Induction Heating in Radio Electron-Tube Manufacture*

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Summary—**The radio electron-tube industry was one of the first to use induction heating extensively. The metal parts of electron tubes must be heated to 500 to 1500 degrees centigrade during evacuation in order to liberate gases occluded in the parts. Since the parts are in a vacuum and are usually surrounded by a glass bulb, induction heating is the ideal method. The heating coils are usually made to fit the bulbs and may be used either on stationary evacuation systems or on rotary systems. Other similar applications are "getter"-flashing and vacuum-firing systems. Still other applications are in sealing metal to glass, in brazing tube parts together, and in welding. In all of these applications the chief advantages are accurate control and speed of heating. The radio-frequency generators are usually of the vacuum-tube type operating at about 200 to 500 kilocycles. Units of about 2 to 15 kilowatts are used. The theory of heating is developed from simple air-cored transformer considerations and an example is given.**

INTRODUCTION

INDUCTION heating is very widely used in the radio electron-tube industry. This has been true starting from the early 1920's. The main use has been in degassing the electrodes of radio tubes during evacuation of the tubes. In evacuating, or exhausting, any type of electron tube it is necessary not only to remove the air from the tube envelope, but also to remove, to a great extent, gases and vapors occluded in the internal tube parts so that they will not be liberated later during use of the tube. The higher the temperature to which these parts can be brought during the exhaust process, the more rapidly the undesired gases can be pumped out. The temperature is limited by such considerations as evaporation of the electrode materials, melting of parts, or melting of the glass envelope. The temperature range is roughly 500 to 1500 degrees centigrade, although higher temperatures may be used in the case of high-power tubes.

In the earliest days of the radio electron-tube industry, heating of tube electrodes was accomplished by lighting the filament so that it would emit electrons, and then applying voltage to the other electrodes so that they would be bombarded by electrons. Under these conditions, the heat dissipated in an electrode is simply the product of the applied voltage and the current to the electrode. This method is still used in many cases, but it has been largely supplanted by induction heating. The reason for this change is that it is inadvisable to require modern filaments and cathodes to emit heavy electron current while the vacuum in the tube is poor. Modern cathodes are usually of the barium-strontium, oxide-coated filament type or of the thoriated-tungsten type. Both of these types of cathodes are very efficient sources of electron emission, but they are also sensitive to gas bombardment or oxidation by oxidizing gases. It is, therefore, very desirable not to heat the cathodes to operating temperature during poor vacuum conditions such as would be present while electrodes are giving off gas and vapor. Induction heating is, consequently, an ideal method of heating the electrodes of tubes, because the cathode may remain unenergized while the electrodes are being degassed. In addition, induction heating may be controlled very easily. It is small wonder, therefore, that this type of heating is so widely used in the tube industry.

APPLICATIONS

A number of typical induction-heating applications will be described. Application to tube exhausting has already been mentioned. There are two main types of such applications, the first to stationary exhausting positions and the second to automatic rotary machines. Fig. 1 shows a stationary application. Here a 500-watt tube is being exhausted. The tube has been sealed to a glass exhaust manifold which leads to a vapor-diffusion pump. The anode of the tube, which is 2 inches (51 millimeters) in diameter and 3 inches (76 millimeters) long,

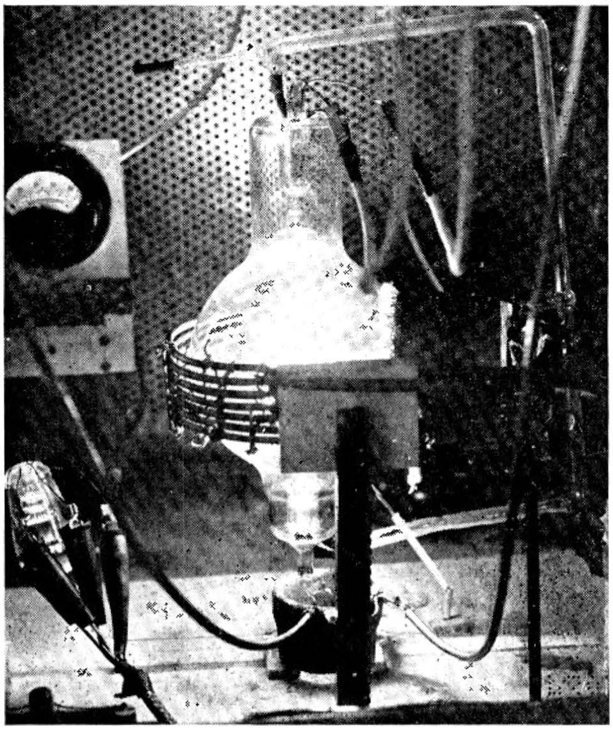

Fig. 1—Induction heating applied to radio tubes.

