Oct. 21, 1969 W. N. PARKER 3,474,209

DIELECTRIC HEATING

Filed April 10, 1967 2 Sheets-Sheet 1

Fig. 2.

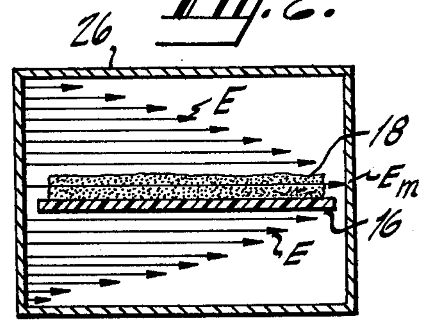

Fig. 1.

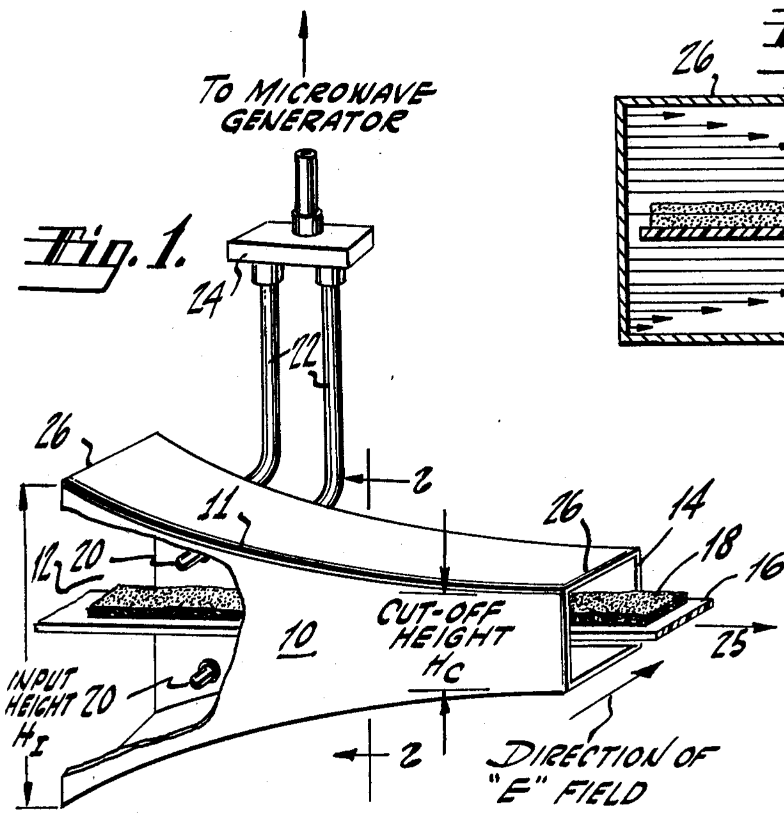

Fig. 3.

