July 22, 1969 W. A. CUMMING 3,457,385

APPARATUS FOR DIELECTRIC HEATING

Filed July 7, 1966 2 Sheets-Sheet 1

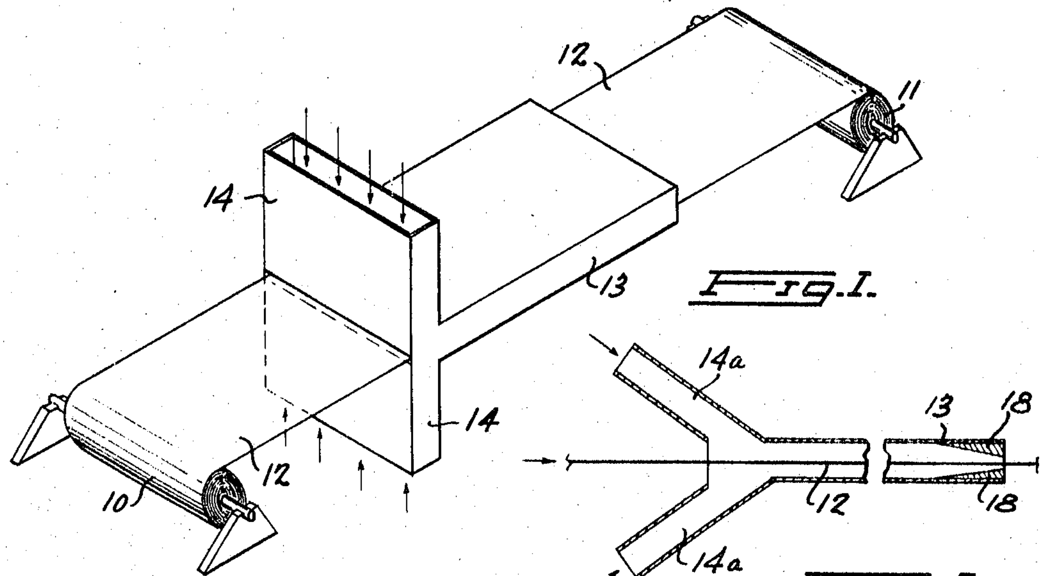
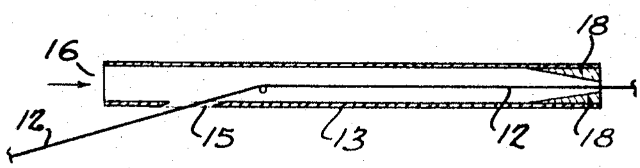


Fig.1.

Fig.2.

Fig.3.



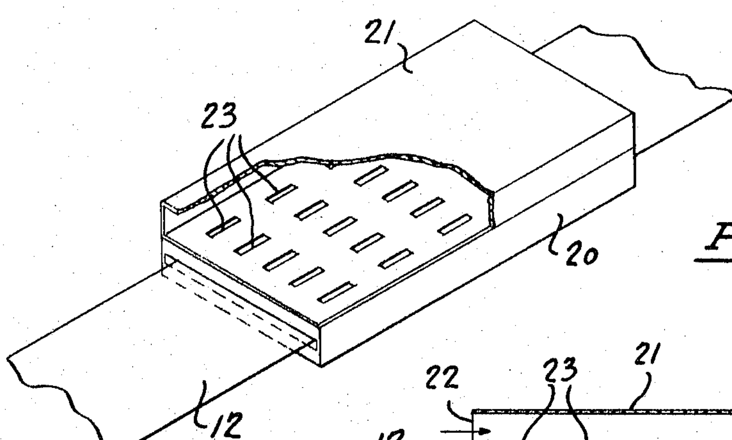


Fig.4.

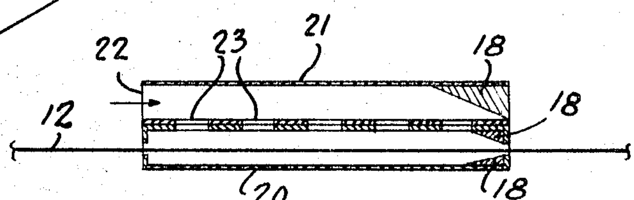


Fig.5.