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and made of tantalum sheet, is being heated to about 1300 degrees centigrade by the multiple-turn heating coil or inductor. The inductor is made of standard 0.25-inch (2.5-millimeter) copper tubing and carries a current of about 150 amperes at about 300 kilocycles. This current is generated by an 8-kilowatt radio-frequency generator, which will be described later. The radio-frequency current is controlled by changing of voltage taps on the high-voltage-supply transformer and by variation of the filament voltage of the oscillator tubes in the generator.

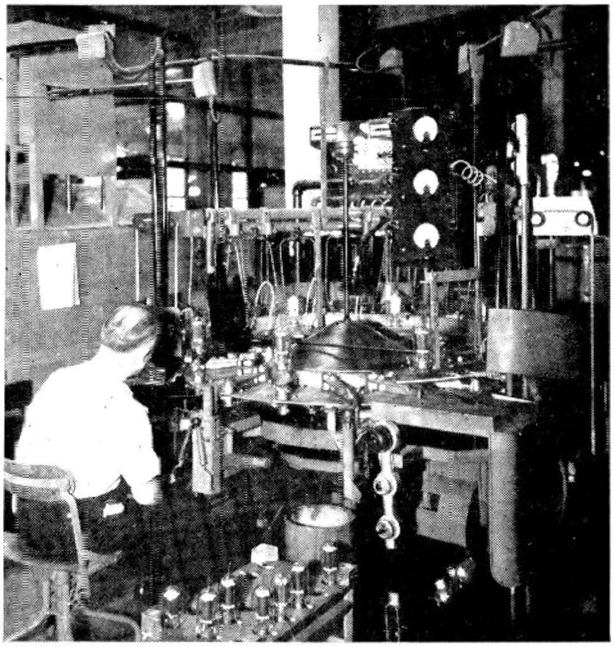
Fig. 2—Automatic rotary exhausting machine.

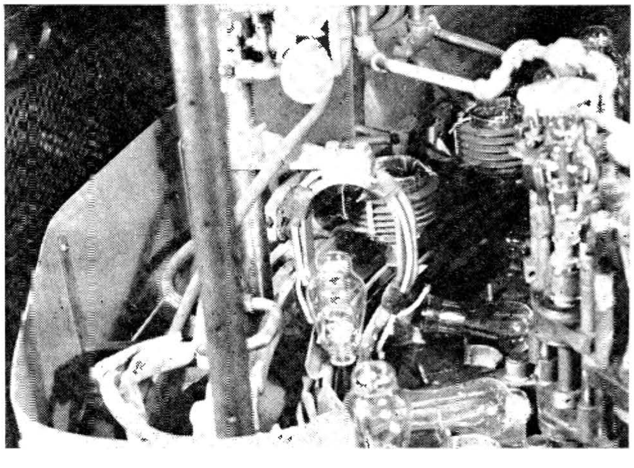
Fig. 3—Induction-heating position on rotary exhausting machine.

Fig. 2 shows an automatic rotary exhausting machine. The exhaust tubing of the tubes is inserted into a rubber exhaust opening and connected by means of manifolds and a rotary valve to diffusion and mechanical pumps. The rotary table carrying the tubes turns at intervals which may be 0.1 to 3 minutes long. To the rear of the machine, the carbon anodes of the tubes may be seen heated to incandescence by high-frequency inductors. Just before the rotary table indexes, the inductors are raised up high enough to clear the tubes. Due to this arrangement, it is not necessary to have the inductors rotate. The radio-frequency generator may be seen in the left background; the heavily insulated leads carrying the current to the machine are in clear view. Several inductors are usually connected in series in order to utilize fully the capabilities of the generator.

Fig. 3 shows a closer view of the machine in Fig. 2. Fig. 4 shows a typical inductor held over a tube. The inductors shown in these two figures are made of flattened 0.5-inch (51-millimeter) diameter copper tubing through which cooling water is circulated. Inductoı currents of 50 to 150 amperes are used; temperatures of 700 to 1200 degrees centigrade are commonly produced in the electrodes of the tubes being exhausted. The inductors are designed to be readily interchangeable by the use of standard pipe couplings. In this way, inductors of varying diameter and construction to suit the job at hand may be installed.

