

[54] **CIRCULAR WAVEGUIDE
MICROWAVE APPLICATOR**

[76] Inventor: **Ray M. Johnson**, 155 Lipton Place,
Danville, Calif. 94583

[22] Filed: **April 19, 1972**

[21] Appl. No.: **245,410**

[52] U.S. Cl. **219/10.55**

[51] Int. Cl. **H05b 9/06**

[58] Field of Search **219/10.55**

[56] **References Cited**

UNITED STATES PATENTS

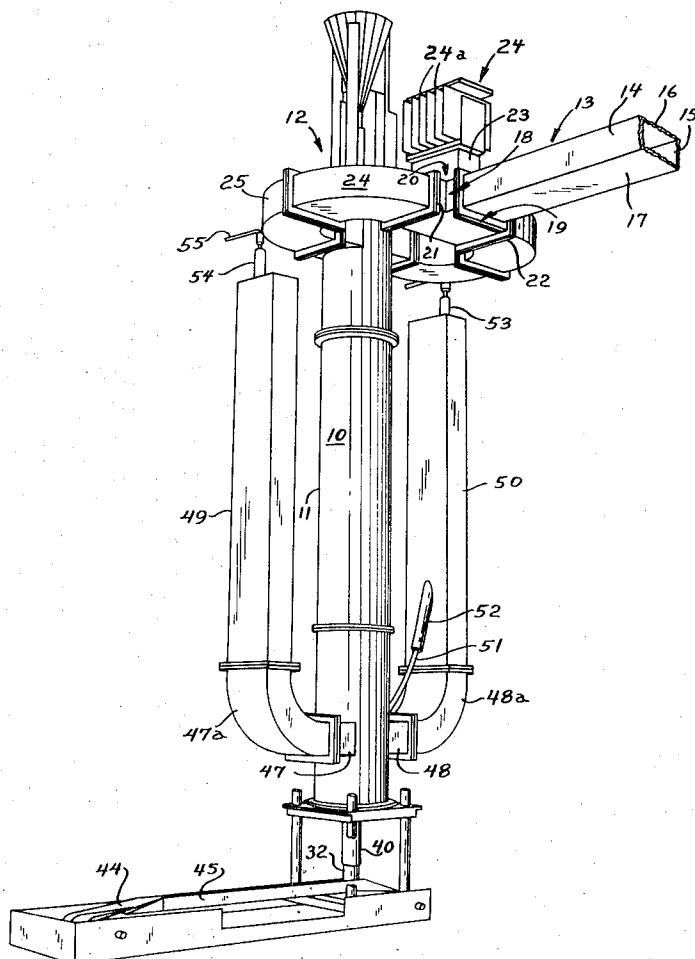
3,590,202	6/1971	Day et al.	219/10.55
3,611,582	10/1971	Hamid et al.	219/10.55
3,626,838	12/1971	Gorakhpurwalla	219/10.55

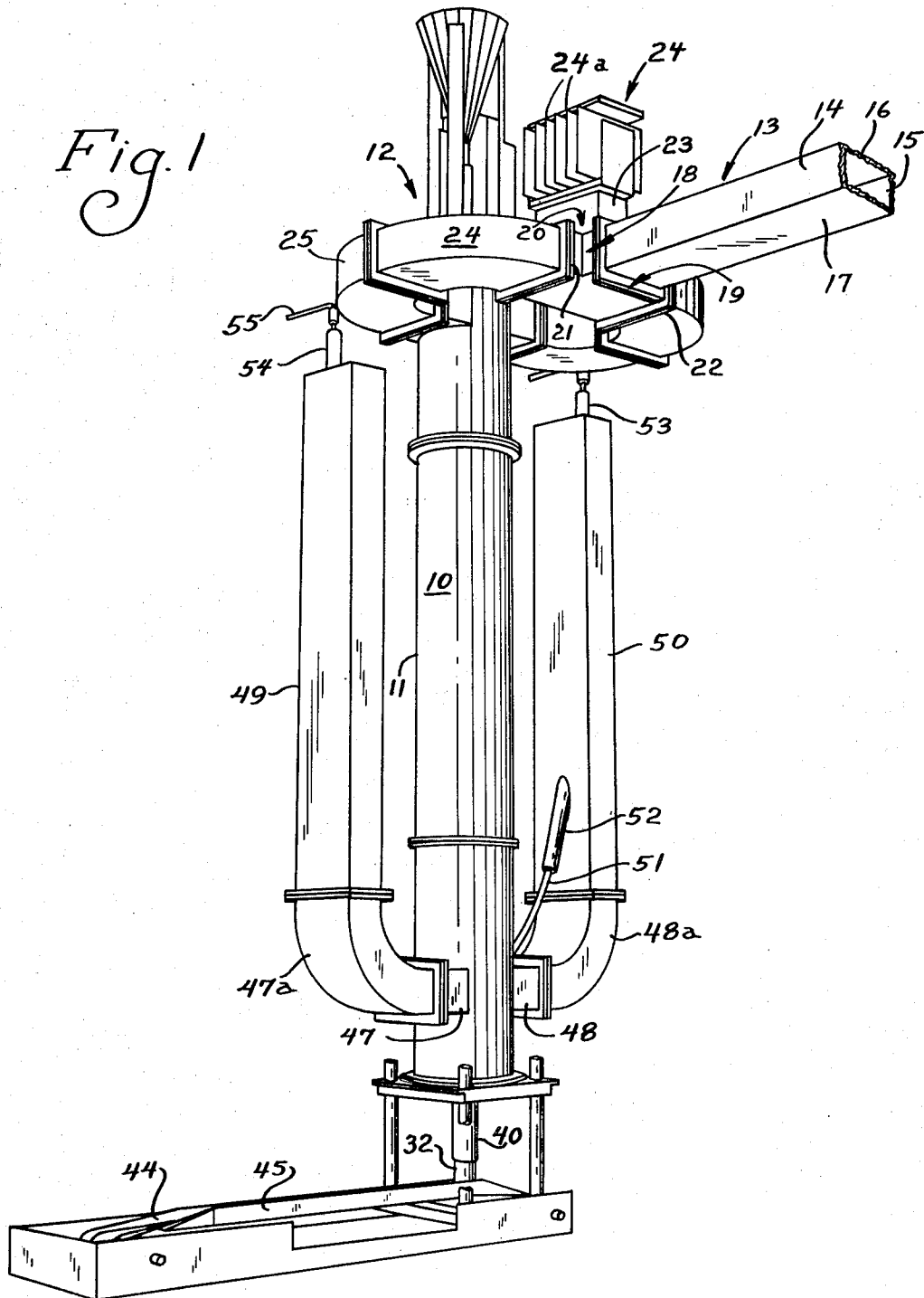
Primary Examiner—J. V. Truhe
Assistant Examiner—Hugh D. Jaeger
Attorney—James J. Hill