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APPARATUS FOR DIELECTRIC HEATING

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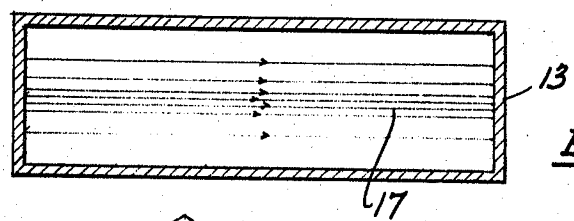

Fig. 6.

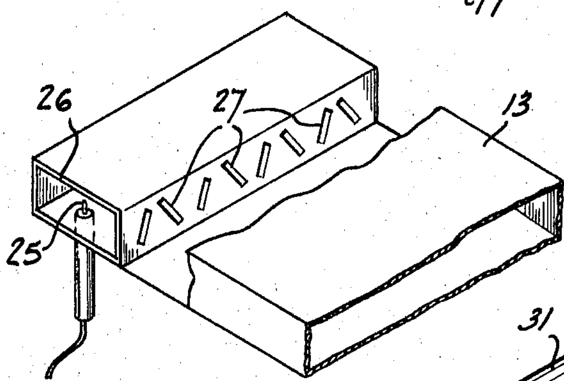

Fig. 7.

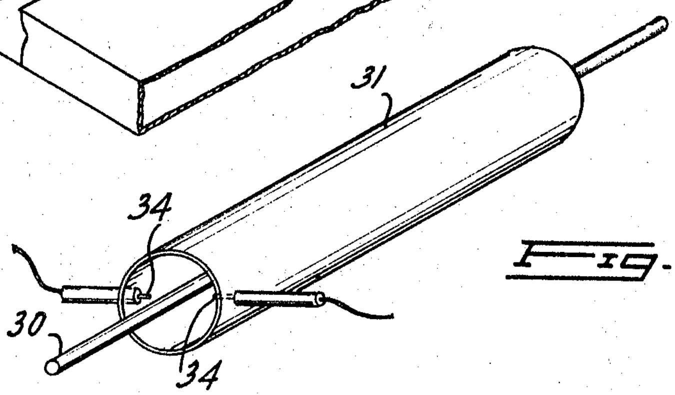

Fig. 8.

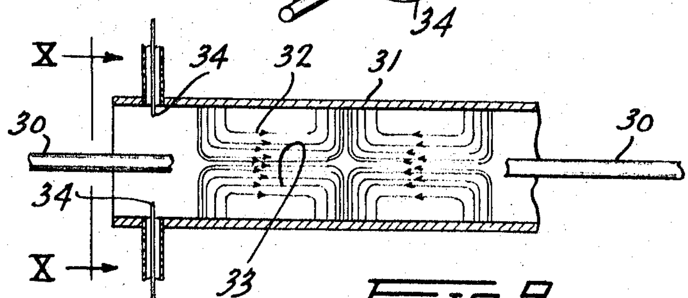

Fig. 9.

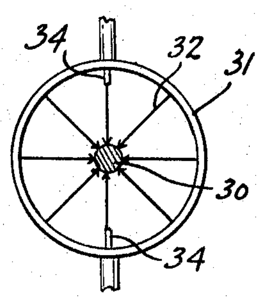

Fig. 10.

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APPARATUS FOR DIELECTRIC HEATING

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U.S. Cl. 219—10.61 5 Claims

ABSTRACT OF THE DISCLOSURE

Microwave energy in the form of a single travelling wave is propagated along a substantially electrically continuous waveguide, the microwave being of an operating mode that yields a concentration of lines of electric force in a certain area of the cross-section of the waveguide, through which area an elongated workpiece is fed along its own longitudinal axis. For web-shaped workpieces, a waveguide of rectangular cross-section is preferable, in which a microwave of the TE_{01} mode is excited, having a concentration of lines of electric force in the longitudinal centre plane of the waveguide, whereas for workpieces in the form of filaments a waveguide of circular cross-section is chosen in which a wave of the $TM_{01}°$ mode yields a concentration of lines of electric force along the central longitudinal axis of the waveguide.

This invention relates to improvements in apparatus for dielectric heating, that is to say the heating of materials by microwave energy. In one particular application, the invention is concerned with the drying of elongated articles by heating the water entrained therein by the application of microwave energy. Such articles may typically be webs of material, paper for example, or filaments such as are produced in the textile industries. For convenience, the article that is to be subjected to drying, or heating for any other purpose (including any entrained substances, such as water) will be referred to below as the workpiece.

More specifically, the invention is concerned with the use of a waveguide for the application of mircowave energy to a workpiece.