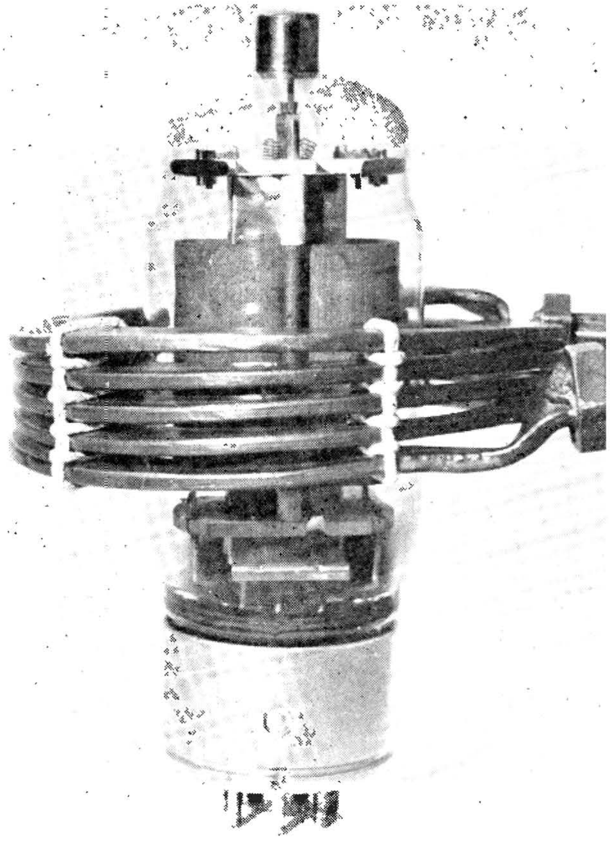
Fig. 4—Typical inductor and radio tube.

Fig. 5 shows an application of induction heating to vacuum firing. It is often desirable to heat tube parts to high temperature in good vacuum prior to assembly of the tubes. Occluded gases can be removed in this manner and it is also possible to remove vaporizable contaminating materials. In the particular case shown in Fig. 5, small tube parts are being vacuum-fired. Since these parts have very poor coupling to the inductor, they are placed in a box made of tantalum sheet. The induction currents heat the box which in turn heats the parts by radiation and conduction. The box is supported within the long, 5-inch (127-millimeter) diameter glass bell jar, which rests on a rubber gasket lubricated with castor oil. The vacuum pumps are mounted below the table. The inductor can be seen surrounding the bell jar. A multiple-turn inductor of 0.25-inch (6 millimeters) copper tubing is used; its power supply is a 16-kilowatt radio frequency generator.

Fig. 5—Induction-heated vacuum firing station.

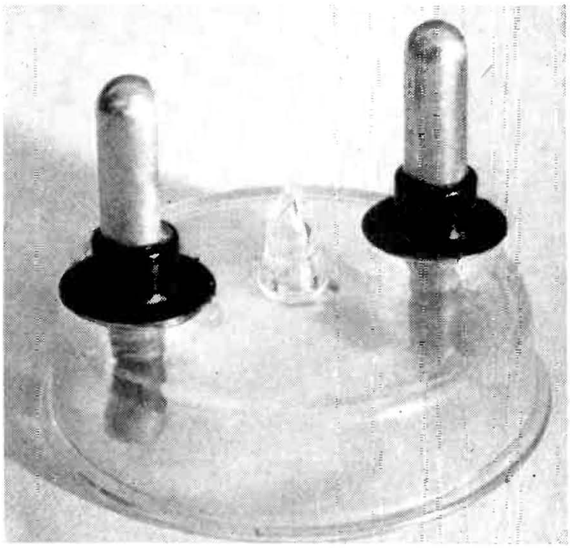

Fig. 6—Metal-to-glass seals made with induction heat.