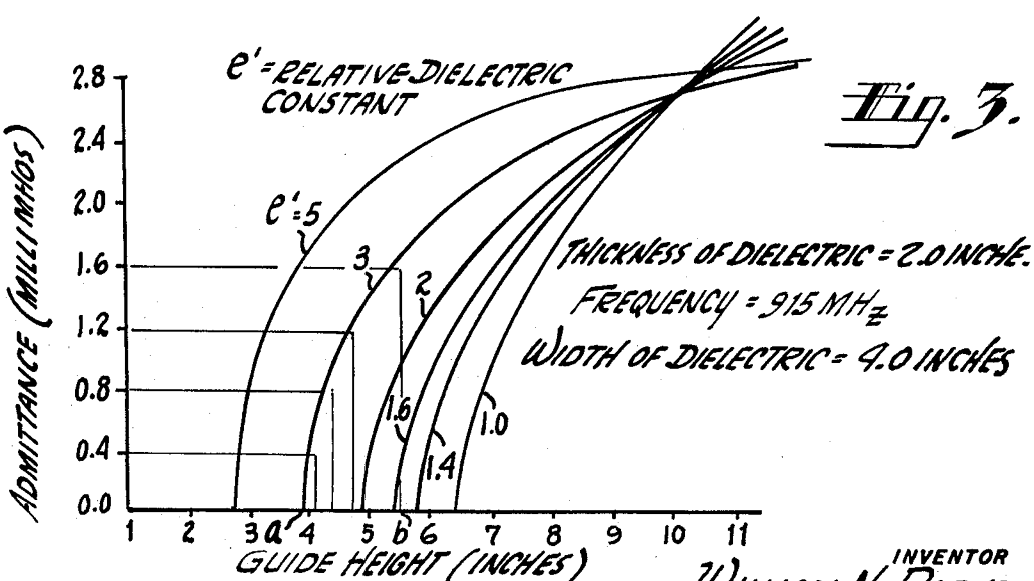

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Fig. 4.

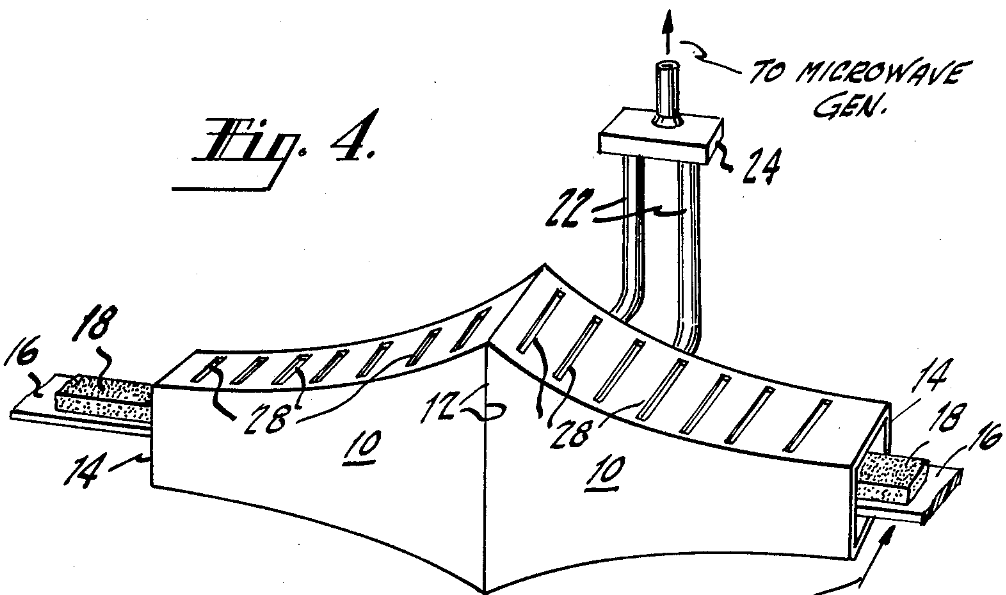
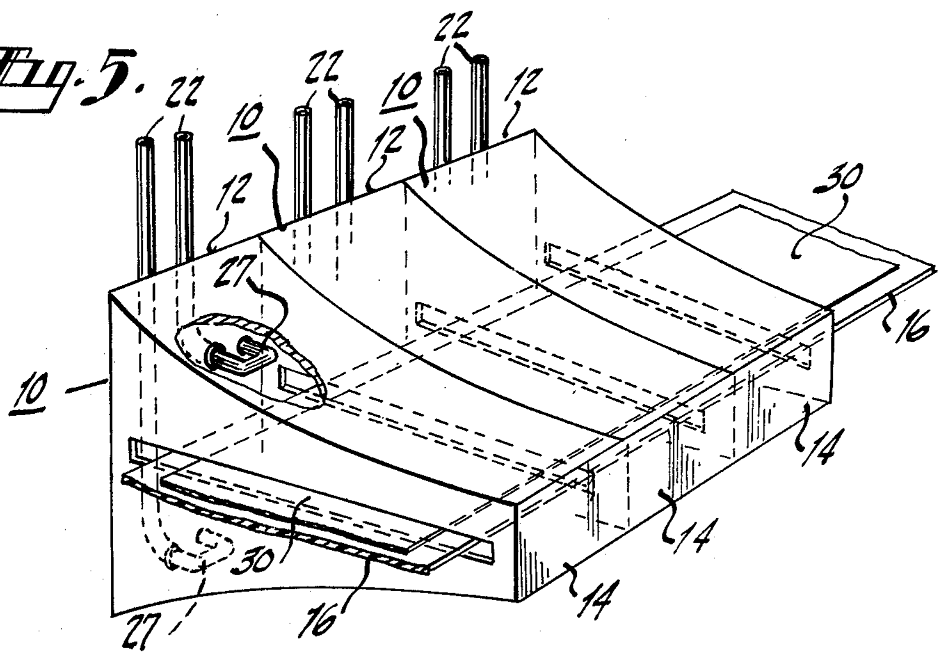


