United States Patent

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[54] **METHOD AND APPARATUS FOR REGULATING HEATING IN A MICROWAVE RESONANT CAVITY**
6 Claims, 7 Drawing Figs.

[52] **U.S. Cl.** **219/10.55,** 219/10.77
[51] **Int. Cl.** **H05b 9/06,** H05b 1/02
[50] **Field of Search** 219/10.55; 333/1.1

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ABSTRACT: The method of operation of a microwave resonant cavity system in a preselected undercoupled or overcoupled mode and with preselected frequency offset provides stable heating of dielectric material advancing through the cavity for the purposes of moisture or solvent removal or heat treating. The system includes a three-port circulator coupled between a microwave power source, a resonant cavity and a water load. Means are provided between the circulator and cavity to establish the preselected coupling mode and between the circulator and water load to feed a portion of reflected power from the cavity due to detuning and decoupling to the power source to regulate the shift in frequency of the power source (frequency offset) according to variations in resonant frequency of the load cavity.

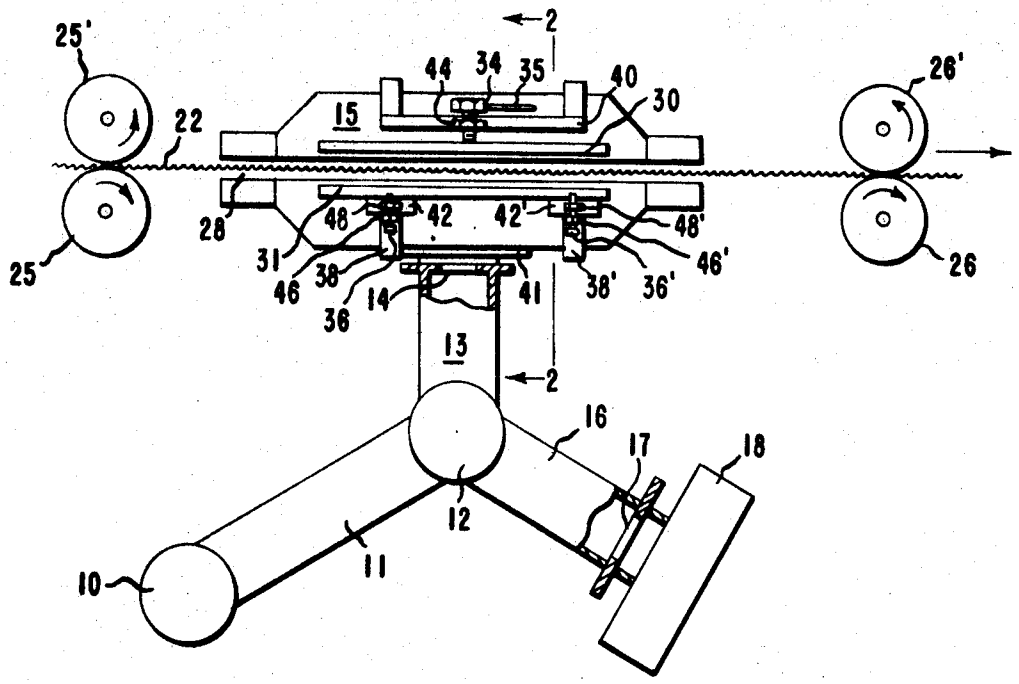


FIG. 1

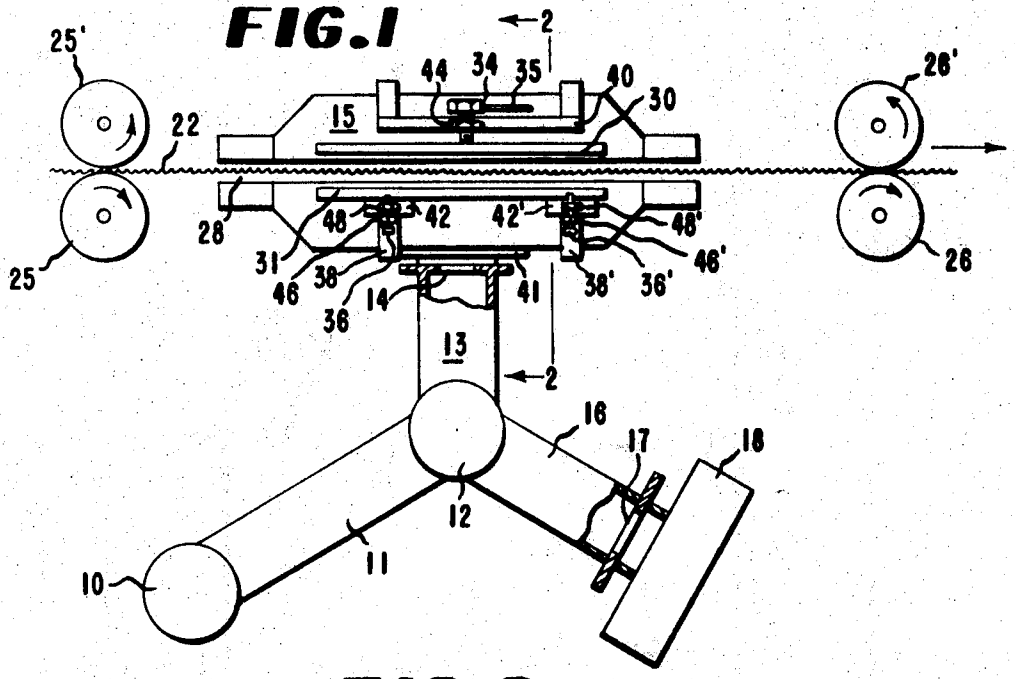
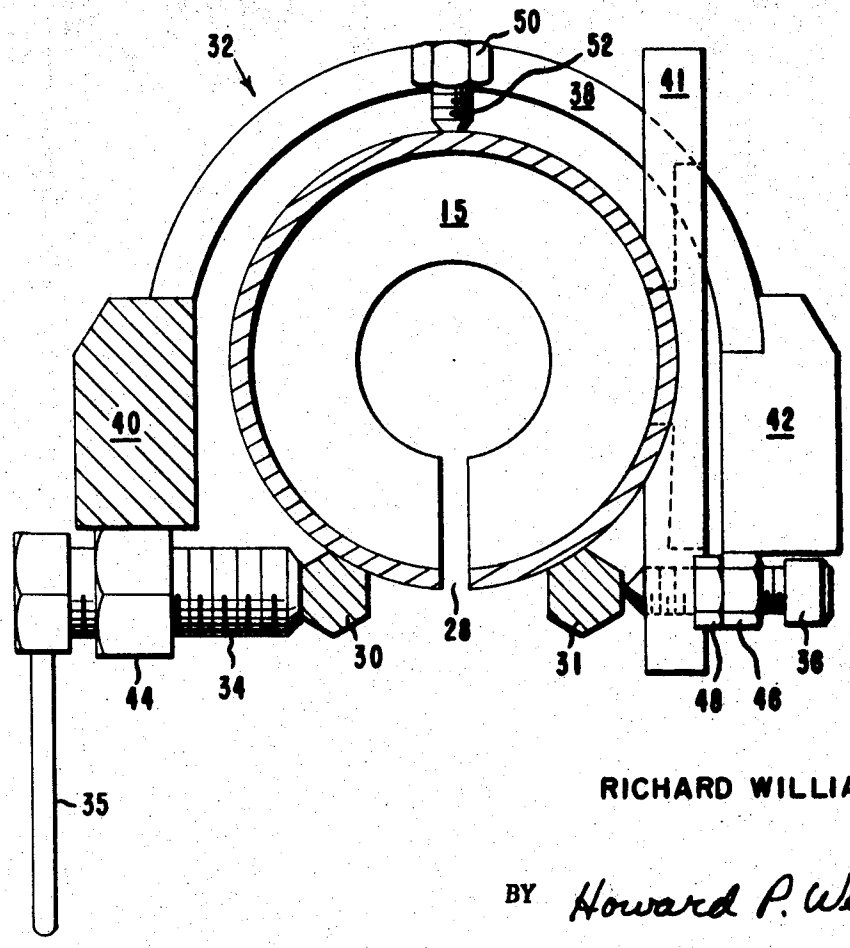


FIG. 2



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FIG. 3

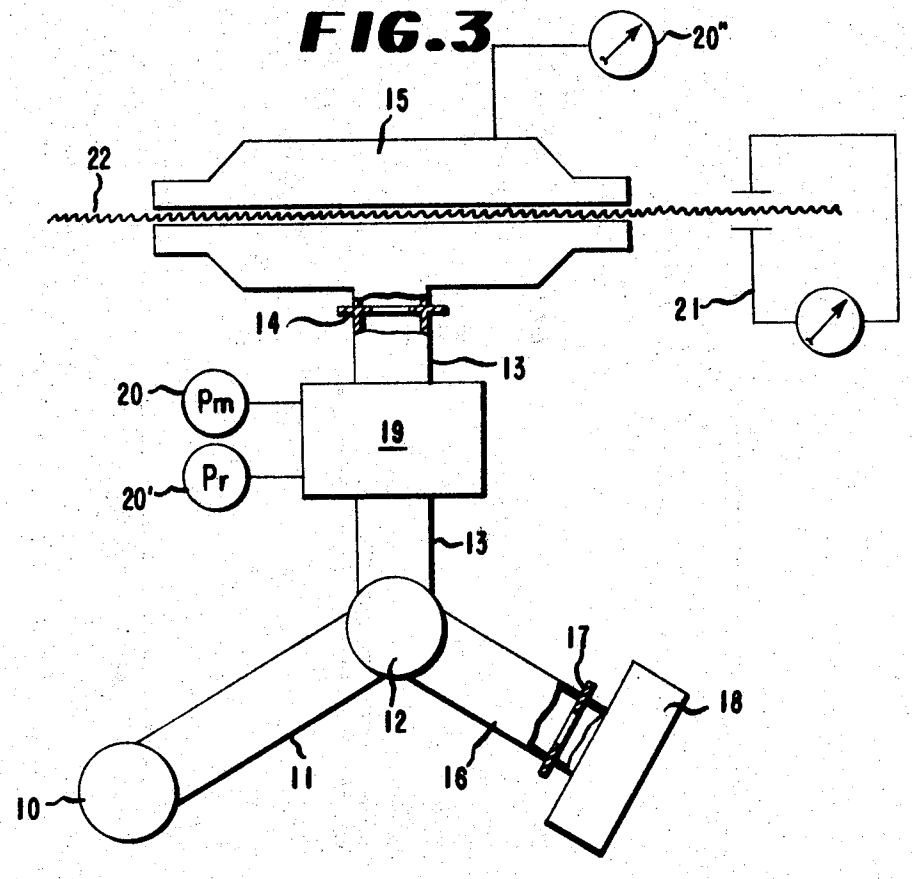
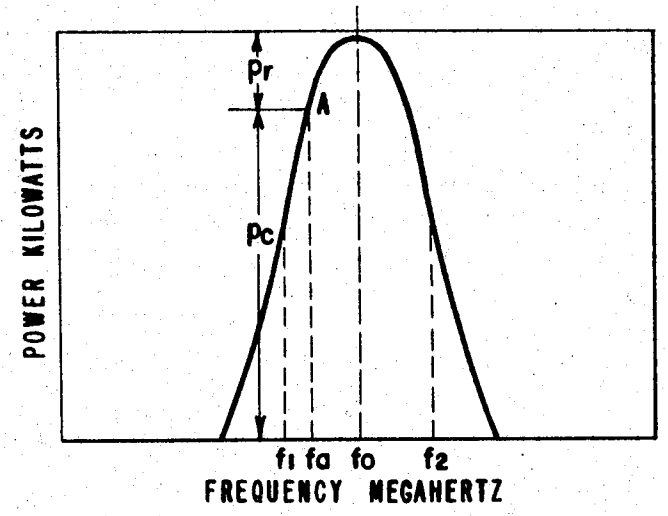