SEALING METAL TO CORNING GLASS

A considerably different application is sealing metal to glass. Fig. 6 shows a completed assembly consisting of a molded glass "dish" and two terminals of Kovar which have been sealed to the "dish." Kovar, an iron-nickel-cobalt alloy, has an expansion curve which closely matches that of Corning No. 705FN glass. As a result, butt glass-to-metal seals of the type shown are readily possible. To make a seal of this type the Kovar and glass can be heated by gas-oxygen flames, but much more uniform results are obtained by heating the Kovar by induction. Fig. 7 shows the setup used for making the seal just described. The glass dish and two terminals are held in position by suitable means. The two Kovar cups are heated by the small inductors. The glass dish may be moved up and down. The Kovar cups are heated until they oxidize slightly and then the glass dish is pressed down so that the two flat-ground openings in the dish contact the cups. Moderate pressure is applied while the cup heating is continued. In a short time the glass softens and flows. In this state it dissolves the surface oxide on the cups, and an intimate bond results. Heating is then stopped and the assembly is placed in a continuous annealing oven so as to remove any strains introduced in the glass. The entire sealing operation requires only about one minute. An 8-kilowatt vacuum-tube radio-frequency generator is used. This method, which has been in use about 5 years with women

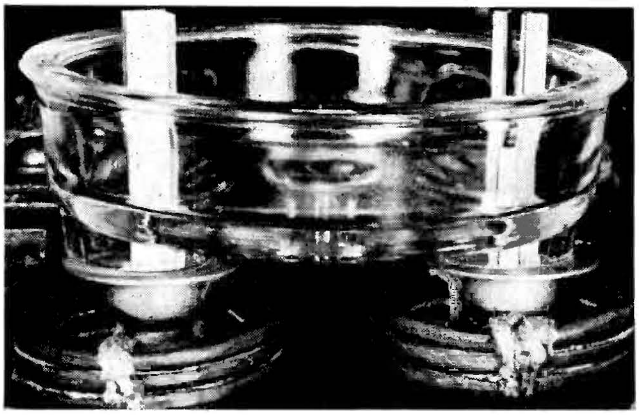

Fig. 7—Metal-to-glass sealing setup

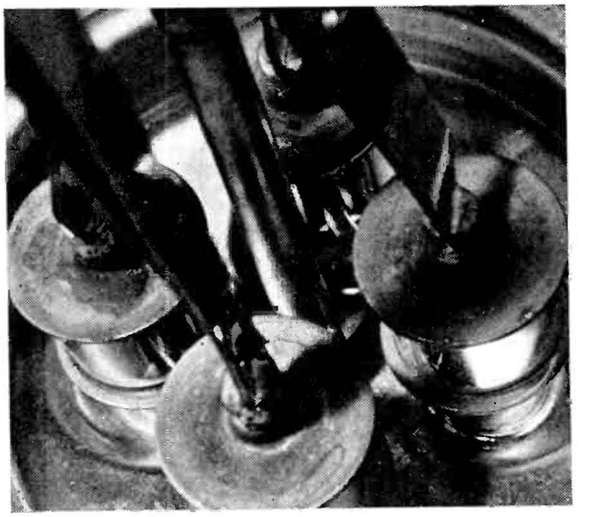

Fig. 8—Typical silver-soldered assembly.

operators, has been singularly free of difficulties although the operation itself was once regarded as a job requiring many years of training.

BRAZING

Still another application of induction heating is in brazing. Fig. 8 shows a typical case. The large flange is made of Kovar and four Kovar glass assemblies are brazed to the flange using Handy and Harman "BT" silver solder. The joint must be vacuum-tight. The flange is mounted, as shown in Fig. 9, over a 5-turn inductor. A single turn of wire solder is placed around the joint to be brazed. A bell jar fed with hydrogen from the top is placed over the work. The radio-frequency generator is then turned on until the silver flows as observed through a window. Since the heating is done in a reducing atmosphere, all metal parts stay bright. An 8-kilowatt furnace is used, although a smaller one would be satisfactory. Experience has shown that soldering of Kovar is much more satisfactory when done this way. Furnace soldering, where the parts are held above the soldering temperature for several minutes, and then cooled slowly, often gives difficulty because the solder can enter grain boundaries in the Kovar and split it open. For certain sizes and shapes, induction soldering may be effected with sufficient speed and the heat so localized that splitting does not occur.