It is fundamental to the art of dielectric drying that the basic material of the workpiece should have a low loss tangent to the microwave energy. On the other hand the frequency of the mircowave energy will be so chosen that water entrained in the material will have a high loss tangent at that frequency. The effect of these circumstances is to cause relatively high absorption of the microwave energy by the water and relatively low absorption of the mircowave energy by the material itself. This is the ideal way to evaporate water from a workpiece, the heating energy being used at high efficiency, while the risk of overheating the material itself is minimised.

It is, however, important, if this theoretical efficiency is to be realised in practice, that the energy transfer be as complete as possible. It is in respect of this aspect of the method that the various prior art proposals for dielectric drying and heating generally have not been entirely satisfactory, and it is the principle object of the present invention to provide improved methods and apparatus for enhancing the energy transfer between microwave energy and workpiece.

Another object of the present invention is to achieve improvements in the uniformity of heating of an elongated workpiece. Methods have been proposed in the past for passing wet webs of material through waveguides, while subjecting the material to microwave energy, but difficulties have arisen in achieving a uniform drying effect transversely of the web. This problem is especially acute when it is desired to achieve a carefully controlled degree

of partial drying. As will appear more fully from the description below, the method adopted in the present invention is especially conducive to the achievement of a uniform distribution of heating effect across the web, as well as along the web.

While the principal utilization envisaged for the present invention is the drying of elongated webs of material, such as paper, or elongated filaments, such as are used in the textile industry, the invention is also applicable to other applications where it is desired to heat elongated workpieces, and particularly elongated workpieces in which it is desired to heat one substance selectively, provided that the workpiece is of a shape suitable for feeding along a waveguide. For example, the method can be used for curing adhesives, or for the setting plastics, always provided that the substance to be heated has a sufficiently high loss tangent at the frequency used to ensure that it absorbs an appreciable amount of energy. The method can also be used for drying pulpwoods.

Various manners in which the invention may be carried into practice are illustrated in the accompaying drawings. It is to be understood that the specific forms of the invention illustrated in the drawings are provided by way of example only and not by way of limitation of the invention, the broad scope of which is defined in the appended claims.

In the drawings:

FIGURE 1 shows a perspective view of a waveguide illustrating a first method of drying a web of material;

FIGURE 2 shows a cut-away side view of a fragment of a modification of FIGURE 1;

FIGURE 3 is a cut-away side view of a further alternative to FIGURE 1;

FIGURE 4 is a perspective cut-away view of yet another form of waveguide;

FIGURE 5 is a cut-away side view of the waveguide of FIGURE 4;

FIGURE 6 is an end view of a rectangular waveguide illustrating the lines of electric force in one mode of operation;

FIGURE 7 is a partly broken away view of structure illustrating a manner of feeding microwave energy to a rectangular waveguide;

FIGURE 8 is a perspective view of a further form of the invention; this form comprising a circular waveguide adapted for drying a filamental material;

FIGURE 9 is a diagrammatic sectional view of the circular waveguide of FIGURE 8 illustrating the lines of electric force in one mode of operation thereof; and

FIGURE 10 is an end view of the waveguide of FIGURES 8 and 9 taken on the line X—X of FIGURE 9 and illustrating this view of the same lines of electric force.

FIGURE 1 shows a workpiece in the form of a web **12** of material, for example paper, that can be fed between one roll **10** and a second roll **11** by suitable driving means (not shown). The web **12** may be made to travel in either direction, the choice of the feed direction depending on various factors that will be more fully explained below. The web **12** travels along the centre line of a rectangular waveguide that consists of a main portion **13** and a pair of perpendicular side arms **14** from which microwave energy is fed into the main waveguide portion **13**.

FIGURE 2 shows a basically similar construction in which the web **12** again travels along a main waveguide portion **13**. However, in this case the arms **14***a* for feeding the mircowave energy into the main waveguide **13** are inclined thereto, rather than being perpendicular to the plane of the web **12**.

FIGURE 3 illustrates another variant of this construction in which the web **12** extends out of the waveguide **13** through a slot **15**. This arrangement enables the microwave energy to be fed directly into the end of the waveguide 13 at its mouth 16.

Essential novel characteristics of the present invention, which will be seen to be embodied in all three forms thereof so far described, reside in the facts that the waveguide 13 is substantially electrically continuous (for uniform propagation of microwave energy therealong) and that the direction of propagation of the microwave energy along the waveguide 13 is along the longitudinal axis of the web 12. In other words, regardless of the direction of movement of the web 12, which can be either with or against the energy flow, the plane in which the web lies extends along the waveguide in the direction of energy propagation. This feature, which is in contrast to many prior art proposals in which a web is caused to travel across a waveguide transversely of the direction of energy flow, is important in the achievement of uniformity in the heating action.