FIG. 4



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FIG. 5

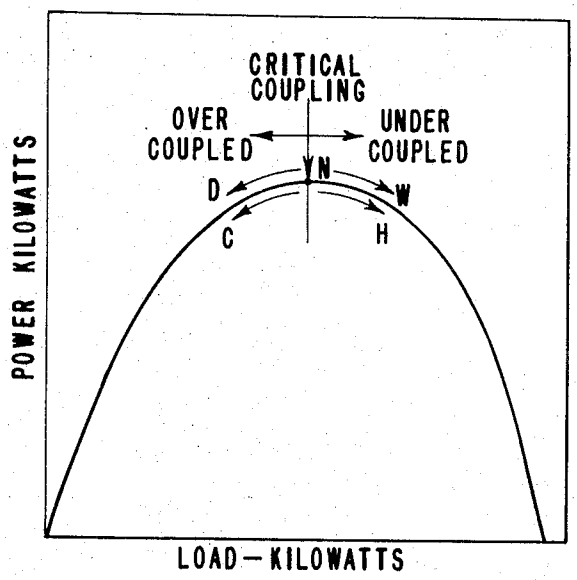


FIG. 6

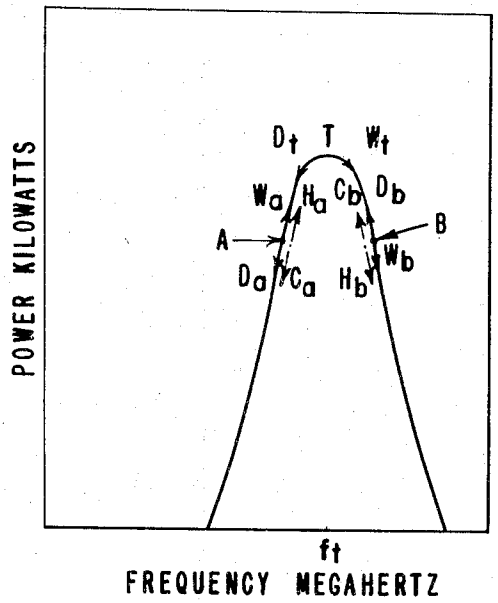
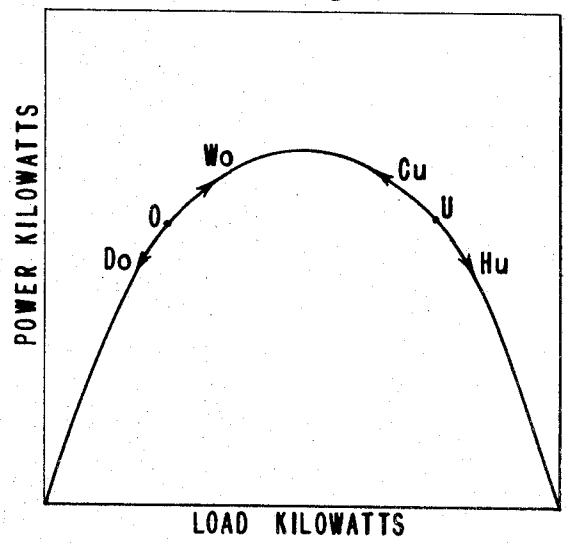


FIG. 7



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METHOD AND APPARATUS FOR REGULATING HEATING IN A MICROWAVE RESONANT CAVITY

BACKGROUND OF THE INVENTION

This invention relates generally to an improved method and apparatus for heating dielectric material by means of microwave energy in which a low loss resonant cavity is employed as a heating chamber. More specifically, it relates to maintaining stability of operation in spite of significant changes in the heating load within the resonant cavity.

One type of resonant cavity to which the present invention applies is disclosed in copending application Ser. No. 590,917, filed Oct. 31, 1966, in the name of Lewis and White and now U.S. Pat. No. 3,461,261.

It is well known to heat various types of materials through exposure to high frequency electromagnetic fields. Conductive or metallic materials are usually heated by placing them in a high frequency magnetic field. Here the predominant heating effects usually result from induced electric currents, but additional heating may result from magnetic hysteresis or other magnetic effects depending on the magnetic characteristics of the material. In contrast, dielectric heating results for many materials which are considered to be nonconductors or dielectrics when they are exposed to a high frequency electric field.