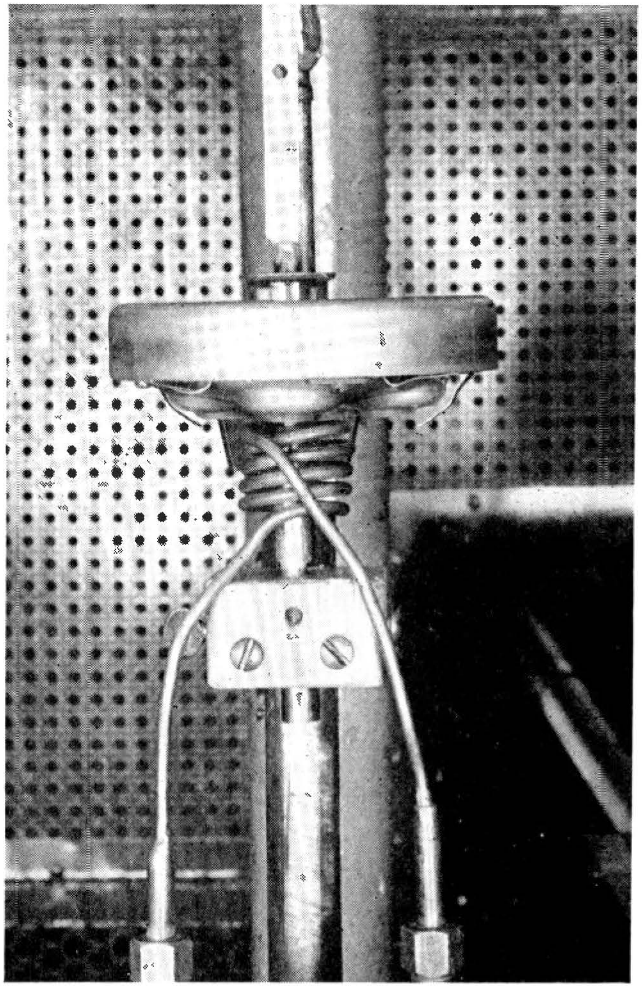

Fig. 9—Silver-soldering setup.

RADIO-FREQUENCY GENERATORS

Fig. 10 shows a typical 8-kilowatt radio-frequency generator as used in manufacturing operations. These generators use two Type 892 water-cooled triodes. These tubes have tungsten filaments and are rated for operation as oscillators with a direct-current power input of 30 kilowatts at 15 kilovolts and 2 amperes. The anodes are rated to dissipate up to 10 kilowatts.

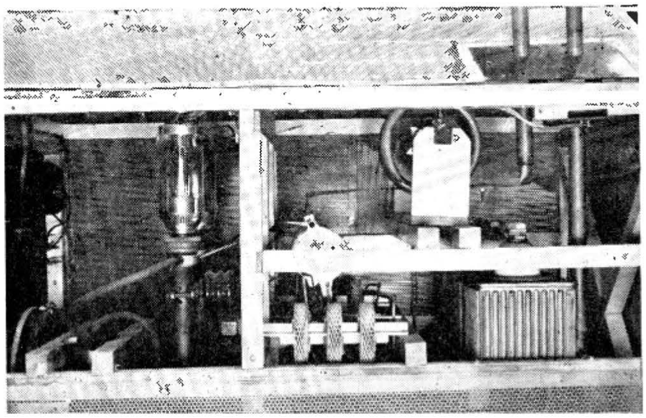

Fig. 10—Eight-kilowatt radio-frequency generator.

Fig. 11 is a simplified circuit diagram of the above generator. In this generator the tubes are operated with 60-cycle alternating-current plate voltage in order to simplify the design of the generator. (When it is desired to utilize the full capability of the oscillator tubes, they are operated with direct-current rather than with alternating-current plate voltage.) Since the oscillator tubes themselves act as rectifiers of the 60-cycle power, it is necessary to use two tubes, operating on opposite secondary-winding terminals of a 60-cycle transformer with the center tap of the secondary grounded. Thus,

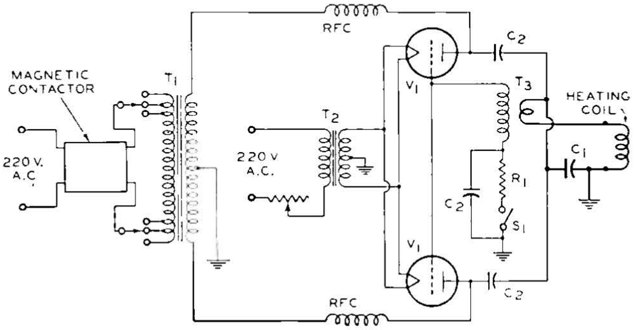

Fig. 11—Eight-kilowatt radio-frequency generator circuit.