It is also essential to the invention that the waveguide is suitably terminated, e.g. by means of conventional absorbing wedges 18. This avoids reflection of the microwave energy and the setting up of standing waves. In other words the energy is propagated in a single travelling wave, in contrast to the double travelling wave that is the equivalent of a standing wave.

The preferred mode of energization of the waveguide 13 is the transverse electric mode known as the TE_{01} mode (employing the usual United States nomenclature). FIGURE 6 shows a cross-section of the waveguide 13 with the lines of electric force represented by arrows 17. The lines of magnetic force have not been illustrated, since they are of no interest to the present invention. The heating energy transfer is effected by the electric field. The lines of electric force 17 shown in FIGURE 6 are those of a rectangular waveguide stimulated in the TE_{01} mode which will normally be the dominant mode. It will be noted that the lines 17 are concentrated along the centre plane of the waveguide, that is to say, the plane extending across the greater dimensions of the waveguide equidistant from its upper and lower plates, i.e. centrally of the shorter dimension. For this reason, the plane of the web 12 is arranged to lie generally along this centre plane of the waveguide, in order to obtain the result that a maximum number of lines of electric force lie within the web 12. In reality the presence of the web 12 has the effect of further concentrating the lines of force, so that with the web 12 present the concentration of lines of force in the centre plane is far greater than can be illustrated in FIGURE 6.

While operation of the waveguide 13 in the TE_{01} mode is much preferred, it is nevertheless still within the scope of the invention to propagate the microwave energy in a single travelling wave in one of the other transverse electric modes, for example the TE_{10} or TE_{11} modes, or in a combination of the various transverse electric modes. For example, the TE_{10} mode could be used with advantage in a case where the apparatus was used to dry one or more relatively narrow webs, each defining a plane parallel to the shorter cross-sectional dimension of the waveguide, because in the TE_{10} mode the lines of electric force extend across the shorter dimension of the waveguide. In a square waveguide the TE_{10} and TE_{01} modes are thus identical. Since one of the prime objects of the present invention is to achieve a high coupling between the microwave energy and the workpiece, by causing a concentration of lines of electric force to extend along the workpiece itself (in contrast to cutting through it vertically or at an inclination), the mode or modes of propagation adopted will be chosen basically with a view to achieving this objective, having regard to the geometry of the waveguide and the workpiece and the location and orientation of the latter in the former.

The preferred range of frequencies for the microwave energy is from 20 cm. to 1 cm. Microwave energy in the region of 1 cm. is the most effective for drying purposes, because the peak in the loss curve for water occurs around 1 cm. On the other hand, energy sources are more readily available and are less expensive at lower frequencies, which considerations will usually encourage the use of the longer wavelengths. Another factor to be considered is that waveguides are larger for propagation of the longer wavelengths in the dominant mode. Thus, since the size of the waveguide will often in practice be determined by the size of the web material, this factor may dictate the wavelength to be preferred, bearing in mind that it will normally be convenient to operate under conditions in which only the dominant mode can propagate.

FIGURES 4 and 5 illustrate an alternative system in which the microwave energy is fed step-by-step into a main waveguide 20 along which the web 12 passes in a manner similar to that of the waveguide 13. The power is fed into a superposed waveguide 21 at its mouth 22 and is then leaked to the operating waveguide 20 through slots 23. This arrangement achieves a more even lengthwise distribution of energy to the operating waveguide 20 than in the previously described embodiments, and is especially useful in the processing of webs having a very high attenuation of the energy, for example a comparatively thick web. Such a thick web might, for instance, comprise one or more lengths of leather to be dried.

The maximum power absorption by the water in the material of the web will tend to be in the power input region of the waveguide. For this reason it will normally be preferred to arrange for the web 12 to travel in the same direction as the energy. In this way a wet web entering the waveguide adjacent the power input will be subjected to the major amount of drying energy. On the other hand, the already partly dried web at the far end of the waveguide will receive less energy, which is in accordance with its requirement. Seldom in a drying operation is it desired completely to dry the article, because this would tend to give rise to brittleness in the final product. The object is usually to provide a controlled amount of drying, and this result can be achieved by suitable regulation of the input power in relation to the moisture content of the web and its rate of travel along the waveguide. Such control is usually more readily achieved when the direction of web travel coincides with the direction of energy propagation.