The rate of dielectric heating follows the relationship $P=CE^2f\epsilon''$, where P is the rate of energy absorption per unit volume, C is a constant, E is the electric field strength, f is the frequency of the electric field, and ϵ'' is the loss factor of the material being heated. In continuous processes such as the drying of a continuously moving textile tow or the heat setting of a running yarn line, the rate P at which heat is required depends on processing conditions, such as the throughput of the material and the amount of moisture to be removed or the required temperature rise. To achieve the desired heating rate, it is necessary to select values of frequency and field strength depending on the loss factor of the material being heated. Breakdown and arcing within the cavity puts a practical limit on the field strength that can be employed. Thus for a given set of process conditions, the heating rate is known and, if the dielectric properties are known so that the values of the loss factor and the maximum electric field can be determined, an appropriate range of frequencies can be found from the above equation. However, when the inlet moisture content fluctuates with time and/or the final temperature of material is to be maintained in an assigned range, the novel method and apparatus of this invention are particularly important and useful. Useful dielectric heating has been achieved at frequencies from 500 kHz. (kilocycles/second) to 500 MHz. (megacycles/second) for such applications as drying of foundry sand molds and pharmaceuticals and the curing of glue lines in plywood. However, when desired heating rates are high and/or the materials to be heated have dielectric properties for which the loss factor is quite low, development of heating equipment in the microwave frequency range of 1,000 MHz. and above has been found necessary. The use of such high frequencies in microwave ovens has been successful in the fields of rapid food cooking, foaming and curing of large foamed polymer mattresses and cushions, and the like. However, these devices produce relatively low electric field strengths and are therefore not practical for heating advancing yarn lines, tow or other process streams.

Extremely high electric field strengths have been achieved in resonant microwave structures with a wide variation of spatial electric field concentration arrangements. A resonant microwave cavity specifically suited for yarn or tow heating is described in the above-referenced Lewis & White copending application. It is to resonant cavities of this type that the present invention is particularly applicable.

The dielectric properties define the loss factor ϵ'' for any given material. The loss factor is the product of the dielectric constant ($'$) and the loss tangent ($\tan\delta$). The dielectric constant is a measure of the energy stored in the electric field that

passes through the material compared to the energy that would be stored in the same electric field passing through a vacuum. The loss tangent is a measure of the ratio of energy absorbed to energy stored that occurs in the material in an alternating electric field.

The term dielectric constant is misleading, since it is rarely a constant. It is, in fact, a function of both temperature and frequency for the material in question. For example, at a microwave frequency of about 3,000 MHz., the dielectric constant of water changes slightly downward with increasing temperature, e.g., from 76.7 at 25° to 52 at 95° C. The loss tangent, however, for water drops from 0.157 at 25° C. to 0.047 at 95° C. Values for 6/10 nylon (polyhexamethylene sebacamide) at 3,000 MHz. are 2.84 at 25° C. and 2.94 at 84° C. for the dielectric constant, whereas the loss tangent varies from 0.128 at 25° C. to 0.356 at 84° C., an increase of nearly threefold. A similar change has been found for nylon 6–6 (polyhexamethylene adipamide).

Thus, variations of these types can significantly influence the operation of dielectric heating systems. Since the dielectric constant is related to the energy stored in the electric field that will pass through the material, an increase or decrease in the dielectric constant can cause a corresponding increase or decrease of the capacitance of the load that can cause a change in reactance of the load. For a fixed value of dielectric constant, an increase or decrease in the loss tangent will cause a corresponding increase or decrease in heating since the loss tangent is a direct measure of energy absorbed by the material at constant field strength.

In the past, it has been normal practice to operate resonant cavities for dielectric heating at the resonant frequency for the power source and at maximum level of energy coupling to the power source. However, when such a system is used for removal of moisture from moving tow, for example, a sudden increase in the moisture content in the cavity will change the loading of the resonant cavity. This change in loading will change the impedance of the cavity and cause a shift in coupling, which will reduce the level of power available to be absorbed by the load. In such a case, the heating will decrease when increased heating is needed and the desired drying level will not be achieved. On the other hand, when heating relatively dry polymeric material for heat treating purposes, the dielectric loss factor of the polymer is increased as temperature increases causing an increase in the rate of energy absorption by the material from the electric field that may result in "run-away" heating if the heating is performed at the maximum level of energy coupling.

Although solutions have been disclosed in the prior art for problems of load changes in dielectric heating systems in which the resonant structure is an inductance-capacitance tank circuit for an oscillator tube (the capacitance section being the heating section) none would apply when a microwave resonant cavity is used as the dielectric heating chamber. In this case, there is no known route to automatic stable operation. This is true primarily because the resonant cavities receive microwave power directly from magnetrons or similar power sources which in themselves are generally resonant systems. Effective energy transfer from one resonant system to another requires a close match in the frequency of the two systems and a close match in impedance. Shifting of cavity resonant frequency and/or cavity impedance due to load change normally results in a reflection of power back to the power source. Although this reflected power will in some cases be beneficial in shifting the frequency of the power source (if a magnetron), the reflected power if too great can cause damage to the power source. Additionally, the reflected power is not available within the cavity for heating.

The key to the successful operation of microwave resonant cavity heating systems was the discovery of a method of coupling the resonant cavity and a magnetron power source that permits their combined operation in a controlled and stable manner with a preselected range of frequency mismatch and reflected power. The ability to preselect a frequency and

impedance mismatch between a microwave resonant cavity and the magnetron supplying power to it makes possible the choice of an inherently stable mode of operation by which polymeric materials can be heated.

SUMMARY OF THE INVENTION

Inherent stability of heating of dielectric material is achieved by this invention in a microwave resonant cavity which is purposefully decoupled and detuned from a critical coupled and matched frequency relationship with the power source in a direction and to an extent depending upon the characteristics of the material being heated. For moisture or solvent removal, the cavity is overcoupled and tuned to a resonant frequency slightly above power source frequency. On the other hand, when heating relatively dry polymeric material primarily for the purpose of raising its temperature to a predetermined level, the cavity is undercoupled and tuned to a resonant frequency slightly below that of the power source.

Operation of a microwave resonant cavity in the preselected undercoupled or overcoupled mode and with the preselected direction of frequency offset of this invention has been achieved in a system in which a preselected percentage of the power reflected from the cavity is purposefully directed back to the magnetron. The percentage of power is chosen so that if total reflection occurs at the cavity, the amount of power reaching the magnetron is below the level which will damage the magnetron. The percentage of power is chosen large enough to provide the required increase in the "pulling" range of the magnetron to accommodate the preselected range of frequency offset.