Fig. 5.



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DIELECTRIC HEATING

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U.S. Cl. 219—10.55 10 Claims

ABSTRACT OF THE DISCLOSURE

There is disclosed a method and apparatus for the microwave heat treatment of an article exhibiting lossy dielectric properties, the apparatus comprising a hollow waveguide having a non-linear taper along one dimension thereof designed so that a uniform density of dielectric heating is achieved by maintaining a constant ratio between microwave energy propagated in the waveguide and the admittance of the waveguide with respect to the microwave energy along the direction of propagation.

BACKGROUND OF THE INVENTION

Many manufacturing processes today require as a step the exposure of the product being processed to a source of heat which may serve as a means for drying or curing. The supply of such heat may presently be accomplished in a variety of ways: the product may be placed in static proximity to a heating source so that the stationary product is subjected to this heating source for a desired period of time, i.e., so called batch-type processing; or the product may be passed over heated structures or platens which tend to transfer heat to the product by conduction; or the product may be caused to travel through an oven or past a source which transfers heat by radiation. Such methods of drying have proven to be successful for many applications despite long processing cycles associated therewith primarily due to the relatively simple equipment employed.

In recent years, much experimentation has been undertaken in the field of heating lossy dielectric substances with microwave energy. To a large extent this surge of research in so using microwave heating has been precipitated by the growing interest of food processors in an area which has come to be known as freeze drying and which will be discussed infra in more detail.

One important advantage of using microwave heating in the processing of dielectric products is the possibility of reduced cost-per-unit of the product due to greatly reduced processing time. A shorter time permits more processing cycles per day and thus provides more total product output. Furthermore, the product load depth can be several times greater with microwave dielectric volumetric heating than for conventional heating methods. Economic studies indicate that the cost savings derived by utilizing microwave heating, for example, in a freeze drying process, can vary between fifty and eighty percent as compared with the more conventional freeze drying techniques. In addition, the capitalization costs for necessary equipment are often substantially reduced when dielectric microwave heating techniques are used to provide energy for a drying function.

One of the major drawbacks to date in so using microwave dielectric heating has been the lack of a microwave applicator capable of uniformly treating a large quantity of product at one time, particularly, where it is desired that the applicator lend itself to a continuous flow process. The lack of such an applicator tends to increase the processing time, handling costs, and consequently the overall cost of processing per unit of product. The technical reasons for this drawback will be discussed more fully hereinafter in the body of the specification. It

is sufficient to state at this point that the uniformity of microwave dielectric heating has heretofore been difficult to regulate and control in a large fixed processing enclosure.

SUMMARY OF THE INVENTION

The invention disclosed herein provides novel apparatus for use in a process requiring as a step the exposure of a lossy dielectric product to a source of heat in the form of a microwave generator. The apparatus takes the form of a waveguide having a properly designed non-linear taper along one dimension thereof into which the product is placed. Microwave energy is launched into the waveguide and propagated along the direction of the taper. The described waveguide permits the product being processed to be exposed to a uniform amount of heat at every point within the waveguide wherein the product is situated. Furthermore, the invention provides a novel method for the heat treatment of the products being processed utilizing the disclosed apparatus.

