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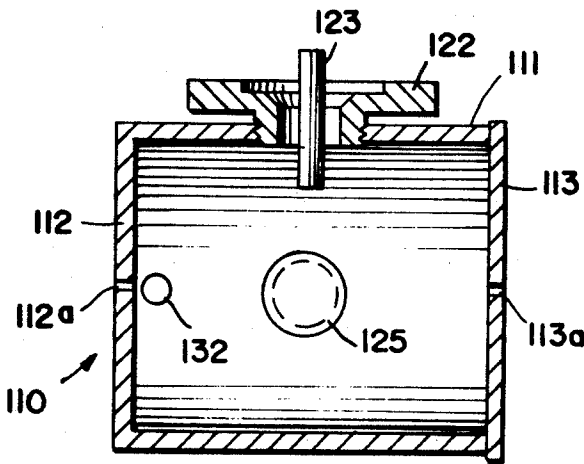
[54] **RESONANT CAVITY MICROWAVE APPLICATOR**
6 Claims, 7 Drawing Figs.

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ABSTRACT: A resonant cavity, defined by a cylindrical sidewall and first and second transverse end plate members, is excited in the TM₀₁₀ mode by a source of microwave energy to generate an electric field with lines extending generally parallel to the axis of the sidewall of the cavity. The intensity of the electric field increases in a radial direction of the cavity from a minimum at the sidewall to a maximum along the axis. A thin, continuous slot is provided in the sidewall and end plates so that a filament can be inserted into the cavity in an axial disposition and then moved lengthwise along the axis of the cavity for drying. Air is preferably circulated through the cavity for carrying away moisture and for cooling the sidewalls of the cavity. An adjustable stub, mounted for radial movement in the cavity, tunes the resonant frequency of the cavity to match the frequency of the source. A coupling probe is located on one of the end plates; and the tuning stub is adjusted to maximize power coupled to the probe for tuning.



RESONANT CAVITY MICROWAVE APPLICATOR

BACKGROUND AND SUMMARY

The present invention relates to an applicator for applying microwave energy to a filament or strand to heat it; more particularly, it pertains to a microwave applicator adapted to heat a filament which is continuously fed through the applicator so that the heating may be carried on without interrupting the application of power to the applicator.

One of the first developments in the application of microwave energy to material was the so-called batch-type oven in which food material is placed within a multimode cavity, the cavity sealed, and the oven excited by a source of microwave energy. The dimensions of the cavity are several wavelengths of the excitation frequency on each side—thus, a number of different modes are permitted to exist simultaneously within the cavity; and mode stirrers and reflectors are located within the cavity to enhance the generation of these other modes in an effort to more evenly distribute the microwave energy per unit volume contained by the oven.

A continuous-type microwave oven was developed for feeding microwave power into an elongated tunnel through a series of slit openings spaced longitudinally of the tunnel. A common waveguide feeds each of the openings in an effort to excite a number of different modes within the tunnel. Hence, these tunnels are themselves multimode cavities. A continuous belt conveys material being treated through the tunnel; and energy-absorbing devices are provided at each end of the tunnel adjacent the entrance and exit openings for preventing the escape of radiation into the surrounding atmosphere and for absorbing excess microwave energy to prevent damage to the system.

Waveguides have been folded into a serpentine configuration to permit the product to pass through aligned slots in opposing broadwalls of a number of waveguide sections folded so that all of the slots are aligned. Energy is coupled into one end of the waveguide to excite a traveling wave which makes a number of passes through the material transverse of the direction of movement of the material finally terminating in a water load.

A copending, co-owned application of Ray M. Johnson for CONTINUOUS MICROWAVE HEATING OR COOKING SYSTEM, Ser. No. 816,722, filed Apr. 16, 1969, describes a rectangular waveguide applicator excited in the TE_{10} mode wherein the material being treated is conveyed to the applicator along the direction of power flow. The symbol "TE" refers to the Transverse Electric field vector; and "TM" refers to the Transverse Magnetic field vector. Reject filters are provided in this system at the input and exit apertures to prevent the escape of microwave energy; and a termination is provided downstream of the heating chamber to absorb microwave energy not absorbed in the material being treated so that the source sees a load which is substantially independent of variations in the amount of material being treated.