The preferred embodiment of a system or apparatus to achieve the objects of this invention comprises a tunable microwave resonant cavity heater, a magnetron source of microwave energy, a circulator and a water load. The circulator is coupled to the source, the heater and the water load by respective first, second and third waveguide sections. A first iris is positioned in the second waveguide section to decouple the heater from a critical coupled relationship with the source and reflect a portion of the energy from the source back through the circulator toward the water load. The heater is also detuned from a matched frequency relationship with the source which causes additional energy reflection. A second iris is positioned in the third waveguide section to reflect a predetermined part of the portion of energy being reflected toward the water load back through the circulator to the source to provide partial pulling of the source frequency which in turn provides required frequency offset. The novel combination of an iris and a water load in one leg of the system has been found to be a very simple yet versatile combination for preselecting the percentage of power which is permitted to return to the magnetron. In the extremes, the absence of the second iris permits essentially all of the reflected power to be dissipated or absorbed in the water load and essentially no power will be fed back to the magnetron to "pull" its frequency in the direction of any shift of resonant frequency of the cavity. On the other hand, a complete reflection at the water load directs all of the reflected power back to the magnetron so that maximum "pulling" of its frequency towards that of the cavity is produced. This latter case nullifies the purpose of the circulator and water load combination which is to permit frequency offset and allow for magnetron protection. Furthermore, operation such as in the latter case is as if there were a direct connection of magnetron to cavity as described in the aforementioned copending application. Operation then would in effect be in a matched frequency condition.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic drawing in partial section showing the component arrangement of the microwave heating system;

FIG. 2 is a partially sectioned end view of a resonant cavity and cavity tuning frame, this view taken in the plane perpendicular to FIG. 1 along lines 2–2 with view rotated 90° counterclockwise and enlarged resonant cavity and cavity tuning frame;

FIG. 3 is a schematic drawing showing the system arrangement with instrumentation for use in setting system operation for optimum control when heating a continuously running length of material;

FIG. 4 is a graphical representation of power transferred into a resonant cavity as a function of frequency;

FIG. 5 is a graph of power transferred to a cavity as a function of the dissipating load in the cavity for a coupling iris of fixed construction having notations to depict the effect of moisture content and temperature variations of the material treated on load;

FIG. 6 is a graph of power vs. frequency as in FIG. 4 except that notations are added to assist in describing effects of both moisture level and temperature of material treated on tuning and consequently on stability; and

FIG. 7 is the graph of FIG. 5 with notations employed to describe effects of overcoupling on stability in drying and undercoupling on stability in polymer heating.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The novel method of heating regulation of this invention is achieved by means of a simple apparatus system in which the desired coupling mode is established through the selection of the cavity coupling iris. The required amount of frequency offset between power source and cavity to provide stability is achieved by selecting magnetrons with a "pulling" range as wide as possible (5—8 MHz. is typical although a magnetron with a range of 20 MHz. has been found) and then adjusting the amount of "pulling" by preselecting the percentage of reflected power that can return to the magnetron to cause frequency "pulling."

Referring to FIG. 1 a magnetron **10** (such as Amperex YJ1160 fitted with a modified Eimac No. EW3–TC2 Laucher for 1⅝ inch coax to a wave guide) energized by a conventional high voltage DC power supply (not shown) is connected through a first waveguide section **11** (Type WR340) to the first port of a three-port circulator **12** (Airtron No. 336359 or Eimac No. EW3–C1). The second port of circulator **12** is coupled by means of a second waveguide section **13** to resonant cavity heater **15** through a first impedance transforming apertured iris **14**. The third port of circulator **12** is coupled by means of a third section of waveguide **16** through a second apertured iris **17** into a water load **18** (Eimac No. EW3–WL2 .5). Iris **17** is positioned in waveguide **16** across its juncture with water load **18**. In the event of frequency mismatch between magnetron **10** and resonant cavity **15** or impedance mismatch of the transmission waveguide **13** and cavity **15** as transformed by iris **14**, power is reflected back through waveguide **13** and into circulator **12**. The function of circulator **12** is to prevent excessive reflected power from being directed back to the magnetron **10** where it could cause damage through arcing or overheating. Thus, circulator **12** directs reflected power from cavity **15** through waveguide section **16** and iris **17** into water load **18**. The amount of this reflected power which is absorbed, and dissipated in water load **18** is dependent on the choice of the aperture of iris **17**.

Waveguide sections **11**, **13** and **16** are chosen of the shortest length which will ensure the proper phase relationship for each component. Using short lengths not only keeps the system compact but also helps alleviate phase shift problems which arise during load variations. It was possible using short lengths of WR340 waveguide in the system shown to eliminate the need for a phase shifter in waveguide section **16**.

The choice of iris **17** is also the key to determining the proportion of reflected power entering waveguide section **16** which will be directed back through waveguide **16** into circulator **12** and then into magnetron **10** to produce frequency "pulling." The greater the proportion of reflected power from

iris 17 the greater the "pulling," which in turn reduces the achievable frequency offset between magnetron and cavity. Conversely a reduction in the proportion of reflected power reduces "pulling" and increases the achievable frequency offset.

As mentioned previously, too great a proportion of reflected power may exceed the safe level for the magnetron in the case where all power is reflected from the cavity. In addition, when the system is being turned on and tuned in (start up), excessive reflected power can cause operating difficulty by forcing the magnetron to oscillate in an undesired mode and not couple to the cavity.

