RADIO-FREQUENCY HEATING*

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IN the last few years the radio-engineer, using his own special technique, has devised two new heating processes, one for metals and one for non-metals. Few recent technical developments have excited more widespread interest among scientific workers, not because any new principle has been established, but because it is recognized that a new tool has come to hand, which in certain respects gives us a command over the forces of Nature that we have not before enjoyed. It may be true that the poor workman always quarrels with his tools; it is none the less true that the scientific workman is always interested in a new one; and physicists and chemists, biologists and metallurgists, as well as engineers, have shown great zest in trying the new tool on their own special problems, particularly their industrial problems. The processes are too young to make possible a considered judgment of their scientific or industrial value: I shall therefore be content to illustrate their special features by a few examples.

When we speak of a heating process, we imply something more than the mere production of heat. The essence of the matter lies in this: we must be able to impart at will an appreciable amount of thermal energy to some particular body. The problem includes not only the production of the energy, but also its transference to the body to be heated; and this transference must be localized and subject to strict control. Two possibilities lie before us: we can generate the energy in the thermal form, and transfer it to the body to be heated in that form, by thermal conduction or convection; or alternatively, we can generate and transfer the energy in some other form, and afterwards convert it into heat in the body to be heated, a process usually described as the absorption of the energy by that body. In the ideal solution of the problem, the heat would appear instantly in the body and nowhere else, in just the amount required and just at the right instant. Both energy and time are involved, and we may say that the process consists essentially in the controlled transference of power, that is, energy per unit time, and its absorption by one particular body, often called by the heating engineer the 'work'. The methods to be discussed here have this feature in common: the power is transferred to the work in the form of electromagnetic vibrations of a frequency lying somewhere in the radio range, say 10 kilocycles to a few hundred megacycles per second, and this is what is implied by the term 'radio-frequency heating'.

The term 'radio' almost inevitably suggests electromagnetic radiation comprising that portion of the spectrum which the radio engineer has taken for his own, say a range of wave-lengths from a few miles to a few millimetres; to avoid misunderstanding it must be emphasized that for the purposes of heating, the power is not employed in the form of radiation: that is to say, in the form of trains of progressive waves such as are employed in broadcasting and television. It is true that such waves are absorbed by both metals and non-metals; and it is because of that very fact that radio-frequency heating is possible; indeed, its peculiar virtues depend very largely on the character and extent of that absorption. But for the purposes of heating, we need to

produce a great concentration of power in the 'work'; radiation is the reverse of concentration—it is the dispersal or diffusion of electromagnetic power throughout the universe. When the wave-length becomes short compared with human dimensions, optical technique can be employed for the concentration of radiation, and heating by means of radiation is then possible, provided the work is a reasonably good absorber. The recent developments in 'infra-red heating' are of this character, and one day perhaps the radio-engineer may perform the same feat with his micro-waves; but with the long waves we are now considering this is quite out of the question.

The methods of radio-frequency heating as practised to-day are possible because we can produce great concentrations of power in the form of electromagnetic vibrations in the coils and condensers of oscillatory circuits; we must think of these as stationary vibrations rather than progressive waves. But if one remembers that stationary waves arise simply from the multiple reflexion of progressive waves in a closed space, and that a vibration is no more than a system of stationary waves, we shall see that there is no essential difference in the nature of the energy in the two cases. Both can be visualized as periodic electric and magnetic fields, concentrated in one case and diffused throughout space in the other. Radio-heating—I now feel justified in using this shorter term—consists of the generation of power in these two forms, periodic electric and magnetic fields, its transference to the work, and its absorption by the work.

Generators

The generators used for the purposes of radio-heating are in principle the same as those used for radio-transmission, and we need only consider one form, the valve oscillator. Its construction is a job for the radio-engineer. The principal components are, first, an oscillatory circuit consisting of a coil connected to a pair of metal plates constituting an air condenser; secondly, triode valves; and thirdly, an auxiliary unit, which takes power from the ordinary electric supply mains, and transforms it to high-tension direct current, suitable for application to the valves.