In the present invention, a resonant "cavity" in the form of a right circular cylinder is excited in the TM_{010} mode by a source of microwave energy. That is, the magnetic field vectors extend in concentric circles. Each circular field line extends in a plane perpendicular to the axis of the cavity and has its center located on that axis. As used herein, the word "cavity" refers to the conductive wall members as well as the volume defined thereby; the volume alone is sometimes referred to as the heating chamber. Thus, the resonant cavity provides a heating chamber for the material being treated.

The cavity is preferably lined with a material having a low resistivity, such as silver, although the material may be aluminum. When the cavity is thus excited, electric field lines are generated within the heating chamber extending generally parallel to the axis of the cylinder. The intensity of the electric field increases in a radial direction from a minimum at the sidewalls to a maximum along the axis; and the intensity is substantially uniform along any given line parallel to the axis.

That is to say, the intensity profile of the electric field in a plane transverse of the axis is at a maximum in the center of the plane and then decreases as one proceeds radially toward the sidewall. Approximately the same intensity profile exists for each such plane along the axis of the cavity.

As mentioned, the magnetic field lines are formed in circles about the axis; and the intensity of the magnetic field is at a minimum along the axis and increases toward the cylindrical sidewalls. The current vectors extend along the cylindrical sidewalls parallel to the axis thereof and radially along the transverse end plates which form the cavity. A slot for initially threading the filament into the applicator is formed in the transverse end plates and along the cylindrical sidewall. The threading slot lies in a plane which extends through the axis of the cavity, and thus, it does not interrupt the current flow and inhibits the radiation of microwave energy through the slot.

Since it is possible to support the TE_{11} mode of propagation when the TM_{010} mode is propagated, the axial length of the cavity is preferably maintained less than one-half wavelength of the excitation frequency to confine the field to the TM_{010} mode.

The cavity is excited by means of a conductive loop energized by the source of microwave energy and extending into the cavity at a location of maximum magnetic field intensity and minimum electric field intensity to minimize the chance of electrical breakdown. The conductive loop also permits matching the input impedance of the cavity to the output impedance of the source. Alternatively, the cavity may be excited by a coupling aperture from a feed waveguide, or it may be symmetrically excited with properly phased coupling apertures if care is taken not to excite the TE_{11} mode.

In the preferred embodiment, the threading slot communicates the exterior of the applicator with the axis of the cavity and facilitates the "threading" of a single-ended filament into the applicator to be moved along the axis. When microwave energy is applied to the filament, the filament extends in the direction of the field lines for maximum coupling, and it lies along the location of maximum field intensity. Thus, the filament may be dried of its moisture content at a fairly high transport rate within a minimum of distance.

An adjustable screw is located in the cylindrical sidewall to adjust the resonant frequency of the cavity; and tuning of the cavity to the source or excitation frequency under load is sensed by means of a coupling probe located on one of the end plates. The tuning screw may be adjusted to enhance the energy coupled to the probe to maximize power into the cavity.

Provision is made for forcing air into the interior of the cavity for carrying away moisture and for cooling the walls of the cavity which are heated by the currents conducted by the interior surfaces of the walls.

In practice, a number of similar cavities could be employed in parallel, each excited by a separate source of microwave energy.

Thus, the present invention provides a microwave applicator which is simple in construction and useful in applying highly concentrated microwave energy in an orientation which permits maximum coupling of the microwave energy into a filament being treated in a reasonably small space and with high efficiency, safety and reliability.

Other features and advantages of the instant invention will be apparent to persons skilled in the art from the following detailed description of alternative embodiments accompanied by the attached drawing.