In the preferred embodiment, a tow or yarn 22 which is to be dried or heated is moved from a supply source (not shown) by means of pull rolls 25, 25', passed through tuned resonant cavity 15, and withdrawn by means of rolls 26, 26'. A longitudinal slot 28 is provided in cavity 15 along one side in order to facilitate stringup of the cavity. When drying a wet tow, this slot is located along the bottom edge of cavity 15 in order that excess liquid from the material being dried may run out from the cavity. Cavity 15 may be tuned to different frequencies by the method disclosed in the Lewis & White reference.

The preferred embodiment of the cavity tuner is shown in FIG. 1 and FIG. 2. Lips 30, 31 on each side of slot 28, respectively, are provided on which tuning frame 32 is brought to bear. Tuning frame 32 comprises two curved pieces 38, 38' separated and held by a bar 40 at one end of each. Pieces 38, 38' are thus arranged to fall on either side of flange 41 for attachment of waveguide section 13 and iris 14. The other end of each curved piece carries a plate 42, 42'. A nut 44 is welded to the center of bar 40 and positioned to receive an adjusting screw 34 so that screw 34 may be brought to bear on lip 30. Similarly, nuts 46, 46' are welded to each plate 42, 42' and positioned to receive thread positioning pins 36, 36'. Lock nuts 48, 48' serve to hold the adjustment of pins 36, 36' which bear on lip 31. A third pair of nuts 50 are welded to the edges at the uppermost points of curved pieces 38, 38' . Set screws 52, fit into nuts 50 and provide vertical supports to tuning frame 32 by bearing on the top of cavity 15. A short rod 35 is welded to the head of screw 34 to provide an adjusting handle.

In operation frame 32 is positioned around cavity 15 as shown in FIGS. 1 and 2. By rotation of screw 34, the transverse cross section of cavity 15 is changed. This changes the resonant frequency of the cavity.

The experimental system for empirically selecting optimum drying system conditions is shown in FIG. 3. This is the same as the system of FIG. 1 with instrumentation added. Thus a dual directional coupler 19, (Microwave Devices No. WRB3 or Eimac EW3–DPM3) including two power indicators such as 20, 20' (1N21 crystal and DC milliammeter), is inserted in wave guide section 13. In the alternative a coupler 19 could be located in waveguide sections 11 and 16. Indicators 20, 20' can be arranged to measure P_m, the power from magnetron 10 or P_r, the power reflected from cavity 15. An indicator 20'' with a sampling loop (M. E. Porter Co.) may also be placed as shown in FIG. 3 so as to measure cavity power. In addition a moisture meter 21, of conventional design (Decker Corp. capacitive moisture meter with capacitor plates sized to accommodate tow to be dried), is arranged and positioned as in FIG. 3 to monitor moisture content of material coming from cavity 15.

For this type of system, many modes of resonance may occur in a microwave resonant cavity of fixed dimension. These resonances involve the store energy of both the electric and magnetic fields in the enclosed volume of the cavity. Energy at any of several frequencies, quite close together, can resonate the cavity depending on how energy is coupled into the cavity and on slight changes within the cavity. As disclosed in the previously referenced copending application by Lewis & White, the cavity can be constructed and arranged in such a way that the particular resonant field configuration which has a strong axial electric field is maintained in the face of disturbances which would normally cause shifting to an unwanted resonant field distribution.

Even for this cavity structure, a significant change in dielectric constant or in the amount of material which is placed in the axial region of the cavity will modify the field distribution by concentrating more field lines in the axial regions if, for example, the dielectric constant change is an increase. Such an increase lowers the resonant frequency of the cavity. Microwave power is usually supplied from magnetrons, amplitrons, klystrons, or the like which supply power at a characteristic frequency with a relatively narrow band width or tunable range. Depending on the type of power source used, a shift in load which changes cavity frequency may or may not be able to "pull" the power source very far in frequency. With power sources with a narrow bandwidth and narrow "pulling" range, the detuning of a cavity due to a small load change could easily be enough so that the cavity would not receive sufficient energy from the power source.

FIG. 4 shows a representative graph of the power that is transferred into a resonant cavity as a function of the frequency of power supplied, with f_o being the cavity resonant frequency, and f_1 and f_2 being the half power bandwidth of the cavity. Since energy transport losses in this type system can be made almost negligible, when the power source frequency is also f_o, the power transferred into the cavity is essentially the output of the microwave power source. When conditions change so that the cavity resonance f_o is higher than the power source frequency indicated as f_a then operation moves to point A in which case the power coupled into the cavity is reduced to a value P_c. The remaining power P_r, in the absence of protective devices will be reflected back to the power source. In some power sources, this reflected power will "pull" the power source frequency from f_a to a value approaching f_o. In other cases, this reflected may cause failure of the power source. As discussed later, the present invention serves to alleviate or eliminate this effect and in addition, uses the "pulling" effect to provide stability in the face of load upsets.

Energy may be introduced into microwave cavity 15 by either a loop or an iris. The preferred coupling for the stable side fed cavity, as explained in the above-referenced Lewis & White application, is through an inductive iris-type coupling. Inductive rather than capacitive irises are preferred since an inductive iris operates with lower voltages across the iris opening and thus there is less likelihood of breakdown and arcing at the iris. The dimensions of the iris affect the amount of microwave power that can be transferred into the cavity 15. FIG. 5 depicts the relationship between power transferred into the cavity and the dissipating load in the cavity for a given iris 14. From this graph, it is obvious that as the load is increased, the power coupled into the cavity increases to a maximum at point N and then, for further increased load, the coupled power decreases.

When the cavity is operated in such a manner that the load draws all of the power from the source, it is said to be critically coupled. Operation to the left of the critical coupling peak N in FIG. 5 such that an increase in load will draw more power into the cavity, is defined as overcoupling. When available power decreases with increased load, i.e., when operating to the right of the peak N in FIG. 5 the system is said to be undercoupled.