Accordingly it is an object of the present invention to provide an improved method of heating a product using microwave energy as the heating source, wherein a high degree of uniformity of heating is maintained. A further object is to provide an improved apparatus for use with a source of microwave energy to apply uniform heating to a product, particularly, in applications where a continuous flow technique is used.

These and other objects and advantages of the present invention will become more readily apparent when the following description is read in conjunction with the accompanying figures wherein like reference numerals indicate like elements.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a perspective view, partly in cross section, of heating apparatus in accordance with the present invention;

FIGURE 2 is a vectorial depiction of the electric field distribution for a TE_{01} mode propagating within the apparatus shown in FIGURE 1 at any point therealong;

FIGURE 3 is a graph wherein waveguide characteristic admittance is plotted as a function of guide height for various materials having different relative dielectric constants; and

FIGURES 4 and 5 are perspective views of additional embodiments in accordance with the concepts of the present invention.

In the interest of clarity, reference will be made in describing the invention to its use in the freeze drying of food. It is to be understood that, while the invention is particularly suitable for use in such an application, it is equally well suited for use in a wide range of other applications where microwave heating can be employed. Freeze drying is one of the newest techniques used in the field of food preservation. It is a sublimation process wherein moisture is removed from frozen products without changing their shapes, colors, flavors, or nutritional value. In the conventional freeze drying process, the frozen raw or cooked products are placed on trays in an atmospherically regulated chamber. A controlled amount of heat (heat of sublimation) is then applied to the products within the chamber through liquid heated trays or platens. The frozen moisture within the food evaporates (sublimes) and the dried food emerges in a solid, sponge-like condition. After hermetic packaging in either film-pouches or cans, the products can be shipped or stored without the need for refrigeration. Prior to heating, cooking, or otherwise handling as fresh food, the products require only re-hydration. During conventional freeze drying with heated platens, the outer layers of food tend to dry more readily and surround the undried frozen inner portions thereby acting as a heat-flow barrier and retarding the further transfer of heat from the hot platens to the interior of the product. Drying times of from eight to twenty-four hours are often required to sublime the ice completely. Dielectric heating, on the other hand, is volumetric in nature and tends to speed up the drying rate significantly thereby increasing the product output and reducing the cost per unit of output.

In utilizing the concept of dielectric drying in either a continuous flow or batch type process, a major problem encountered to date has been that of subjecting the product to a uniform amount of heat. In previous efforts to use microwave dielectric heating, the generated power has been generally distributed to the load via a waveguide. The resulting electrical phenomenon in accordance with waveguide theory causes an attenuation of power along the guide and consequently an uneven distribution of heat. For example, as an initial approach a conveyor belt carrying the product to be dried was passed through the length of a waveguide having a uniform cross section. Microwave energy was introduced into the waveguide and propagated down the length of the guide parallel to the direction of conveyor movement. As a result of attenuation of the propagating power as it passed down the guide the heating effect tended to be quite uneven, initially burning the product at the input end of the guide while becoming virtually ineffective by the time it had propagated to the output end of the guide.

A variety of approaches toward alleviating the aforementioned problem were investigated. One solution considered was to decrease the length of the waveguide, terminate it at the remote end with a matched load and utilize only a fraction of the propagating power in the guide to heat the food. This approach was found to be unsatisfactory in that it resulted in a large waste of electric power. A second solution considered entailed supplying microwave energy at various input points along the length of the waveguide. Uniformity of heating was difficult to achieve because of standing wave patterns set up by interference of the wave energy from the various sources and end reflections.