The condenser, when charged by the high-tension current, discharges through the coil in an oscillatory manner, at a frequency determined by the dimensions of the coil and condenser, the commonest sizes of coils and condensers giving frequencies in the radio range. Now what happens in the oscillatory discharge is this: the electropotential energy of the charged condenser, which we represent as an intense electric field between its plates, is transformed into the electrokinetic energy of the discharge current, which we represent as the magnetic field of the coil. Strictly speaking, it is the magnetic field of the whole circuit, but we can usually regard it as localized in the coil, the contribution of the condenser being negligibly small. The condenser having been drained of its energy, the current ceases, the magnetic field dying away and thereby inducing an E.M.F. in the coil, which again charges the condenser, and so on in the familiar way. There is a periodic transformation of the energy of the circuit from one form to the other, potential to kinetic and vice versa, at the natural frequency of the circuit; and these two forms are to a large extent concentrated, one in the coil and the other between the plates of the condenser. Some of this energy is inevitably absorbed

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by all solid bodies in the immediate neighbourhood of the circuit including the coil and condenser themselves, and a little is lost as radiation, so that the oscillation dies down unless additional energy is supplied. This additional energy is supplied by the valves; their control-grids and anodes are connected to the oscillatory circuit in such a way that each valve is automatically triggered by its grid to pass into the circuit a pulse of energy at just that part of the cycle, and of just the amount, that is required to maintain the vibration at a steady level. The ratio of the radio-power to the direct-current power supplied is the efficiency of the oscillator; this can be brought up to about 50-60 per cent, the remaining power being lost as heat in the valves.

It may be well to note at this stage the scale on which radio-heating is practicable. We have read with some satisfaction that during the War the B.B.C. set up the world's most powerful transmitter, delivering no less than 800 kW. of radio-power to the aerial. We have only to express the power transferred in heat units, and divide by the thermal capacity of the 'work', the product of its mass and specific heat, in order to find out the rate at which its temperature will rise, apart from heat losses. In this way we find that if the 800 kW. of power were concentrated into a cubic yard of water at ordinary temperature, it would take about six minutes to bring it to the boil; if concentrated into 1 cu. in. of steel, it would take about 1/16 sec. to bring the whole mass to a uniform temperature of 800° C., say to a cherry-red heat. But outside the oscillator the power is *not* concentrated; it is very thinly spread by the aerial, so evidently there is no danger in wandering through a powerful broadcast. Compared with the 60,000 kW. of an ordinary electric power station, the power is trifling, and it becomes obvious that if quantity and cost are important considerations, radio-power is no competitor of power in the commoner forms: its special virtues lie in its qualities rather than quantity.

We have now to consider the transference of the power to the work and its absorption by the work, and it is here that we find the different treatments for metals and non-metals, a difference that arises from the following facts. First, non-conductors can be permeated by both magnetic and electric fields, but can only absorb power from electric fields. Secondly, good conductors cannot be penetrated by electric fields, but are penetrated to some extent by magnetic fields and absorb power from them very readily. The processes of radio-heating are all developments of these basic experimental facts.

Induction Heating

The transference of power to a metal by the magnetic field is a direct consequence of Faraday's law of induction. Power is the quantity we have to transfer to the work, but for the radio-heating of metals, we always picture the process as the induction of currents, and we often speak of the process as induction, or eddy-current, heating. The power is transferred by the magnetic field exactly as in a transformer, and one of the chief virtues of the radio-frequency is that it makes possible efficient transformer action in simple systems consisting of a very few turns in air, as against the many turns in iron required at low frequencies. Any metal object provides paths of low resistance for the circulation of eddy-currents, and these paths may be regarded as short-circuited turns of a transformer, the coil pro-

ducing the magnetic field being the primary coil. Very heavy currents are induced by the rapidly fluctuating magnetic field in these short-circuited turns, and the heat is generated by these currents in overcoming the resistance of the metal.