The known practice is to operate the microwave resonant cavity at design frequency (f_o in FIG. 4) and critically coupled so that small load changes have minimum effect on available power and reflected power is kept to a minimum. This type of operation generally results in unstable system performance when appreciable changes in conditions of the load are encountered.

The operation of resonant cavities which are critically coupled at normally expected load is also illustrated by FIG. 5 using, for example, a process of drying wet tow by heating the tow as it is being transported through a resonant cavity wherein the cavity is critically coupled at the normal moisture level of the tow entering the cavity, operation will be that as indicated by point N. Tow which is drier than normal entering the cavity will present a reduced load to the cavity and require

less power. This condition follows arrow D and is a stable operating condition, for if moisture level returns to normal, the available power will follow the increase in load requirements back to point N. However, if tow wetter than normal enters the cavity, operation will follow arrow W. Now it is obvious that the increased load is supplied with reduced power and, therefore, a drying rate below normal will exist when a higher drying rate is required.

In addition to the above effect, the effect of changes in load on resonant frequency of the cavity are important as illustrated in FIG. 6. Considering again the process of drying tow in a resonant cavity, if usual conditions are selected for tow of average dryness, the system will be operated with power source and resonant cavity matched in frequency at f_t and the maximum power will be transferred to the cavity as indicated by point T. If drier tow enters the cavity, the cavity is detuned to a higher resonant frequency (for convenience still represented by point T) but the magnetron frequency is "pulled" only to point D_t and the amount of power coupled into the cavity is reduced. Reduced power is required in this case and, therefore, the operation under these conditions is stable. However, when wetter tow enters the cavity, it is detuned to a lower resonant frequency. If the cavity resonant frequency in this case is again represented by point T, the magnetron frequency will be "pulled" to follow part way to point W_t and again the amount of power coupled into the cavity is reduced which in turn results in a reduction of drying rate at a time when an increased drying rate is required.

Thus, when drying continuously moving material in a conventional system which is critically coupled and tuned to a matched frequency of cavity and power source based on normal expected moisture content of the material, an unstable system results with material of increased moisture whereas a stable system results for conditions of reduced moisture. This unstable system condition for increased moisture may be alleviated by purposefully detuning the cavity so that a small increment of frequency between the cavity resonant frequency and the "pulled" frequency of the magnetron exists in the properly selected direction. If this increment is set such that the magnetron "pulled" frequency is lower than the cavity resonant frequency as illustrated by point A of FIG. 6, increased moisture would decrease the cavity resonant frequency and operation would shift to W_a which increases the power coupled into the cavity and thus increases the drying rate. Decreased moisture would increase the cavity resonant frequency and operation would shift to D_a at which point power coupled into the cavity is decreased resulting in a reduced drying rate. Thus, stability is enhanced for both wetter and drier than average material when the system is adjusted so that the cavity resonant frequency for average moisture conditions is slightly above magnetron "pulled" frequency. However, operation at critical coupling (FIG. 5) continues to present unstable operating system conditions and detuning alone is not completely satisfactory for inherent system stability. Detuning the cavity to a frequency below magnetron "pulled" frequency such as represented by point B on FIG. 6 results in instability for both wetter (W_b) and drier (D_b) material.

For the process of microwave heating of a moving polymeric (e.g., nylon) yarn, a situation is presented which is similar in many respects but different in others to the above-discussed drying process. If effects of denier variability are neglected, variations in entering yarn temperatures will have the predominating effect on cavity operation. As noted hereinabove, a rise in temperature generally increases the loss tangent significantly for a polymeric material, but has little effect on the dielectric constant. Thus, the major shift in cavity operation with temperature would be an increase in load with increased temperature rather than any effect on tuning. Thus, if the temperature of the yarn entering the cavity becomes higher than normal (corresponding to arrow H of FIG. 5), the load on the cavity will increase. However, as indicated by this graph, the available power would decrease in this situation and therefore, the heating would stabilize and therefore, not "run-away." On the other hand, if the entering yarn temperature were lower than normal (arrow C of FIG. 5), the available power would be decreased. Now to achieve the desire end temperature, the heating rate should be increased but this cannot be achieved with the decrease in power available as indicated by this graph. Thus, as with drying, critical coupling is not satisfactory for heating a running yarn if inherent temperature control is desired.

For moisture removal the greatest inherent operating stability of a microwave resonant cavity is achieved by the mode of operation comprising overcoupling for normal load and detuning of the cavity to a frequency slightly above the microwave power supply frequency. The effect of operation with overcoupling is shown in FIG. 7 at point 0. If higher moisture content material enters the cavity, the load will increase (arrow W_o) and the available power will increase to compensate for this system upset. Reduced moisture (arrow D_o) with reduced load will require and receive reduced power. Both conditions, therefore, tend to be stable. Similarly, when the cavity is detuned to a frequency slightly higher than the magnetron "pulled" frequency (point A on FIG. 6) the stabilizing influences for both wetter and drier entering material (as explained earlier) combine with the stabilizing effects of overcoupling to provide inherent system stability for moisture removal.