THE DRAWING

FIG. 1 is a perspective view of a microwave applicator adapted to heat a filament according to the present invention;

FIG. 2 is a cross section view of the output coupling probe of the applicator of FIG. 1;

FIGS. 3 and 4 are respectively transverse and longitudinal cross section views of the applicator of FIG. 1;

FIG. 5 is a longitudinal cross section view of an applicator excited by a probe;

FIGS. 6 and 7 are respectively transverse and longitudinal cross section views of an applicator according to the present invention excited by a waveguide.

DETAILED DESCRIPTION

Referring to FIGS. 1—4, there is shown an applicator, generally designated by reference numeral 10, for applying microwave energy to a single-ended thread or filament. In one application, the applicator 10 may be used for drying single-ended yarn on a twist frame as is used in the manufacture of twisted, single-strand Fiberglass. During the manufacturing process, the strand is quenched in water; and prior to being wound on a spool for packaging, the water must be removed from the strand. With the compact, reliable apparatus shown, it is possible to perform the drying and twisting operations simultaneously. For example, the filament may be fed and twisted at a rate of 1,000 feet per minute. At this rate, 0.3 pounds of water are required to be removed from a strand each hour. As will be appreciated from subsequent discussion, the water removal is preferably achieved through the combination of the applied electromagnetic heating as well as the inherent evaporation of air passed through the cavity (wherein it is heated) and over the moving filament.

The heating applicator 10 has the general shape of a right circular cylinder including a cylindrical sidewall 11, a transverse bottom plate 12 (FIG. 3) and a removable transverse cover plate 13 all of which define the heating chamber. The cylindrical sidewall 11 defines an axis (designated 14 in FIG. 3) along which a filament 15 is transported.

The transverse end plates 12 and 13 together with the cylindrical sidewall 11 provide a resonant electromagnetic cavity which has the form of a right circular cylinder. When referring to the mechanical structure of the resonant cavity, these boundary walls are sometimes collectively referred to herein as the housing of the cavity; and the housing bears the general designation 16. A slot 16a is formed in the housing 16 of the cavity which slot communicates the axis of the cavity with its exterior. The slot 16a includes three portions; one is designated 12a in FIG. 3 and formed along a radius of the bottom plate 12; a second portion is formed longitudinally of the sidewall 11 and designated 11a; and the third portion is formed radially of the transverse cover plate 13 and designated 13a. Thus the slot 16a lies in a plane which passes through the axis of the cylindrical sidewall of the cavity.

The slot 16 enables an operator to first connect the filament to the transport and twisting mechanism under slight tension before threading it into the applicator. Threading is simply and safely accomplished by flexing the connected, tensioned filament, aligning it with the axial portion of the slot 16 and permitting it to return to its operating position under urging by the tension force. Conversely, the filament is easily removed from its operating position by a simple flexing and pulling motion without ever requiring an operator to place his hand within the cavity or even to touch the housing.

Preferably, the housing 16 for the cavity is formed of two separate pieces. A first cup-shaped member includes the cylindrical sidewall 11 and the end plate 12; and the second transverse end plate or cover plate 13 is formed in the shape of a disc. The cover plate 13 is secured to the open end of the cylindrical sidewall 11 by means of screws as at 17.

A threaded aperture 21 is formed in the sidewall 11 for receiving a flange member 22. The flange 22 is adapted to be connected to a coaxial line or a waveguide coupling a source of microwave energy (not shown) to the applicator 10 to excite the resonant cavity. As seen in FIGS. 3 and 4, a feed center conductor 23 extends through the aperture 21 and is provided with an end coupling loop 24 for exciting the resonant cavity 16.

An externally threaded screw member 25 is also received in a threaded aperture in the cylindrical sidewall 11. The screw 25 is adjustable in a radial direction in the sidewall for tuning the resonant frequency of the cavity to the frequency of the excitation source. A locknut 26 secures the tuning screw 25 in fixed position once the adjustment is made.