[57] **ABSTRACT**

A circular waveguide microwave applicator is excited in either the TM_{01} mode or the TE_{11} mode by means of a hybrid input network receiving energy from a source of microwave power. The material being heated may be conveyed under gravity axially through the circular applicator and along the axis thereof, guided by a dielectric tube extending coaxially with the cylindrical side wall of the applicator. Remnant power is then conducted to terminating water loads connected to the applicator.

7 Claims, 11 Drawing Figures





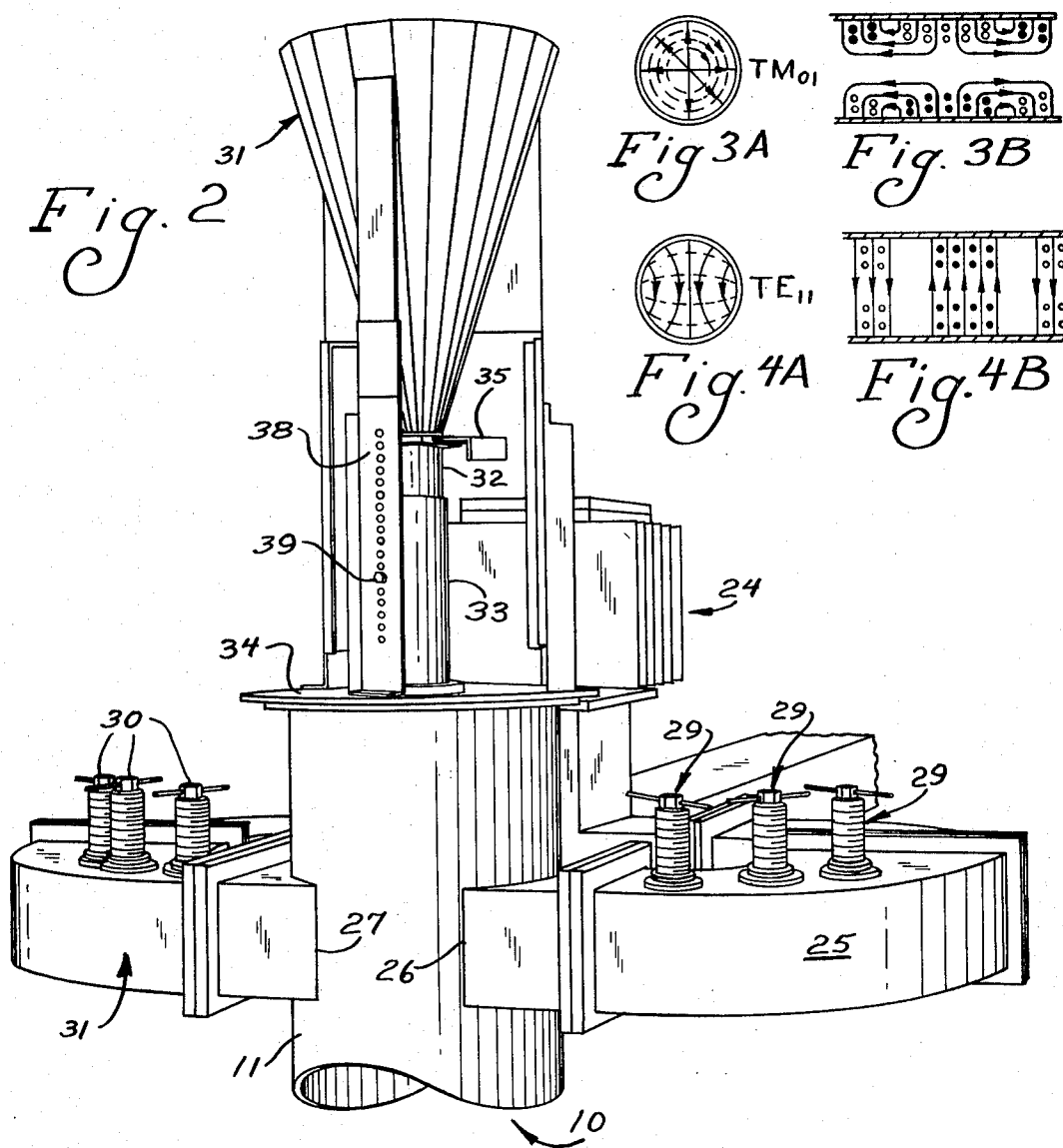


Fig. 8

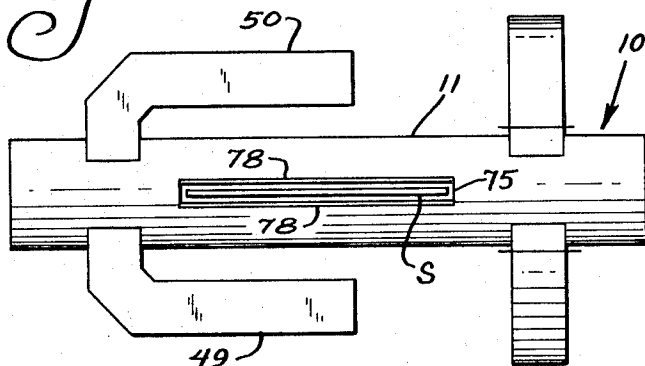


Fig. 9

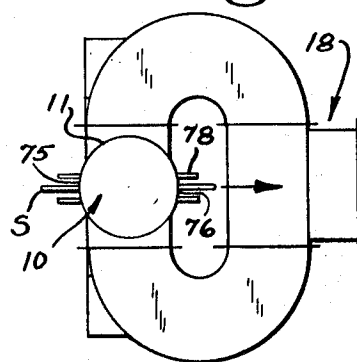


Fig. 5

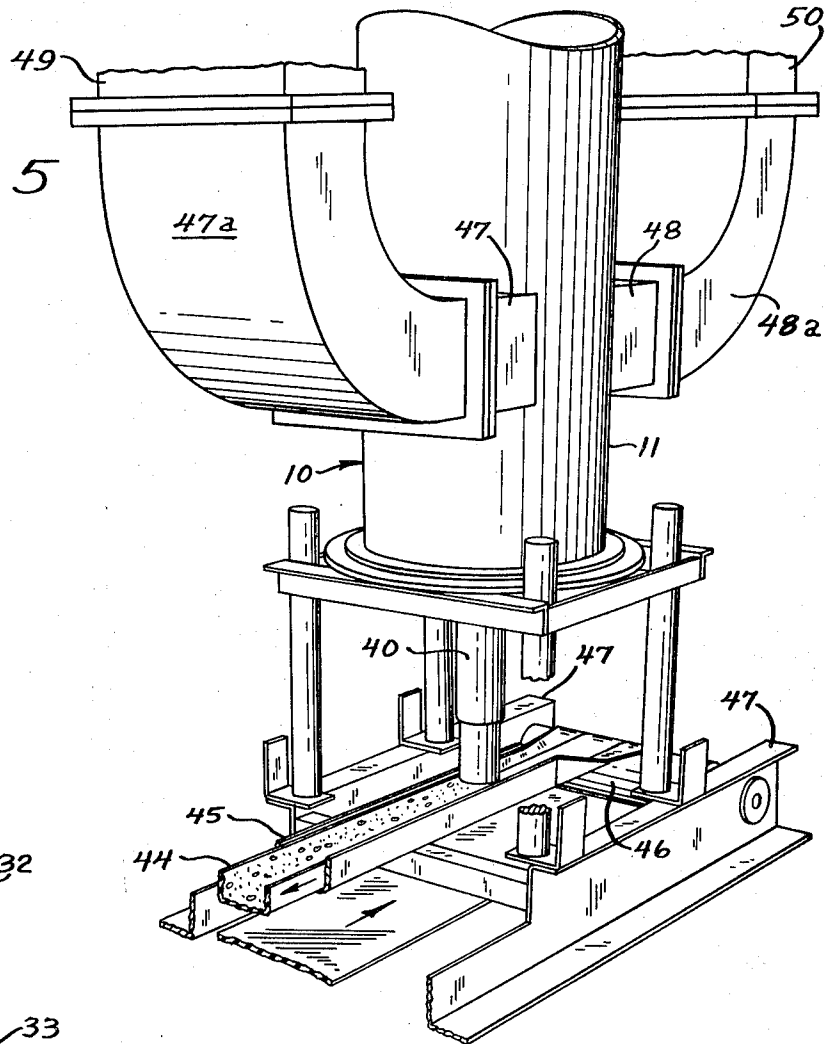


Fig. 6

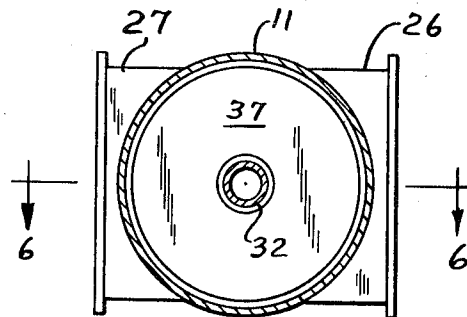
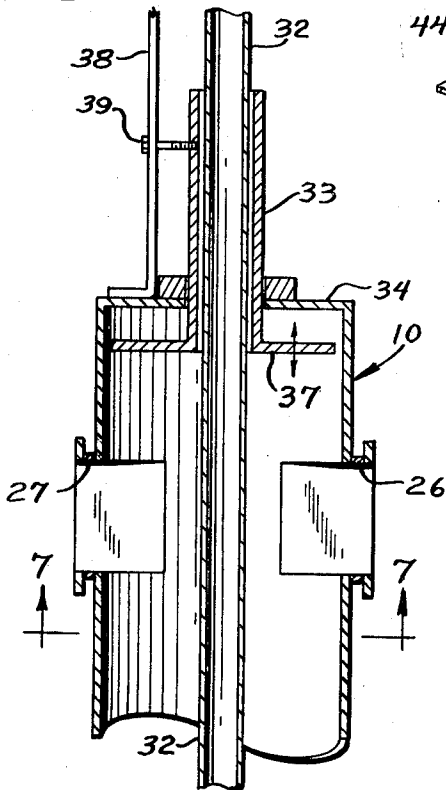


Fig. 7

CIRCULAR WAVEGUIDE MICROWAVE APPLICATOR

BACKGROUND AND SUMMARY

The present invention relates to a microwave applicator—that is, a system for applying microwave energy to heat a material. The present applicator has particular utility in heating or processing particulate matter, such as rice. Alternatively, it may be used to apply microwave energy to sheet material to heat it.