It is a well-known fact that electric currents of radio-frequency are very largely confined to the surface skin of the metal, and the result is that in the radio-heating of metals nearly all the heat is produced in the surface layers of the 'work', the interior remaining cool except in so far as it is heated by thermal conduction from the surface. The concentration of current in the surface can be deduced mathematically from Faraday's law, but we may also describe the whole process as follows. The power is transferred from the generator coil to the metal in the form of the electrokinetic energy of the magnetic field, which freely crosses any space either in air or vacuum. The metal is, however, such a very good absorber that all the energy is absorbed at the surface on which it is incident. The actual depth of penetration can be worked out from a knowledge of the frequency, the resistivity of the metal and its magnetic permeability, so that we can find out what frequency must be used in order to get the energy to penetrate to any desired depth.

The phenomenon has important applications in the case-hardening of steel tools, gear wheels, etc. Since all the heat appears in an extremely thin layer at the surface nearest to the inducing coil, the volume of metal that is heated can be made almost as small as we please: by a suitable disposition of inducing coil, we can transfer all the power available to one portion of the surface, so that the heated portion can be controlled in both area and depth. The concentration of the absorbed power can therefore be made extremely high even with a generator of moderate power. Thus power concentration of, say, 20,000 kW./cu. in. are obtainable with no more than, say, 20 kW. of total power. It is therefore possible with such a generator to heat the surface of a steel tool to a white heat in a second or less, and then by immediate quenching to harden the surface without affecting the main bulk of the material in any way, the whole process being very rapid, subject to precise control, and obviously not in the least likely to cause any distortion of the tool.

Induction heating has also been applied with success to soldering and brazing, the melting and general heat-treatment of metals *in vacuo*, and to many other processes where controlled surface heating is necessary. There are of course many technical details to be considered: the form of inducing coil, and the method of keeping it reasonably cool (water-cooling is usually necessary), the method of coupling the inducing coil to the oscillator in order to ensure the transference of all the power available, or the matching of the load to the generator; but since both the transference and absorption of the power are governed by laws that are well understood, the conditions required for success can usually be predicted from the results of a few trials and a knowledge of the appropriate data for the material to be treated and for the oscillator.

Dielectric Heating

In the induction heating of metals the power is transferred to the metal by the magnetic field, which penetrates the outer layers of the metal, and there induces eddy currents or the circulation of free electrons, which dissipate the whole of the power before

it has penetrated to any considerable depth: the material can be said to be very *opaque* to the flux of energy. The same action must occur to some extent in a dielectric; but it is usually too small to be detected, because these materials do not contain enough free electrons or ions to carry appreciable eddy currents. In other words, the dielectric is *transparent* to the flux of energy, the magnetic field penetrating it completely.

The most characteristic property of a dielectric and the one which distinguishes it from a conductor is that when it is placed in an electric field a definite potential gradient or electric stress is established within it, which stress produces an electric strain or displacement, the material thereby acquiring energy that is distributed throughout its volume. The energy of a charged condenser is a very familiar instance, and we know that every element of volume of the dielectric of such a condenser must be credited with stored energy of a concentration that is proportional to the product of its dielectric constant κ and the square of the field-strength F . It is in this way that the energy is transferred to the material in dielectric heating. We must now consider how it is absorbed, but before doing so we may note that no such transfer occurs to a metal because the field does not penetrate the metal.

The extent to which the energy transferred is absorbed when the field is periodic will depend entirely on the character of the forces controlling the displacement. A displacement of an elastic type, being always in phase with the driving force, gives rise to no net loss or absorption of energy in any number of complete cycles, but a displacement that is retarded by any force of a frictional or viscous character will lag in phase with respect to the driving force, the electric field, and will give rise to a definite loss or absorption of energy in each cycle. It is found in radio practice that for solids and liquids there always is an observable phase difference, δ , between the electric force and displacement, and that within wide limits δ is characteristic of the material and independent of its size and the field-strength F . This can only mean that in every cycle a definite fraction of the total energy put into any element of volume of the material by the field is absorbed, and this fraction turns out to be proportional to $\tan \delta$, which is therefore called, somewhat loosely, the 'power factor' of the material. It follows that the concentration of absorbed power in any element of volume of a dielectric is proportional to $\kappa f \tan \delta F^2$, where f denotes frequency.