A coupling probe generally designated 28 in FIG. 1 and seen in cross section in FIG. 2 is threadably received in the cover plate 13; and it includes a center conductor 29 which partially extends within the cavity 16 in an axial direction and is supported by means of a connector 30 which may be a Type N coaxial connector. The center conductor 29 is then connected by means of coaxial cable to a power meter to monitor the power coupled from the cavity 16. It will be observed from FIG. 1 that the location of the coupling probe 28 is toward the outer peripheral edges of the plate 13. This minimizes the amount of power coupled from the cavity (preferably, of the order of milliwatts). A second function of this probe is to permit matching the input impedance of the cavity to the output impedance of the source by the coupling loop by merely observing power levels.

Also located in the sidewall 11 at a location adjacent the end plate 12 is an internally threaded aperture 32 (FIG. 3) which receives a conduit 32a for communicating the cavity 16 with a source of pressurized air, not shown, to continually force air into the cavity 16. The air will be exhausted through the threading slot 16a described above.

Turning now to the embodiment of FIG. 5, the applicator is generally designated 110, and it includes a cylindrical sidewall 111 together with a transverse end plate 112 integral with the sidewall 111 and a removable transverse cover plate 113. Aligned apertures 112a and 113a are formed respectively in the centers of the end plates 112 and 113. A tuning screw, similar to the previously described tuning screw 25 is designated 125; and an aperture through which air is forced into the cavity is designated 132. A flange 122 is threadably received in the sidewall 111 for coupling a coaxial cable from an excitation source to the cavity; and a straight coupling probe 123 extends colinear with the axis of the circular flange 122. Thus, the embodiment of FIG. 5 is similar to the first embodiment, but the means for exciting the cavity is in the form of a probe as distinguished from the prior loop coupling.

A further means for exciting the cavity is illustrated in the embodiment of FIGS. 6 and 7. In this embodiment, the applicator is generally designated 210; and it includes the cylindrical sidewall 211, a transverse end plate 212 integral with the sidewall 211 and a removable transverse cover plate 213. The axial apertures through which the filament is continuously fed are designated 212a and 213a respectively located in the end plates 212 and 213. A tuning screw designated 225 is threadably received in the sidewall 211 and adapted for radial movement of the cavity. A radially extending threading slot 216 is formed in the end plates 212 and 213 as well as along one side of the sidewall 211 for communicating the axial apertures 212a and 213a with the exterior of the applicator. As with the prior embodiments, the slot 216 is adapted for receiving a single ended filament or thread in the heating chamber defined by the cavity. The sidewall 211 also defines an input power coupling aperture generally designated 250.

As viewed in transverse section (FIG. 6), the input coupling aperture 250 is bounded on either side by progressively narrowing portions of the sidewall designated 211, designated respectively 251 and 252. The edges 251 and 252 of the input coupling aperture provide matching iris's to match the characteristic input impedance of the cavity to the impedance of a waveguide adapter generally designated 253. The adapter 253 is rigidly secured to the exterior of the sidewall 211 about the input coupling aperture 250, and it includes a rectangular flange 254 for receiving a corresponding flange of a rectangular waveguide section coupling energy from the source (not shown). The adapter 253 includes first and second broad walls 255 and 256 (FIG. 7) and first and second sidewalls 258 and 259. The sidewalls 258 and 259 are inclined inwardly of the flange 254 toward their respective connections with the sidewall 211 of the applicator—thus, the broad walls 255 and 256 are progressively narrowed proceeding toward the applicator sidewall 211. The tapered waveguide adapter 253 together with the matching iris's 251 and 252 permit excitation of the resonant cavity applicator without significant reflection of energy back to the source.

In operation, the cavity of the microwave applicators in each of the illustrated embodiments is excited in the TM_{010} mode. The magnetic field lines extend substantially circumferentially about the axis of the cavity. That is, the magnetic field lines, in any one plane transverse of the axis, are arranged in concentric circles, all centered on the axis of the cavity. The intensity of the magnetic field is at a maximum near the interior cylindrical wall of the cavity; and it diminishes proceeding toward the axis of the cavity.