FIGURE 1 shows a waveguide **10** having a non-linear taper **11** along its length such that the height of the guide decreases from an initial height of H_I at the input end **12** of the guide to a height of H_C at the output or cutoff end **14** of the guide. In accordance with the embodiment shown, a conveyor belt **16** for carrying food or other product **18** to be processed passes down the length of the waveguide **10**. The belt **16** is preferably made of a thin non-lossy material and is of a constant width, as is the waveguide **10**. A source of energy, e.g., a microwave generator (not shown), supplies energy to the input end **12** of the waveguide **10** via a pair of antenna probes **20**, coaxial leads **22**, and, as shown in the embodiment of FIGURE 1, a power divider **24**.

Investigations were carried out using a frequency of 915 mHz. and, although discussion herein will be limited to that frequency, it should be understood that the methods and apparatus disclosed can be designed so as to operate at other frequencies.

As the power enters the waveguide **10** via the antenna probes **20**, a traveling wave is established along the length of the guide; the wave propagating down the length of the guide in the direction of cutoff **14**. Where it is desirable that the process be continuous flow in nature, the direction of conveyor movement may be either toward the input end of the guide **12** or, as shown in FIGURE 1, toward the cutoff end **14** of the guide **10**. Should it be desirable to utilize a batch-type process the product **18** to be heated can be positioned within the guide **10** and then permitted to remain stationary therein for the desired period of time. To obtain the maximum heating effect from the traveling wave to the product being processed, the waveguide **10** is designed to support a TE_{01} mode such that the electric field strength is always greatest in a plane slightly above the plane which is defined by the belt or support **16**.

FIGURE 2 represents the electric field distribution E at any point along the waveguide **10**. It is important that the guide be designed to have a width **26** narrower than a half-wavelength such that the guide will be unable to support undesired TE or TM modes. As shown in FIGURE 2 the belt **16** is positioned slightly beneath the center of the waveguide **10** so that the maximum electric field E_m passes through the center of the processed product **18** which sits upon the belt **16**.

A natural first approach for supplying microwave power as described is to attempt to utilize a wave traveling along a waveguide of constant cross section containing the lossy dielectric to be heated. However, the heating effect of such an applied traveling wave is rapidly diminished as it progresses down the length of the waveguide due to the power within the traveling wave being attenuated as it passes through the lossy medium. Any dielectric or insulating medium other than a vacuum will absorb part of the energy from an electromagnetic wave passing therethrough. This loss may be taken into account by considering the complex dielectric constant e of the form $e=e'-je''$ where e' is referred to as the relative dielectric constant and e'' is referred to as the loss factor. As the power attenuates, the heat into the product being processed tends to decrease exponentially with distance from tne power source, and much of the belt or other product support length is practically useless for processing. The foregoing problem will be better understood after a review of the following equations wherein Equation 1 defines the amount of power dissipated as heat:

$$P_d = 0.278\, E_m^2\, Fe'' \times 10^{-12} \text{ watts/cm.}^3 \qquad (1)$$

where:

F is the frequency in cycles per second;
E_m is the peak electric field strength in volts/cm.; and
e'' is the loss factor of the processed material.

Assuming for the present that F and e'' maintain constant values, it is apparent that the power dissipated (P_d) is a function of the square of the electric field strength (E_m^2).

Equation 2 defines the following relationship between P_p the power propagating through the waveguide, Y the admittance of the waveguide at any point along its length, and V the voltage across the waveguide:

$$P_p = V^2 Y/2 \qquad (2)$$

recognizing that $E^2=V^2/d^2$ where d is the distance in the direction of vector E, in this case the width **26** of the waveguide **10** and a constant, it becomes apparent by substitution that:

$$E^2 = (f)\frac{P_p}{Y} \qquad (3)$$

and, since P_p attenuates as the wave travels down the guide, the only way to maintain E^2 constant so that P_d can remain constant (Equation 1) is to decrease the admittance Y of the waveguide along its length so that the ratio of P_p to Y remains constant. Recognizing that the admittance Y is a function of the cross section of the guide at any point therealong, the effect of the foregoing relationships may be summarized by saying that to deliver to a lossy dielectric material within a waveguide a uniform heat density, it is necessary that the cross section of the guide be appropriately varied as a function of guide length.