Heretofore, microwave applicators in commercial usage generally have taken the form of a multimode cavity wherein a source of microwave energy (usually a magnetron tube operating at a single frequency) energizes a tunnel or oven constructed of conducting wall material in a number of different modes. In other systems, rectangular waveguides excited in the TE_{10} mode have been used either in a serpentine configuration or in an elongated, straight configuration to heat material passed either perpendicularly through the broadwalls or entirely within the applicator in a direction parallel to the broadwalls.

In addition to such waveguide applicators, cylindrical resonant cavities have been used to heat filaments and the like. It has also been suggested to use a circular waveguide to heat sausage, as in U.S. Pat. No. 3,537,385.

The primary differences between a cylindrical resonant cavity and a circular waveguide are that the microwave energy travels along the axis of a waveguide, whereas the energy does not propagate in a resonant cavity, and secondly, the field intensities capable of being achieved in a resonant cavity are much higher than are normally achieved in a waveguide.

In the present invention, a circular waveguide is excited preferably in the TM_{01} mode. In this mode, an electric field vector distribution is concentrated along the axis of the cylinder, and the microwave energy propagates from an input section axially along the waveguide to an output section. The remnant microwave energy is conducted to absorbing water loads from the output section. The intensity of the microwave energy is thus uniform for all azimuthal positions, depending only upon the distance from the axis of the waveguide. This system has advantages over resonant cavities in that while large electric field intensity values are capable of being achieved, the extremely large values found in a resonant cavity are not present, and the present system is not as sensitive to the presence of material within the applicator—leading to a greater stability in the system operation.

Excitation of the waveguide of the present invention is accomplished by means of a hybrid input network which divides the incoming energy coupled to the network by means of a rectangular waveguide excited in the TE_{10} mode. The energy is divided and fed to diametrically opposite locations at the input section of the cylindrical waveguide.

In an alternative embodiment, a sheet of material may be processed by passing it diametrically through the center of the waveguide.

Other features and advantages of the present invention will be apparent to persons skilled in the art from the following detailed description of a preferred embodiment accompanied by the attached drawing

wherein identical reference numerals will refer to like parts in the various views.

