed above, the density of energy at different portions of the length of the associated tunnel 12 may be controlled. FIGURE 5 shows a waveguide 23' as modified for this purpose, a first portion of the slots 27' being larger than the adjacent series of slots 27" in order to radiate more energy. Such an arrangement is highly useful for many microwave processes, such as drying products, wherein a substance should be initially subjected to the maximum irradiation and subsequently subjected to less energy as the water content of the product decreases in passage through the chamber.

It will be apparent that forms of microwave transmission means other than the hollow waveguide herein discussed may be utilized for the purposes of the invention provided that such transmission means is of a type capable of emitting microwave energy from distributed points along the length thereof. Coaxial lines, strip lines, and the like can be adapted for this purpose.

Summarizing the operation of the apparatus, with reference again to FIGURES 1 and 2, the product to be treated, such as containers of food 18, is continuously fed onto conveyer 19 and passes through the tunnel 12. Microwave energy from source 26 is transmitted to the chamber by waveguide 23 and injected downwardly into the tunnel 12, at a plurality of points distributed along the length thereof, through the waveguide apertures 27. As a non-resonant array is employed in this embodiment, the tendency for energy to be injected toward the ends of the tunnel is compensated for by the reflectors 27 as hereinbefore described.

The principles of the invention may be applied to forms of processing chamber differing considerably from the example hereinbefore described. Referring now to FIGURES 6 and 7 for example there is shown a vertical drying tower 34 for processing granular, particulate or liquid products. The form of tower shown in FIGURES 6 and 7 utilizes a combination of microwave heating and a warm dry gas flow to effect drying of the products which may, for example, be onions, wood chips, potato flakes, citrus powders, apples, or chemicals. This combination of drying techniques is particularly efficient in that the microwave heating, in contrast to prior forms, establishes a temperature gradient in the product which

is highest at the center thereof, thereby expediting the migration of moisture to the surface of product where it is removed by evaporation into the dry gas atmosphere.

Tower 34 is provided with an upright cylindrical casing 36 formed of electrical conductor material and having upper and lower end closures 37 and 38 respectively. To provide for the input of the product which is to be treated, a feed pipe 39 is transpierced through the upper closure 37 and projects a distance downwardly into casing 36 along the axis thereof. In some instances, such as a tower designed for the treatment of liquid products, the feed pipe may be extended completely through the casing 36, provided that it is formed of a dielectric material which can be penetrated by microwaves.

A product output pipe 41 is transpierced through the lower closure 38, coaxially with respect to casing 36, and connects with a flaring conical receiver 42 disposed inside casing 36 immediately above the lower closure and in position to collect the product which has dropped along the axis of the casing as indicated by arrow 43.

A source 44 of heated dried gas, which may be air, for example, is connected with the lower end of casing 36 through a conduit 46 and control valve 47. A gas flow outlet conduit 48 is connected to the top of the casing 36 and may lead to a vent or to source 44 for recycling. To prevent the accumulation of product at the bottom of casing 36 and to provide for a uniform gas flow, a conical baffle 51 is disposed coaxially in the lower portion of the casing. Baffle 51 has an upper end with a diameter equal to that of the casing and a narrower lower end which extends a distance downwardly into receiver 42 in spaced relation therefrom. Similarly, an annular baffle 52 is secured coaxially in casing 36 immediately beneath gas outlet conduit 48 and is formed with a downwardly projecting central section 53 which encircles product input pipe 39 in spaced relation thereto.

Considering now the means for a distributed input of microwave power to casing 36, three waveguides 54 are disposed within the casing in parallel relationship to the axis thereof. Waveguides 54, which are of circular cross section in this embodiment, are equidistantly spaced from the axis of casing 36 and equiangularly disposed therearound. The upper end of each waveguide 54 is angled and projects through the wall of casing 36 to connect with a separate microwave generator 56 for each waveguide.

A series of slots 57 are provided in each waveguide 54 on the sides thereof which face the center of the casing 36, the slots having a configuration, spacing and dimensions determined by the considerations hereinbefore discussed.