This simple relation has several important consequences. First, other things being equal, the concentration of absorbed power, and therefore the heating, is proportional to the frequency and to the power factor of the material. For this reason dielectric heating is usually carried out at as high a frequency as is practicable, and materials of high power factor are selected for treatment if possible. Secondly, if the material is homogeneous and the field can be made uniform, the heat is uniformly distributed throughout the whole of the material. Thirdly, when the field is not uniform, there is a strong concentration of heat in the part of the material occupying the strongest part of the field. Fourthly, when a composite material is treated, the rates of heating of the several components are controlled by their dielectric properties, κ and $\tan \delta$. The great importance of these features of the process will be illustrated by a few typical examples.

Uniform Heating in Depth

Probably the most important characteristic of dielectric heating is that, when a homogeneous material is placed in a uniform field, the heat is distributed uniformly throughout its volume, however thick the material may be. By this process we can, therefore, heat uniformly very thick layers of a material that may be a very poor conductor of heat, an operation that cannot be performed by any other method. Dielectric heating is indeed our only process for the heating of poorly conducting solids in depth.

The following examples illustrate the value of this feature of the process. The first is the moulding of plastics. Heat must be supplied to the moulding material in order to bring it into the plastic condition in which it can flow under pressure into every part of the mould. The heat is commonly supplied by contact with the mould itself, which is heated for the purpose, but the rate at which the heat penetrates the material is restricted by its low thermal conductivity, and this sets a limit to the speed of the whole operation and the thickness of the mouldings that can be satisfactorily made. These limitations are overcome by the dielectric heating of the material immediately before the actual moulding operation. The moulding material, usually supplied in the form of cold-pressed pellets, is placed between the condenser plates of a radio-generator, and in a matter of seconds its temperature throughout rises to the point at which it will flow evenly under pressure. It is then transferred to the press and the moulding operation completed.

Plywood manufacture affords another example. The synthetic resin glues, now largely used, set in say eight hours when cold, but can be made to set in a few minutes by heating to 60°–80° C. Thus the bonding of thin veneers with these glues to form plywood can be greatly accelerated by the application of heat. Considerable pressure is required for the production of good glued joints, and if this is applied by means of a press with heated platens, small thicknesses of wood can be heated by conduction from the platens, but with large thicknesses the operation becomes slow and uneven. By means of dielectric heating, stacks of plywood up to 2 ft. thick can be heated uniformly and bonded in one operation. A thin metal plate in the centre of the stack forms one electrode, and the two platens of the press, which are necessarily connected together by its framework, form the other. A few hundred kilowatts of radio-power is applied to the condenser so formed, and the temperature throughout the mass of 50 cu. ft. or so of laminated wood rises to the point at which the whole bonding operation is completed in a matter of minutes instead of hours.

The application of the method to the rapid production of curved objects in wood will be, I think, sufficiently obvious. The veneers are thin enough to bend very readily, and it is only necessary to bond them together while they are pressed in a jig between rigid surfaces of wood or metal having the required contour.

The process is also of great value in certain drying operations. The drying of poorly conducting materials in large masses in ovens and kilns is always a very tedious business, because the conduction of heat into the centre of the material, and the diffusion of water out of it, are both very slow processes. When dielectric heating is used, the centre of the material is heated instantly and soon becomes hotter than the

outer layers, which are cooled by evaporation and air convection. The relatively high internal temperature produces a correspondingly high internal vapour-pressure which under favourable conditions drives out the water with great speed. I should perhaps mention that the process must be applied with caution to any material that is liable to be damaged by heating to a temperature of 100° C. or less.

Spot Gluing and Welding

Another important quality is the ease and precision with which dielectric heating can be localized. It has been seen that the heat generated is proportional to the square of the electric field strength. If therefore we wish to heat one particular spot of a material only, we merely have to place two small electrodes one on either side of the spot, and deliver the appropriate amount of power to them. The field being almost entirely concentrated in the narrow gap between the electrodes, the heat appears there only. This localized heating provides us with several operations for the jointing of non-metals, analogous to the soldering, brazing and welding of metals.