THE DRAWING

FIG. 1 is perspective view of a waveguide applicator incorporating the present invention;

FIG. 2 is an upper perspective view of the input portion of the system of FIG. 1;

FIGS. 3a and 3b are diagrammatic cross sectional and longitudinal sectional views illustrating a circular waveguide excited in the TM_{01} mode;

FIGS. 4a and 4b are respectively transverse cross sectional and longitudinal cross sectional views of a circular waveguide excited in the TE_{11} mode;

FIG. 5 is an upper perspective view of the output section of the waveguide system of FIG. 1;

FIG. 6 is a longitudinal cross sectional view of the input section to the waveguide system of FIG. 1;

FIG. 7 is a transverse cross sectional view taken through the sight line 7—7 of FIG. 6; and

FIGS. 8 and 9 are diagrammatic side and end views respectively of a circular waveguide system according to the present invention modified to process sheet material.

DETAILED DESCRIPTION

Before describing the preferred embodiments in detail, an overall description of the invention will be given. Microwave energy from a conventional source, such as a magnetron, excites a rectangular waveguide in the TE_{10} mode, and it is fed to one of two input/output ports of a rectangular hybrid network. The hybrid network has two output ports which are coupled by means of rectangular waveguide coupling sections of equal length to diametrically opposite locations at one end of a cylindrical waveguide applicator.

Depending upon which input port of the hybrid network is excited, the circular waveguide applicator is excited either in the TM_{01} or the TE_{11} mode, and the resulting microwave energy is propagated axially along the circular applicator.

Granular product is conveyed through a dielectric tube along the axis of a cylindrical applicator, either under flow of gravity or by means of a conveyor. Remnant microwave energy at the end of the applicator opposite the end at which the microwave energy is fed in, is coupled out of the applicator and fed to terminating sections. This minimizes reflected power and safeguards against damage due to reflection of power back to the source.

Referring first to FIG. 1, reference numeral 10 generally designates a cylindrical waveguide applicator excited in the TM_{01} mode and adapted to process particulate matter. The waveguide 10 has a cylindrical conductive side wall 11, and its axis is oriented vertically so that the particulate matter may flow through the waveguide under force of gravity. Alternatively, it is envisioned that applications may call for reducing the speed of throughput of the material being processed or shaking it, in either of which cases it may be desirable to incline the axis of the cylindrical side wall 11 relative to the vertical. Still another embodiment is shown in FIGS. 8 and 9 wherein the axis of the cylindrical side wall 11 is oriented horizontally.

At the top of the circular waveguide 10 there is an input section generally designated by reference numeral 12. Both the product and the microwave energy are fed into the input section 12, although the invention is not so limited—that is, the microwave energy could be coupled into the bottom section of the waveguide. The microwave energy in either case propagates along the axis of the circular waveguide 10.

Input microwave energy is coupled from a source (not shown) by means of an input rectangular waveguide 13 excited in the TE_{10} mode. The rectangular waveguide 13 has relatively narrow side walls 14 and 15 together with top and bottom broadwalls designated 16 and 17 respectively. When excited in the TE_{10} mode, the electric field intensity vector extends perpendicularly between the broadwalls 16, 17, and the intensity varies sinusoidally, being zero at the side walls 14, 15 and at a maximum midway between them. The microwave energy propagates from the source through the rectangular waveguide 13 to a hybrid input network generally designated by reference numeral 18. The hybrid input network 18 has four separate ports, including a first input port 19 sometimes referred to as a "sum" port connected to the output of the input waveguide 13; a second input/output port 20 taken at the top broadwall of the hybrid network 18, and first and second output ports 21, 22. The output ports 21, 22 share a common broadwall with the input port 19, and the input/output port 20 (sometimes referred to as the "difference" port) extends upwardly perpendicular to the input port 19, and it is connected by means of a rectangular waveguide 23 to a terminating load generally designated by reference numeral 24. The broadwalls of the connecting waveguide 23 extend parallel to the direction of propagation of microwave energy in the input waveguide 13. The load termination 24 takes the form in the illustrated embodiment of a series of parallel radiator plates 25 for dissipating any energy that may pass through the difference port 20. Ideally, however, no such energy passes through the difference port, the incident energy being evenly split between the two output ports 21, 22. The hybrid network 20 is a 180° hybrid sometimes referred to as a "magic tee" network. This device is fabricated of rectangular waveguide, and when the input port 19 is excited in the TE_{10} mode the incident power is divided equally between the output ports 20, 21, and the output power of both ports have the same phase. No power is ideally coupled out of the difference port 20. Conversely, if power is fed into the difference port 20, it again divides equally between the output ports 21, 22; however, the electric field intensity vectors are out of phase by 180° , although they are of equal intensity. Hence, by exciting the appropriate input/output port, the output electric fields are either in phase or 180° out of phase. This is important, as will be explained in more detail below, to achieving an excitation of either the circular TE_{11} or TM_{01} modes, as desired, depending on which port of the hybrid serves as the input port. In the configuration shown, the output waveforms are in phase, as already mentioned. The output power from port 21 is coupled by means of quarter-circle rectangular waveguide sections 24 and 25 into one side of the cylindrical wall 11; and the output power of the other port 22 is similarly coupled into a diametrically opposite

side of the cylindrical side wall 11, both coupling locations being adjacent the input end of the circular waveguide 10, as best seen in FIG. 2 and designated respectively by reference numerals 26 and 27. To form such input ports, sections of the cylindrical side wall 11 are cut out so as to conform with and receive the respective rectangular input coupling waveguides.