Having thus theorized a solution it next becomes necessary to design a waveguide having dimensional characteristics which will satisfy the foregoing relationships. With this end in mind a sample calculation will be carried out for a product havng a relative dielectric constant e', a loss factor e'', a thickness c, and a width d; it being assumed that the microwave energy is to be supplied at a frequency of 915 mHz.

As an initial step it is necessary to determine that the width **26** of the waveguide **10** which for the purpose of attaining maximum heating efficiency should be as close to the width d of the product as possible, be incapable of supporting a mode other than a TE_{01} mode. At 915 mHz. a half wavelength will be approximately 6.45 inches in free space. It is important therefore to make sure that the width **26** of the waveguide **10** be designed to be somewhat narrower than this figure.

The next step in the calculation is to determine the cutoff height H_C of the waveguide at its narrow end **14**. Cutoff is defined for purposes of this application as that point along the length of the tapered waveguide **10** where, for a constant frequency and guide width, the characteristic admittance of the waveguide **10** becomes zero and the waveguide is incapable of supporting a travelling wave thereby resulting in the power propagated becoming zero. To find the height of the waveguide at cutoff H_C, it is convenient to make use of curves such as shown in FIGURE 3. These curves plot the waveguide admittance Y as a function of guide height H for materials having various dielectric constants. These curves may be calculated based on the work of P. H. Vartanian et al. as disclosed in the IRE transactions on Microwave Theory and Techniques, 1958, in an article entitled, "Propagation in Dielectric Slab Load Rectangular Waveguide." The calculations involved in arriving at the curves shown in FIGURE 3 require the solution of simultaneous transcendental equations for fixed frequency and dielectric parameters. In the case of the curves shown in FIGURE 3, 915 mHz. was used as the frequency and a dielectric having a thickness of two inches and width of four inches was assumed. Assuming further that the relative dielectric constant of the product e' is three (3) it can be seen from the curves of FIGURE 3 (at a point a) that the cutoff height H_C is approximately 3.95 inches.

Having thus determined the cutoff height H_C of the waveguide the next step is to determine the height H_I of the guide at its input **12** and then the height at various intermediate points thereby determining the shape of the taper. To determine the input height H_I it is first necessary to calculate the value of a parameter referred to as the conductance G of the dielectric which is defined as follows:

$$G_{(\text{millimhos per unit length})} = \omega e'_0 e'' \frac{c}{d} \tag{4}$$

where:

$\omega = 2\pi F$;
e_0' is the dielectric constant of free space;
e'' is the loss factor for the diven dielectric;
c is the thickness of the dielectric; and
d is the width of the dielectric.

Assuming that the conductance G as calculated is found to be 0.1 millimhos per inch and, arbitrarily choosing a guide length L of 16 inches, the input height H_I is found by multiplying the conductance G and the length L which results in a pure admittance figure; in this case 1.6 millimhos. Referring to the curves of FIGURE 3 and following the ordinate thereof at point 1.6 millimhos across to the curve representing an e' of 3, we read on the abscissa (at point b) a guide height of approximately 5.5 inches which is the input height H_I of the guide. It is important to note that the input height must be selected so as to be incapable of supporting a TE mode other than a TE_{01} mode, i.e. a TE_{02} mode, and since the input height H_I is a function of the guide length as has been shown, the length chosen should be selected so as to satisfy this requirement.

Having so determined the terminal heights H_I and H_C of the guide the intermediate heights can be readily determined by interpolation. In this example let us define the length of the guide L as being equal to zero at the input end ($H_I=5.5$ inches; $Y=1.6$ millimhos) and equal to 16 inches at the output or cutoff end ($H_C=3.95$ inches; $Y=0$ millimho). At L equal to four inches ($Y=1.2$ millimhos) the guide height H would be 4.8 inches; at L equal to 8 inches ($Y=.8$ millimho) H would equal 4.3 inches: and at L equal to 12 inches ($Y=.4$ millimho) H would be equal to 4.05 inches. Additional intermediate points would be determined in a similar manner. It may be seen that the shape so determined will correspond to a slowly changing (i.e. non-linear) taper.