For heating a running yarn of polymeric material, such as nylon, the greatest inherent operating stability of a microwave resonant cavity system is attained by a mode of operation comprising undercoupling for normal load and detuning of the cavity to a frequency slightly lower than the microwave power source frequency. As evident from FIG. 7, this undercoupled mode (point U) of operation for heating nylon yarn is inherently stable since material with higher than normal or desired temperature would increase the load presented to the cavity which in turn would decrease the power available (arrow H_u) whereas cooler yarn entering the cavity would receive increased heating due to the greater power available (arrow C_u). For the former situation, heating rate would decrease and the temperature rise would level out and not "run-away." In the latter situation, heating rate would increase and the increased temperature rise would cause system operation to move back towards the condition represented by point U. Now if the only effect on cavity operation for nylon yarn heating were the influence of changes in loss factor with temperature, the cavity would be inherently stable for all three-frequency situations, points A, T and B considered in FIG. 6. However, there is a slight increase in dielectric constant with temperature which has a slight frequency effect. An examination of FIG. 6 shows that operation of the cavity tuned to a resonant frequency slightly lower than the power source frequency (Point B) adds to the inherent stabilizing influence of undercoupling, using the analogy of hotter (H_b) and cooler (C b) yarn entering the cavity, and thus is important to the preferred mode of operation for heating polymeric yarns. It is obvious from FIG. 6 that detuning the cavity to operate at a resonant frequency slightly higher than the power source frequency (Point A) would result in adverse conditions in that increases in dielectric constant would tend to lead to a "run-away" condition (H_a) which would tend to counteract some of the stabilizing effect of the undercoupled mode, while cooler (C_a) yarn entering the cavity would cause available power and heating rate to decrease.

An important advantage of the apparatus of the present invention is that it provides the means for achieving the desired modes of control with a minimum of auxiliary equipment while providing excellent protection to the power source. The use of tunable magnetrons with frequency measuring devices providing feedback for achieving the desired frequency offset to compensate for load disturbances would require much more complex systems than the one described.

The use of a ferrite isolator in place of the circulator-water load-iris combination (12, 16, 17 and 18, FIG. 1) to provide

protection to the magnetron against excessive reflected power for the magnetron which will give the desired "pulling" range has several disadvantages at present. Each process for which control is desired will require that the isolator provide a specific degree of isolation and possess a specific power dissipation capability which in many cases will require the production of a special isolator which will be far more expensive than an "off the shelf" component. Then once the system is in operation, process changes are not easily accommodated. Design of the preferred embodiment of this invention requires merely the choice of a water load of sufficient power handling capacity (wide range of "off the shelf" items) and selection of an iris size; and since process changes might require system component changes, this is easily effected with the availability of water loads of a wide power handling range and the simplicity of an iris change (an easily machined, slotted aperture plate).

EXAMPLE

The following illustrates the use of this invention to dry a Teflon* yarn, which is coated with a water dispersion, to a specified moisture level content with a minimum fluctuation in moisture levels.

A Teflon yarn coated with a Teflon water dispersion at a process speed of 56 yards per minute then is passed through a microwave system similar to that as shown in FIG. 1. Water load iris 17 was chosen to provide a coefficient of coupling of 2 (11 percent reflection) to provide a half power pulling range of 4—5 MHz.

The following are the input conditions:
9450 denier dry yarn (53.8 gm./min.)
160% dispersion based on dry yarn (86.1 gm./min.)
Dispersion:
65% Teflon (56 gm./min.)
35% Water (30.1 gm./min.)
Total Teflon, 109.8 gm./min.
Total Water, 30.1 gm./min. (27½%)

Normal steady state system requirements for desired drying, i.e., 4—5 percent residual water content to give best dispersion retention indicated a required power level of 1,300 watts. Variations in dispersion application had shown that power requirements would vary as much as ±300 watts. The results of providing the power variations needed by coupling and/or frequency pulling of varying combinations (items A—E) is shown in table I.

TABLE I

	Cavity coupling coefficient	Freq. pulling, MHz.	Coupling reserve power, watts	Pulling reserve power, watts	Output moisture level, percent
Item:					
A	1.0(Critical)	+1	0	100	3±2
B	1.7(Over)	0	140	0	3.8±1
C	do	+1	140	100	2.6±0.4
D	2.23(Over)	0	300	0	3.8±0.5
E	do	+1	300	100	4.5±0.2

* Registered Du Pont Trademark.

These results show that overcoupling yields a far more uniform drying operation than with critical coupling and this uniformity is further enhanced by the 1 MHz. frequency offset.

I claim:

1. A method comprising the steps of:
a. advancing a dielectric mass axially through a microwave resonant cavity said mass presenting a changing load to said cavity;
b. transmitting microwave frequency energy to said cavity from a magnetron source to heat said mass, said cavity being purposefully decoupled and detuned in a preselected direction from a critically coupled and matched frequency relationship with said source for operation at the decoupled and detuned condition selected, a portion of said energy being reflected away from said cavity; and
c. absorbing a part of said portion, the remainder being reflected back to said source to regulate its frequency.

2. A method of drying a wet tow having a changing moisture content comprising:
a. passing the tow axially through a microwave resonant cavity;
b. transmitting microwave frequency energy to said cavity from a magnetron source, said cavity being in an overcoupled relationship with said source and being tuned to a frequency above a matched frequency relationship with said source for operation at said relationships, a portion of said energy being reflected away from said cavity; and
c. absorbing a part of said portion, the remainder being reflected back to said source to regulate its frequency.

3. The method as defined in claim 2, said tow comprising multifilament yarns from poly(tetrafluoroethylene).

4. The method as defined in claim 3, about 11 percent of said portion being reflected back to said source to regulate its frequency.

5. In a microwave dielectric heating apparatus that includes a cylindrical resonant cavity heater, a microwave frequency energy source for supplying energy to the cavity, a water load and a circulator, said circulator being coupled to said source, said heater and said water load by respective first, second, and third waveguide sections, there being a first iris positioned in said second waveguide section, the improvement comprising: means coupled with said heater for varying the transverse cross section thereof to provide tuning capability for said heater; and a second iris positioned in said third waveguide section.

6. The apparatus as defined in claim 5, said source being a magnetron.