There are three screw tuners 29 located in the upper broadwall of the quarter-circle curved feed waveguide 25 which are used to match the impedance of the feed-in waveguide to the input impedance of the circular waveguide 10. Similar screw tuners 30 are located in the upper broadwall of the complementary curved feed waveguide designated 31 which is coupled to the rectangular feed-in waveguide 27.

Still referring to FIG. 2, a feed-in topper for the granular material is designated generally 31, and it takes the general form of an inverted cone, the narrow end of which is connected to a dielectric tube 32 which extends coaxially through the center of the circular waveguide 10. A metallic conductive sleeve 33 extends around the feed tube 32 externally of the circular waveguide 10 and upwardly of the upper end plate 34 thereof for preventing radiation of the internal microwave energy into the atmosphere. A transversely slidable shut-off plate 35 is located between the lower part of the funnel hopper 31 and the input of the dielectric tube 32 to shut off the feed in of particulate matter, if desired.

As best seen in FIG. 6, the lower portion of the feed-in sleeve is provided with an annular plate 37 which is located within the waveguide 10 and adjustable axially thereof by means of a vertical apertured rack 38 (FIG. 2) and a bolt 39 threadably received through one of the apertures of the rack 38 into the collar or sleeve 33. The plate 37 acts to reflect microwave power transmitted upwardly of the circular waveguide 10, and by being able to adjust it axially relative to the feed-in location of the rectangular feed-in guides 26, 27, reflection downwardly may be optimized. That is, the plate 37 is adjusted, together with the screw tuners to minimize power reflected back to the source while propagating the power along the axis of the circular waveguide for processing the material.

Referring now particularly to FIGS. 1 and 3, at the discharge end of the circular waveguide 10, a cylindrical conductive sleeve 40 is connected to and extends beneath a transverse end plate (not shown), and the sleeve 40 also protects against radiation of remnant microwave energy into the atmosphere. The dielectric tube 32 extends through the discharge protective tube 40, and deposits the granular material onto a conveyor belt 44 which is formed into a trough by means of a metal supporting channel 45. The conveyor 44 is driven in the direction of the arrows, and it is returned about an end-driven roller 46 journaled in the sides of two channel frame members 47.

Located above the transverse bottom plate forming the lower end of the circular waveguide 10 and conductively coupled to the cylindrical side wall 11, are two diametrically opposite output waveguides 47 and 48 which are continued in an upward direction respectively by means of curved rectangular waveguides 47a and 48a which lead respectively into vertically oriented rectangular straight waveguides 49 and 50. Each of the

vertical waveguides 49 and 50 are provided with water loads—that is, water is continuously fed through these respective waveguides to absorb any remnant microwave power which is coupled to them adjacent the discharge end of the circular waveguide 10. In the illustrated embodiment, the remnant energy is coupled into the rectangular termination waveguide 49 and 50 in the TE_{10} mode, and the water loads thus preferably take the form of a dielectric conduit (designated 51 in FIG. 1) extending along the transverse center of the terminating waveguide section 50 because the electric field intensity is at a maximum at this location for this particular mode. The aperture into which the conduit 51 is fed may be protected against radiation by means of a cylindrical sleeve 52 at the input, and 53 at the output. A similar water load is provided for the termination waveguide section 49, and the output protective sleeve 54 can be seen, the output continuation of the conduit being designated 55.

Turning now to FIGS. 3A and 3B, there is shown in diagrammatic form the idealized representations of electric field vector and the magnetic field vector for a circular waveguide excited in the TM_{01} mode. The electric field vectors are shown in solid line, and the magnetic field vectors are shown in dashed line. In FIG. 3A, the electric field vectors are seen to extend radially outward of the axis of the cylindrical side wall, and the intensity of the field at the center is the same in all directions of azimuth. The intensity does, however, diminish from a maximum and at the center to zero at the conducting side walls. The magnetic field vectors extend in concentric circles about the axis. Referring to FIG. 3B, there are shown adjacent phases of the propagating electromagnetic field. The circles represent cross sections of the magnetic field vector, the darkened circles being representative of magnetic field lines extending into the plane of the page, and the undarkened circles representing magnetic field lines extending outwardly of the plane of the page.

The TE_{11} mode is shown in FIGS. 4A and 4B, again the lines and circles representing idealized field lines. In this mode, the electric field vectors extending in any one cross sectional plane are of the same polarity, extending from one hemisphere to the other in the generally circular arcs shown. The magnetic field vectors are orthogonal to the electric field vectors.