The electric field lines are orthogonal to the magnetic field lines; hence, the electric field lines extend perpendicularly between the transverse end plates in substantially parallel arrangement. All of the electric field lines being parallel to the axis of the cavity. The intensity of the electric field lines is uniform in the axial direction and varies along a radius as the Bessel function of the first kind, order zero. That is, in a transverse plane, the electric field intensity is at a minimum along the cylindrical sidewalls of the cavity and increases to a maximum along the axis of the cavity; and the profile of the electric intensity is substantially the same for any transverse plane taken along the axis and within the cavity. The intensity also increases with frequency.

The radius of the cavity is selected to be slightly lower than the wavelength of the lowest expected resonant frequency of the particular power oscillator used to excite the cavity. By inserting the turning screw into the cavity at a position of high magnetic field, the resonant frequency can be increased with a minimum of displacement. This increase is a function of screw diameter and depth of insertion.

In addition to the mismatch caused by the introduction of the wet filament, an additional frequency shift may be caused by the heating of the cavity due to I^2R losses which will cause an expansion of the walls of the cavity. Thus, the compensation afforded by means of the tuning screw in each embodiment offsets such frequency shifts.

The condition of resonance permits an electric field to be generated with much greater intensities than would otherwise be possible, and with moderate input power. High electric field intensities can be directly related to rapid heating rates in the lossy dielectric material being treated.

The current flow exhibits the skin effect phenomenon along the interior surface bounding the cavity. However, because the cavity is excited in the TM_{010} mode, the currents flow radially of the end plates and axially along the interior surface of the cylindrical sidewalls—that is, in lines substantially parallel with the slots formed in the two illustrated embodiments. Since the threading slots do not interrupt current, there is little or no escape of microwave energy through radiation. Further, it will be realized that the length over which the energy is applied is fairly small, the heating chambers being confined by the respective cylindrical housings.

The intensity requirement for the electric field will, of course, vary from application to application depending upon the axial length of the applicator and the volume of water sought to be removed per unit time. It will, however, be observed that in both embodiments, the orientation of the electric field lines is parallel with the surface of the material being treated at the location of maximum field intensity. This effects a maximum coupling of microwave energy into the material being treated for heating it.

For those applications in which the filament is comprised of wet strands of Fiberglass, we prefer to use a microwave frequency of 2.45 gigaHertz (GHz.) with an axial internal dimension of the cavity of 6 inches and an internal diameter of about 3.5 inches. For rapid heating, large electric field intensities are required. However, dielectric breakdown may occur at the larger field intensities, so it is desired to use as high a frequency as possible. The power requirements for evaporation of the entrained water are somewhat modest, however. The actual coupled power necessary according to calculation is of the order of 100 watts. The realization of high electric field intensities with low power input is accomplished by means of the resonant cavity applicator.

At resonance, the input impedance of such a cavity is real, that is, the capacitive reactance is equal to the inductive reactance. Thus, the average energy stored in the electric field is equal to the average energy stored in the magnetic field.

At microwave frequencies metallic enclosures or cavities are commonly used to replace the usual lumped constant parameter resonant circuits. As mentioned, a cavity is a chamber or space enclosed by a conducting surface and within which an electromagnetic field may be excited and sustained. The electric and magnetic energies are stored in the chamber of the cavity. The current-conducting walls give rise to a power loss, and thus are equivalent to some resistive value in an equivalent circuit. The introduction of a lossy dielectric material gives rise to additional power loss and thus modifies the effective resistance and Q of the cavity. Q is the ratio of dissipated energy to total energy; and a higher Q will permit higher field intensities. The fields in the cavity are excited by means of a coaxial loop, probe or aperture.

In the embodiment of FIGS. 1—3, impedance matching between the source impedance and the impedance of the resonant cavity is achieved by orientation of the end loop 24 of the center conductor 23 projecting into the cavity 16 to couple the maximum amount of power into the cavity. Matching of the frequency at which the cavity resonates to the source frequency in order to minimize the amount of power reflected back to the source is accomplished by means of the tuning screw 25 (or the tuning screws 125 or 225 in the embodiments of FIGS. 5 or FIGS. 6—7 respectively). With the frequency of the cavity tuned to the frequency of the source and the impedance of the cavity matched to the impedance of the source and feeding waveguide, a maximum field intensity within the cavity and a higher efficiency are achieved.