In order to stimulate the waveguide 13 uniformly across its width, one of the various known input devices may be employed. For example, a parabolic input (not shown) may be used. Alternatively, there may be used the known system illustrated in FIGURE 7 in which a probe 25 feeds microwave energy into an input waveguide 26 from which it is injected into the end of the main waveguide 13 uniformly across the width thereof through oppositely inclined slots 27. Similar injection means can be used to feed energy into the waveguides 14 and 14*a*. Wherever not shown, the waveguides may include conventional attenuating means, such as absorbing wedges, located at their ends remote from the power inputs, in order to absorb residual microwave energy.

FIGURES 8 to 10 show an application of the invention to the dielectric drying of a filamental material 30 by means of microwave energy in a circular waveguide 31. Again, it is an essential feature of the present invention that the filament 30 extends along the waveguide in the same direction as that of energy propagation. However, in the case of a filamental workpiece and a circular waveguide, it is preferred to operate the waveguide in the transverse magnetic code known as the TM_{01} mode, in which the electric lines of force 32 are as shown in FIGURES 9 and 10. In this case it is the portions of the lines of force 32 that extend along the central axis of the waveguide, rather than those that extend across the waveguide, that are exploited to obtain a high concentration of heating effect (see the concentration of lines of force demonstrated at 33). The filament 30 is accordingly fed between suitable feeding means (not shown), as far as practicable along this central axis. As in the previous examples, the natural concentration of lines of electric force along the centerline will be substantially increased by the presence of the filament **30** itself. The direction of travel of the filament **30** is optional, as before, but travel in the same direction as the energy propagation is usually preferred, for the reasons already explained.

The TM_{01}° mode, which is the preferred mode of propagation, is not the dominant mode in the waveguide **31.** The dominant mode will be the TE_{11}° mode. However, excitation in the TM_{01}° mode with avoidance of excitation in the TE_{11}° mode can be achieved by the use of a pair of diagonally located input probes **34**, as shown in FIGURES 8 and 9.

As will be apparent, a filamental workpiece is best handled in a waveguide that has so-called orthogonal symmetry, that is, a waveguide of a shape that can be turned through 90° about its longitudinal axis and yet remain basically the same in appearance, e.g. a circle, or a square, in contrast to a rectangular waveguide, for example.

Indeed the use of energy propagating in a transverse magnetic mode (not necessarily mode TM_{01}) and having a component of the electric field along the axis of the waveguide may be adopted for waveguide shapes other than those having orthogonal symmetry, e.g. rectangular waveguides. Such an arrangement might well have application to the heating of a flattened filament, or a relatively narrower but thick web, although the use of this arrangement is not restricted to any particular workpiece shape.

I claim:

1. Apparatus for subjecting a workpiece in the form of an elongated web to dielectric heating, comprising

(a) a substantially electrically continuous waveguide of rectangular cross-section,

(b) means for moving said web along its own longitudinal plane along a selected plane in the waveguide, said selected plane extending along the waveguide and across the greater cross-sectional dimension thereof at a location substantially central of the shorter cross-sectional dimension thereof,

(c) and means for propagating microwave energy in either direction along said waveguide principally in the TE_{01} mode to yield a concentration of lines of electric force in said selected plane occupied by the workpiece at a wavelength at which at least a part of said workpiece will absorb said energy to generate heat.

2. Apparatus according to claim **1** wherein said propa-

gating means comprises means for injecting said energy into an end of the waveguide substantially uniformly thereacross.

3. Apparatus according to claim **2**, wherein said propagating means comprises means for injecting said energy into said end of the waveguide simultaneously from both sides of said workpiece.

4. Apparatus according to claim **2**, wherein said means for moving the workpiece along the waveguide includes means for introducing said workpiece through a side wall of the waveguide, and said propagating means comprises means for injecting said energy directly endwise into said end of the waveguide.

5. Apparatus according to claim **1**, wherein said propagating means comprises

(h) a further similar rectangular waveguide superposed on the main waveguide along which the workpiece moves,

(i) means for injecting said energy into an end of said further waveguide in said TE_{01} mode,

(j) and openings communicating between said waveguides, said openings being arrayed across the width and along the length of said waveguides whereby to transmit energy into said main waveguide gradually along the length thereof and substantially uniformly across the width thereof.

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