As mentioned, the input feed network, including the rectangular guide hybrid tee network may be used to excite the TM_{01} mode by coupling the input microwave energy to the sum input port and by feeding the output energy from both output ports into diametrically opposite locations of the circular waveguide. Alternatively, if the load 24 is connected to the sum port, and the rectangular input feed guide is connected to the difference port 20, again excited in the TE_{10} mode, then the output fields will be 180° out-of-phase at the rectangular input coupling waveguides 26, 27 and the TE_{11} mode will be generated. The lowest order mode of propagation for the circular waveguide is the TE_{11} mode, and if it is desired to propagate this mode, the radius, a , must be greater than $(1/3.41) \lambda_0$. Other modes may be suppressed by keeping the radius, a , of the circular applicator beneath cut-off of the TE_{21} mode, that is, a should be less than $(1/2.06) \lambda_0$, where λ_0 is the free-space wavelength of the excitation

frequency. If, on the other hand, it is desired to propagate the TM_{01} mode, then a should be equal to or greater than $1/2.61 \lambda_0$. By maintaining a less than $(1/2.06) \lambda_0$ the propagation of higher order modes will again be suppressed. It is desired to have substantially all of the energy in the TM_{01} mode for those applications which require large values of electric field intensity parallel to and along the axis of the cylindrical side wall of the applicator and in which it is desired that the intensity of the electric field vector be dependent only on the radius vector, r (that is, the distance from the axis) and independent of azimuthal position. Since the TE_{11} mode can propagate simultaneously with the TM_{01} mode, it is highly advantageous to excite the circular waveguide in the manner illustrated in FIG. 1 to maintain the energy substantiated entirely in the TM_{01} mode. In this connection, the oppositely facing input couplers from the rectangular hybrid tee network should be of equal length from the output port of the network to the input of the circular waveguide to maintain proper phase relationship. Since the TM_{01} mode can propagate in both axial directions, the shorting plate 37 is placed on the inlet side of the coupling section to reflect power propagating into the shorted section. The short position is set so that a minimum of power is reflected from the coupler toward the power source. Thus, the power is contained substantially entirely in the TM_{01} mode and propagates axially down the circular guide toward the output coupling section and into the terminating arms.

The power remaining is then coupled into the water load terminating sections and dissipated.

Since the largest magnitude of the electric field intensity is parallel to the axis at the radius vector equal to zero (that is, along the axis) the product to be heated is conveyed along the axis of the cylinder. I have calculated the strength of the electric field squared on the center of the circular waveguide since power dissipated per unit volume of products being treated is proportional to the square of the internal electric field. A plot of this parameter, normalized with respect to the microwave power in the mode reveals their values in excess of those obtained in a WR975 rectangular waveguide are possible, and hence, much higher heating rates are possible in such a device.

For granular products treated in a 915 MHz. applicator (or any other product capable of traveling axially within a 2 to 3-inch diameter tube) conveyed in the axial direction, the heating is essentially uniform across the cross section. In steady state processing, the effects of standing waves in the TM_{01} mode along the applicator are minimal. In a particular applicator, I excited the applicator with a frequency of 915 MHz, and a power level up to 30 KW. The applicator axis was horizontal, and a 2-inch internal diameter quartz tube was used as the dielectric tube. A flexible Teflon-coated Fiberglass belt was used as a conveyor to convey the product axially in the horizontal position. Alternatively, when the applicator is vertically oriented, as in the embodiment illustrated in FIGS. 1 and 2, a screw conveyor could be used to control volume flow or, the speed of the discharge belt at the bottom could be used to control discharge rate. Tests conducted on rice and vermicelli have demonstrated a uniform processing in very rapid heating periods. It is possible to puff essentially dry rice

(10-14 percent moisture) and to cook pre-soaked rice very uniformly.

The position of the top and bottom transverse endplates are selected to match the feed network to the waveguide and to match the waveguide to the water load terminations respectively. For the illustrated structure, these endplates were positioned with respect to the opposing WR975 waveguide ports without conveying product to the dielectric tube but with the dielectric tube extending coaxially with the cylindrical side wall. The addition of granular products, especially those with high moisture contents (that is, 20 to 50 percent on a dry weight basis) provided various magnitude mismatches to the generator that had to be minimized for optimum microwave power usage and magnetron protection by means of the symmetrical arrangement of screw tuners 29 and 30 that are used to compensate for the product-dependent mismatch at the feed end of the applicator. With product standing in the dielectric tube, the screws 29, 30 are inserted symmetrically about the applicator until the impedance mismatch is minimized over the operating frequency of the power source. By symmetrically, I mean, for example, that both inboard screws are inserted to the same depth in the guide, both middle screws are inserted and equal distance (although not necessarily the same as the inboard screws), etc. In this manner, the phase delays in the curved input feed guide sections are maintained equal and the excitation in the TM_{01} mode is assured. In addition to the screw tuner arrangement, the shorting plate 37 within the TM_{01} mode guide is adjusted in position either by the fixed incremental positioning mechanism illustrated or by means of screw threads until the minimization using both the screw tuners and the plate is sufficiently low and broad band to insure good system performance.