The monopole-coupling probe 28 located in the end plate of the resonator couples a small amount of power (of the order of milliwatts) from the cavity. For a given incident power, the cavity is tuned by means of the screw 25 until the power coupled out through the probe 28 is maximized. This peaking of output power for a constant input power indicates the resonant condition of the cavity—that is, the frequency is adjusted until resonance is achieved. The tuning screw 25 permits the exact matching of the cavity resonant frequency with the oscillation frequency of the magnetron (or other source of microwave energy).

The input power coupler places this loop in the side of the cylinder at a position of high magnetic field intensity but low electric field intensity. By avoiding input coupling (or excitation) at a position of high electric field intensity, the possibility of electric field breakdown at the probe position is significantly reduced.

The provision of the means for blowing air into the cavity insures that the air within the resonator does not become saturated with moisture; and it serves to cool the interior surface of the structure since the power dissipated in the cavity walls results in a pronounced heating of the metal.

For all other parameters constant, the efficiency of the resonator is strongly influenced by the resistivity of the metal used for fabrication (of particular importance because of the skin effect is the metal forming the interior boundary of the cavity). The lower the resistivity of this metal, the smaller are the losses to the resonator walls for a given electric field intensity along the centerline of the cavity. The power coupled to the material along the centerline is directly proportional to the square of the electric field intensity—thus, the resultant increase in efficiency is apparent.

Silver has a very low resistivity and therefore is a desirable material for use in interior surface of a cavity. The plating thickness of 0.2 mil is sufficient to exceed the skin depth of the currents at 2.45 GHz. and thereby to provide the necessary shielding from the bulk portion of the metal comprising the resonator. The use of metals with an even greater conductivity will result in a corresponding increase in efficiency.

The inventive applicator is further suitable to applications requiring a tandem operation wherein the filament is feed

through a number of applicators in succession. In this case, it is desirable to provide a separate microwave oscillator (or source) for each resonator.

Having thus described in detail alternative embodiments of the invention, persons skilled in the art will be able to substitute equivalent elements for those described to perform similar functions, or to otherwise modify the structure or operation of these detailed showings without departing from the inventive principle; and it is, therefore, intended that all such modifications and substitutions be covered as they are embraced within the spirit and scope of the invention.

We claim:

1. Apparatus for applying microwave energy from a source to a material in the form of a filament or thread comprising: a resonant cavity having a cylindrical conductive sidewall, means receiving the microwave energy from said source to excite said cavity to generate an electric field therein substantially the TM_{010} mode wherein the electric field lines are substantially parallel and concentrated along the axis of said sidewall, said cavity receiving said material in a disposition substantially along the axis thereof, and conductive screw means received in said cylindrical sidewall of said cavity and selectively extendible radially of said cavity to tune the resonant frequency of said cavity to the frequency of said source.

2. The apparatus of claim 1 further comprising means for

forcing air through said cavity.

3. The apparatus of claim 1 further comprising block means associated with said screw means for locking said screw means in a predetermined position to thereby fix the resonant frequency of said cavity.

4. The apparatus of claim 3 further comprising probe means in said cavity for coupling a small amount of energy from said cavity to determine the maximum coupling of energy from said source means to said cavity as said conductive screw means is adjusted whereby the resonant frequency of said cavity may more easily be adjusted to the resonant frequency of said source.

5. The apparatus of claim 4 wherein said cavity further includes first and second transverse end plates extending substantially in planes passing through said axis of said sidewall and wherein said cavity defines a continuous slot in said sidewall and said first and second transverse end plates to communicate the axis of said cavity with its exterior to facilitate threading of said material into said cavity.

6. The system of claim 1 wherein said means for exciting said cavity comprises a loop extending within said cavity to excite the same, and means for adjusting the orientation of said excitation loop for matching the input impedance of said cavity with the output impedance of said source.

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