The process is used in assembling the complex wood structures that go to build up, say, the Mosquito aeroplane. Many such structures consist of thin skins of plywood moulded to the desired streamline contour, and supported and made rigid by girders or bulkheads, also of wood. The veneers from which the plywood is built up and also the supporting members are bonded with synthetic resin glues by means similar to those already considered, which involve the application of considerable pressure while the glues are hardening: only in this way can the full strength of the joint, which, I may say, exceeds that of the wood itself, be obtained. But some means must be provided for tacking the various pieces into their proper positions while the structure is being built up into a form to which the necessary pressure can be applied. Metal screws, pins and staples are often used for the purpose, but they are undesirable since they necessarily weaken the wood at the point at which they pierce it. Spot gluing by localized radio-heating solves this problem. The equipment consists of a small radio-generator which delivers, say, 100 watts of power at 100–200 Mc./sec. through a flexible cable to a pair of small electrodes mounted on a handle shaped like a short gun. The tip of the gun barrel forms one electrode, while the other is a central stud, which when not in use projects a little beyond the end of the barrel, but can be pushed back against a spring. The gun is pressed on the spot to be glued; the inner stud is thus pushed back into the barrel until both electrodes make contact with the surface of the wood. The movement of the stud operates a switch and timing device, which switch on the radio-power to the electrodes for the few seconds required to harden the glue-film at the spot covered by the gun. The electric field is of course most highly concentrated around the surface of the small inner electrode and it is here that the heat is localized. The timing device is adjusted to suit the work in hand. The operation is very simple and rapid.

Thermoplastic material in sheet form can be welded by a somewhat similar technique: both spot welding and seam welding are practised. In seam welding the overlapping sheets are drawn between two small roller electrodes, and the power and speed are adjusted until the power is just sufficient to soften the material in the short time it remains between

the two rollers. The pressure of the rollers makes the two soft materials flow together and ensures a good weld, and the joint is cooled by the surrounding air as soon as it emerges from between the rollers. The device can be made to be operated like a sewing machine. Spot welding is performed by means of another gun in which the central electrode has the form of a small roller which is pressed on to the overlapping sheets. Again intense local heating occurs in the strong field immediately surrounding the small electrode, and a good spot weld is made in a second or less.

Selective Heating

One of the most interesting features of dielectric heating still remains to be considered: we can sometimes arrange to supply heat to a mixture of two substances in such a way that nearly all the heat appears in one of them only. We have seen that the concentration of the heat generated within any material is proportional to the product of its power factor, dielectric constant, and the square of the field-strength or voltage gradient. Now although the field between the electrodes may be uniform before the body is inserted, it is not necessarily so afterwards: the relative field strength in the two constituents of a mixture depends on their dielectric constants. However, the variation of this property from one material to another is usually trifling in comparison with the differences of power factor; and in practice, therefore, the concentration of heat in the two constituents of a mixture is roughly proportional to their power factor, and any part of a composite body having a very low power factor remains quite cool in a field which generates considerable heat in parts of high power factor.

A single example will be sufficient to show the value of this property. Take, for example, its bearing on the sterilization of foodstuffs and biological materials generally. If we can find a frequency at which the power factor of the pests we want to get rid of is high, and that of the material to be sterilized is low, we shall have an ideal sterilizing process. An appropriate electric field applied for a very short time would heat the pest enough to kill it without causing any unnecessary and possibly harmful heating of the good material. A very early suggested use for the process was the killing of pests in plant bulbs, and experiments have also been made on grain and other materials. The process is undoubtedly effective in killing the pests; but the extent to which selective heating has occurred is doubtful.

I have here selected those features of radio-heating that are of scientific interest. The industrial value of the process is largely bound up with economic considerations that I have barely mentioned. Radio power is at least ten times as expensive as heat in its cheaper forms, and its industrial use for heating purposes is therefore only justified when it results in a considerable saving of labour, time or floor-space or some such item as is far more costly than mere power in bulk. Nevertheless, it has had some remarkable industrial successes, and no one can doubt that it will have an important place in the industry of the future. It is, however, as a new scientific tool that I have preferred to consider it; a tool that enables us to manipulate thermal energy with precision in circumstances where others fail, and which therefore in some measure extends the range of experimental inquiry.