The absorption in the TM_{01} mode with substantially all of the products tested has been found to be greater than 90 percent over the applicator length; hence, a mismatch at the termination or discharge end does not have a significant effect over the reflected power to the microwave power source. That is, this mismatch is buffered by the absorbing product and it has been found not necessary to reduce this mismatch. Further, heat transfer from hot air flowing within the structure cocurrent or counter current to the propagation of microwave power may be used to maintain the external temperature of the dielectric tube to a desired value.

In one particular embodiment, operating at a frequency of 915 MHZ in the TM_{01} mode, the internal diameter of the cylindrical side wall was 11.5 inches, and the overall inside axial length was 102 inches. The unit has been used to process at input microwave power levels varying from 2 KW to 30 KW. Slurries and fluids could also be heated within an applicator and the tube of the type illustrated.

Turning now to the embodiment diagrammatically illustrated in FIGS. 8 and 9, the circular waveguide 10 has its axis extending horizontally; and again, the rectangular hybrid input network is designated 18. Terminating waveguide sections are also designated 49 and 50. In this case, the endplates do not contain apertures, as the product, designated by S is fed through slots 75, 76 formed in diametrically opposite locations in the cylindrical side wall 11. The sheet material S is con-

veyed diametrically, as illustrated through the center or axis of the cylindrical side wall. Radiation is suppressed by means of conductive plates extending outwardly of the side wall of the guide, parallel to the direction of conveyance of the product. These plates are designated by reference numeral 78, and they are located, as shown, above and below each of the slots 75, 76.

The TM_{01} mode has currents generated on the cylinder walls that are oriented parallel to the axis of the applicator. The slots thus formed are parallel to the current direction, and this helps to minimize leakage by radiation.

The configuration has advantages over other types of microwave applicators in that high electric fields parallel to the web or sheet material being processed can be applied without high waveguide wall losses, as occur in some wave-guide applicators.

Having thus described in detail preferred embodiments of the present invention, persons skilled in the art will be able to substitute equivalent elements for those which have been disclosed and to modify certain of the structure that has been described while continuing to practice the principle of the invention; and it is, therefore, intended that all such modifications and substitutions be covered as they are embraced within the spirit and scope of the appended claims.

I claim:

1. A system for applying microwave energy to a product comprising: a rectangular hybrid input feed network excited in the TE_{10} mode and having a sum input port, a difference input port, and first and second output ports; a cylindrical waveguide applicator elongated in an axial direction and having a radius, a, large enough to propagate the circular TM_{01} mode and small enough to suppress higher order modes; a pair of rectangular coupling waveguides of equal transmission length and coupling respectively said first and second output ports of said hybrid tee network to diagonally opposite locations of said cylindrical waveguide to excite the same either in the TM_{01} mode or the TE_{11} mode; and means for passing a material to be treated through the axis of said cylindrical waveguide.

2. The system of claim 1 wherein the sum input port of said hybrid tee network is excited by a source of microwave energy in the TE_{10} mode, whereby said cylindrical waveguide is excited in the TM_{01} mode, and wherein said means for conveying said product includes a dielectric tube extending coaxially with the cylindrical side wall of said cylindrical waveguide for conveying the product in a neighborhood surrounding the axis thereof.

3. The system of claim 1 wherein said cylindrical waveguide further includes diametrically opposite axially elongated slots adapted to convey sheet material transverse of the axis thereof.

4. The system of claim 1 further comprising output termination waveguide means for coupling remnant microwave energy passing through said circular waveguide to a terminating load to absorb the same.

5. The system of claim 1 wherein said cylindrical waveguide comprises first and second endplates, said pair of rectangular coupling waveguides being located adjacent said first endplate, said system further comprising a shorting plate interposed between said first endplate and said rectangular waveguides; and means

for adjusting said shorting plate axially of said cylindrical waveguide for reflecting power along said cylindrical waveguide while minimizing reflection to said source of microwave energy.

6. The system of claim 5 further comprising symmetrical tuner means in each of said rectangular coupling waveguides for matching the output impedance of said coupling waveguides to the input impedance of said cylindrical waveguide.

7. A system for applying microwave energy to sheet or rod material comprising: a rectangular hybrid tee

input feed network excited in the TE_{10} mode and having an input port, and first and second output ports; a cylindrical waveguide applicator elongated in an axial direction; a pair of rectangular coupling waveguides coupling respectively said first and second output ports of said hybrid tee network to excite said cylindrical waveguide; and means for passing said sheet or rod material diagonally through the center of said circular waveguide.

* * * * *

15

20

25

30

35

40

45

50

55

60

65