To carryout the method of the present invention, vis-a-vis its application to a freeze drying process, for example, the food to be dried is first placed into a frozen state in accordance with state of the art techniques. While in such condition it is then admitted into an atmosphere which is controlled as provided in the present state of the art such that the partial pressure of water therein is below the saturation vapor pressure of the frozen food. The presence of such an atmosphere is necessary to permit sublimation of the frozen water within the food during the subsequent heating step. Also contained within said atmosphere is one or more tapered waveguides, designed in accordance with the properties of the food as discussed supra. The frozen food is then either held or passed through the waveguide and thereby exposed to the microwave energy propagated therein, resulting in the evaporation of the water directly to the gaseous state. To facilitate the mass transfer of this vapor from the waveguide, the guide can be provided with a series of strategically located narrow slots **28** (or holes) as shown in FIGURE 4.

As the power propagates through the waveguide it will be attenuated due to absorption by the food as a result of its lossy dielectric properties. A uniform electric field is maintained however as a result of the decreasing admittance characteristic of the waveguide. As previously discussed, the food to be processed is in this manner essentially exposed to a uniform heat density through the entire length of the waveguide. As the food emerges from the waveguide it may either be removed from the controlled atmosphere and then processed for packaging or, if desired, it may be passed through additional waveguides within the atmosphere for further drying before being removed and packaged.

Although the foregoing has been described in connection with continuous processing, it should be understood that the advantage of uniformity of heating ascribed to this form of tapered waveguide applicator applies equally well to batch type processing where the food remains stationary during the processing cycle.

FIGURE 4 shows a further embodiment of the invention wherein two tapered waveguides **10** are connected in tandem with their power input ends **12** coinciding. Propagating energy is simultaneously launched in both directions along the lengths of each guide via the antenna probes. This has the effect of decreasing the number of source inputs **22** per waveguide thereby further reducing the overall cost of the process. A large continuous process installation might employ several such tandem sections in cascade.

It was previously assumed for the purposes of example that the complex dielectric constant ($e'-je''$) of the processed product remained at a constant value throughout the course of the process. In actuality the value of this parameter will vary as the temperature of the dielectric increases and the frozen moisture sublimes in the case of freeze drying, for example. This variation can be compensated for, however, by changing the design of successive cascaded sections such that the various sections are designed in accordance with the anticipated properties of the dielectric as it passes through that particular section or, should additional accuracy be desired, by taking such variations into consideration in the design of the individual sections.

Thus far the discussion has been directed largely to the utilization of the present invention in the area of freeze drying. Although this area will derive particular benefit from this invention it should be understood that the utilization thereof need not be so limited. In effect the concepts disclosed are applicable to a variety of heating techniques be they performed in a controlled atmosphere, as in the case of freeze drying, or be they performed under normal atmospheric conditions.

FIGURE 5 presents a further embodiment which will find particular application in the continuous drying or curing of relatively thin products such as textiles, paper, plywoods, adhesives, plastics, etc. As shown in FIGURE 5 the thin product **30** is passed through the width of the waveguide **10** rather than down its length while the direction of the traveling wave and the electric field distribution remain the same as shown in FIGURE 1. Such a configuration will often be desirable where the width of the product to be dried is greater than the maximum width to which the guide can be designed and still prevent the establishment of undesirable modes. As shown in FIGURE 5 a number of waveguides may be placed one next to the other i.e., side by side, and a thin slot provided in their sides to permit the passage of the product therethrough. The number of guides necessary is dependent upon the speed at which it is desired the product travel and the magnitude of power being supplied thereacross. Often the composition of the product **30** will be rigid enough to be self supporting, thereby obviating the need for the supporting belt **16.** FIGURE 5 further illustrates an alternative method of coupling microwave power to the waveguide by the use of loops **27.**

What is claimed is:

1. Apparatus for processing a lossy dielectric material comprising

a tapered waveguide dimensioned to hold therein said material,

means for applying electromagnetic energy at the largest end of said waveguide so that said energy propagates along the tapered length of said waveguide,

the degree of said taper being determined to maintain a constant ratio between said energy propagated in said waveguide and the admittance of said waveguide with respect to said energy along said tapered length in the presence of said material within said waveguide.