An advantage of the circular geometry of this embodiment is that the injected power is concentrated at the axis of the chamber along which the product passes. The embodiment illustrates still a further advantage of the invention in that no appreciable interaction occurs between the microwave generators 56 supplying the several waveguides, a condition which is not present where conventional structure is employed.

While the invention has been herein described with reference to certain exemplary embodiments, it will be apparent that many variations and modifications are possible within the scope of the invention and thus it is not intended to limit the invention except as defined in the following claims.

What is claimed is:

1. Apparatus for treating products with microwave energy comprising, in combination, a long tunnel structure having conducting walls and forming a microwave chamber, means at each end of said chamber for suppressing the emission of microwave energy therefrom, a conveyer extending through said tunnel structure for carrying said products therethrough, at least one long waveguide extending along a substantial portion of the tunnel and having a sidewall facing products carried on said

conveyor, said sidewall having open areas distributed along a substantial portion of the length thereof and constituting a non-resonant array for emitting microwave energy into said chamber, a microwave source coupled to said waveguide, and a plurality of spaced apart electrically conductive reflector elements transversely disposed in said tunnel between said waveguide and said conveyer.

2. In apparatus for treating products by microwave irradiation, the combination comprising a housing having electrically conducting walls and forming a microwave chamber, a conveyer extending through said housing for carrying said products therethrough, a waveguide extending along at least a portion of said chamber along the path of said conveyer and having an electrically conducting wall which is open to said chamber at least at spaced apart points along an extensive portion of the length thereof, and a plurality of spaced apart electrically conducting reflector plates disposed in said chamber in proximity to said wall of said waveguide and in substantially perpendicular relationship thereto, said plates being distributed along said path of said conveyer.

3. In apparatus for irradiating products with microwave energy, the combination comprising a processing chamber formed of electrically conducting material and having product input and output openings, means for conveying the products through said chamber along a path of travel from said input to said output openings, a microwave guide extending along at least a portion of said chamber and having an electrically conductive wall facing said path of travel and electrically open to said chamber at each of a plurality of positions distributed along said path of travel and spaced apart therealong by other than half the wavelength in said guide to form a non-resonant array tending to radiate energy into said chamber in inclined relation to said wall, a source of microwave energy coupled to said guide, and reflector means fixed in said chamber having electrically conductive reflector material disposed substantially transversely to said path of travel and in spaced relation to products carried along said path of travel, whereby precision tuning is rendered unnecessary because of said non-resonant array and whereby said reflector material acts to control the distribution of microwave energy radiated into said chamber by said non-resonant array.

4. In apparatus for irradiating products with microwave energy, the combination comprising a microwave generator, a processing chamber formed of electrically conducting material and having product input and output openings, means for conveying the products through said chamber along a path of travel from said input to said output opening, and an elongated microwave guide having one end thereof coupled to said generator for excitation thereby, said guide extending along at least a portion of said chamber and having an electrically conductive wall facing said path of travel and electrically opened to said chamber at each of a plurality of apertures which are distributed along said elongated guide and along said path of travel and which have sizes and spacings forming a non-resonant array, whereby the output of microwave energy from said generator is divided into a plurality of increments which are injected into said chamber from successive ones of the apertures in said wall of said elongated guide as said output of energy travels along said guide from said one end thereof.

5. In apparatus for treating substances with microwaves, the combination as set forth in claim 4 further including dielectric material physically screening the interior of said guide from the interior of said chamber at the sites of said apertures while permitting injection of said microwave energy into said chamber through said apertures and said material.

6. In apparatus for treating substances with microwaves, the combination as set forth in claim 4 wherein the sizes and spacings of said apertures at successive positions along said guide are of values which increase the

percentage of available microwave power injected into said chamber from said guide in direction along said guide away from said one end coupled to said generator, said increase being by predetermined amounts which divide the output of microwave energy from said generator substantially evenly along a predetermined length of said elongated processing chamber.

7. In apparatus for treating substances with microwaves, the combination as set forth in claim 6 wherein said apertures include apertures of different sizes, said sizes becoming larger in said direction away from said one end coupled to said generator.

8. In apparatus for treating substances with microwaves, the combination as set forth in claim 6 wherein the spacings between said apertures include different spacings, said spacings becoming smaller in said direction away from said one end coupled to said generator.

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