2. An apparatus for heating a moisture laden article comprising,

a non-linearly tapered waveguide,

means for applying microwave energy to said waveguide so that said energy propagates along the tapered surfaces within said waveguide,

means for supporting said article within said waveguide to cause the maximum electric field of said energy to pass through said article when so supported,

the degree of said taper being determined to maintain a constant ratio between said energy propagated in said waveguide and the admittance of said waveguide with respect to said energy along said tapered surfaces in the presence of said article within said waveguide.

3. An apparatus as claimed in claim **2,**

said last-mentioned means being designed and arranged to continuously convey said article into and out of said waveguide.

4. An apparatus as claimed in claim **2,**

said waveguide having disposed within a surface thereof a plurality of apertures for venting moisture vapor from said waveguide.

5. An apparatus as claimed in claim **2,**

said first-mentioned means operating to establish said

propagating energy in a TE_{01} mode within said waveguide.

6. An apparatus for use with a source of microwave energy to provide uniform density heating to a moisture laden article comprising,

a hollow chamber arranged to allow the passage of said article therethrough and along one dimension of said chamber, said energy being propagated within said chamber along said one dimension with said chamber having a non-linear taper along said one dimension designed to provide a constant ratio between said propagating energy and the admittance of said chamber with respect to said energy at any point along said one dimension.

7. Apparatus for processing a lossy dielectric material comprising,

a first hollow chamber arranged to allow the passage of said material therethrough, said first chamber having a non-liner taper along one dimension thereof,

a second hollow chamber arranged to allow the passage of said material therethrough, said second chamber having a non-linear taper along one dimension thereof,

said first and second chambers being disposed in axial alignment along said one dimension with the larger ends of said tapered chambers coinciding,

means for applying electromagnetic energy at said larger ends of said chambers so that said energy propagates along the tapered length of said chambers,

the degree of taper of said chambers being determined to maintain a constant ratio between said energy propagated in each of said chambers and the admittance of each of said chambers with respect to said energy along said tapered length in the presence of said material within said chamber.

8. Apparatus for processing a lossy dielectric material comprising,

a plurality of waveguides having a non-linear taper along one dimension thereof, said waveguides being disposed so that the tapered surfaces of each waveguide coincide to form a continuously tapered surface, said waveguides being formed with openings to permit said material being processed to pass through each of said waveguides in a direction transverse to said tapered dimension,

means for applying electromagnetic energy at the largest end of each of said waveguides so that said energy propagates along said tapered dimension within each of said waveguides,

the degree of each of said tapers being determined to maintain a constant ratio between said propagated energy and the admittance of said waveguide with respect to said energy along said tapered length in the presence of said material within each of said waveguides.

9. A method for heating an article having lossy dielectric properties which comprises the steps of,

positioning said article within a hollow chamber having non-linear tapered surfaces along one dimension thereof,

supplying microwave energy within said chamber and along said one dimension so that with the design of said tapered surfaces a constant ratio is maintained between said propagating energy and the admittance of said chamber with respect to said energy along said one dimension.

10. A method for freeze drying a water laden lossy dielectric article wherein the water content within said article has been previously placed into a frozen state which comprises the steps of

positioning said article within a waveguide having non-linear tapered surfaces in one dimension thereof,

propagating microwave energy from the larger end of said waveguide along said one dimension to maintain with the design of said tapered surfaces and the dielectric constant of said article a constant ratio between said energy and the admittance of said waveguide with respect to said energy along said one dimension.

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