Range = 250 to 400 kilocycles.
V_1 = RCA-892 water-cooled power tube
T_1 = 12.5-kilovolt power transformer. Total secondary voltage 7 to 18 kilovolts
T_2 = filament transformer
T_3 = feedback transformer
RFC = radio-frequency choke coil
C_1 = mica capacitor, 0.014 to 0.021 microfarad, 140 to 210 amperes
C_2 = mica capacitor, 0.004 microfarad
R_1 = grid-bias resistor, 1000 to 6000 ohms
S_1 = output control switch

one oscillator tube operates on one-half cycle and the other on the other one-half cycle. The rectified currents supplied by the tubes buck each other and there is, therefore, no direct-current flux produced in the transformer.

The Type 892 tubes are effectively connected in parallel for radio-frequency currents by means of mica capacitors. The radio-frequency circuit consists partly of a bank of mica capacitors of 0.014- to 0.021-microfarad capacitance and rated to carry 140 amperes to 210 amperes at 300 kilocycles, and partly of a parallel inductance composed of the external inductors and leads, and an internal coil which couples to a second coil for feedback of excitation voltage to the grids of the Type 892 tubes.

Control of output current is obtained by means of taps on the primary of the plate-supply transformer and by means of a filament voltage control. The latter gives fine control by varying the electron emission of the Type 892 filaments. The generator is equipped with a filament voltmeter, plate-current meter, and a radio-frequency output-current meter.

Since the Type 892 tubes are water-cooled, a water-flow meter and interlock are provided so that the generator is shut off automatically if the water flow drops below a safe value. A plate-current overload relay is also provided.

The generator is turned on and off when in service by opening the grid-leak resistor. This method very effectively cuts off the generator and, since the current in the grid resistor is only a few hundred milliamperes, no unusual relay is needed. Generators of this type have proved very reliable and flexible.

THEORY OF INDUCTION HEATING

Many cases of induction heating in the radio industry concern thin-walled cylinders. In other cases, the depth of penetration of the current is so small that the load can be considered a thin-walled cylinder, with the wall thickness equal to the depth of penetration. The inductor and the load can thus be considered as an air-cored transformer. The mathematical solution of this heating problem is very simple.[1,2,3] The expression for the efficiency of heating is

$$n = \frac{1}{1 + \dfrac{1}{K^2}\left(\dfrac{1 + Q_2^2}{Q_2Q_1}\right)} \tag{1}$$

where K = coefficient of coupling between inductor and the load

$Q_1 = Q$ of the inductor

$Q_2 = Q$ of the load.

Q is defined as the ratio of reactance of a circuit element to the series resistance of the element.

In the case of an inductance L having a resistance R at a frequency of f,

$$Q = \frac{2\pi fL}{R} = \frac{\omega L}{R}.$$

A study of (1) shows that efficiency increases with Q_2 and is essentially at its maximum value when $Q_2 = 3$.

Further, the current required in the inductor to produce W watts in the load is

$$I = \frac{\sqrt{W}}{K\sqrt{\omega L_1}}\sqrt{\frac{1 + Q_2^2}{Q_2}} \tag{2}$$

where L_1 = unloaded inductance of the inductor.

The voltage across the inductor is

$$E \cong I\omega L_1\left(1 - K_2\frac{Q_2^2}{1 + Q_2^2}\right). \tag{3}$$

In the application of the above equations, practical units are to be inserted; i.e., henries, ohms, watts, root-mean-square volts and amperes, and cycles per second.

The question now arises, how are these quantities to be determined? If both the inductor and load are coaxial cylinders, the inductance of each and also their mutual inductance may be calculated.[4] The coupling coefficient is then the mutual inductance divided by the square root of the product of the two individual inductances. The reactance of the load can be calculated at the operating frequency. The resistance around the periphery of the load can also be easily calculated. If the thickness of the wall of the load is greater than the depth of penetration of the current, the thickness should be taken as equal to the depth of penetration. The Q of the load and the reactance ωL_1 of the inductor are next calculated. Thus, all constants for (2) and (3) are known, and with further insertion of the watts desired in the load, both inductor current and voltage may be obtained. Since it may not be practical to calculate the Q of the inductor very reliably, measurement may be necessary if determination of efficiency is desired.

If neither the inductor nor the load possesses geometrical shapes for which there are formulas for inductance and mutual inductance, measurement can be made. A Boonton Model 160-A Q meter is very convenient for this purpose. First, a model of the inductor is made of the same length and cross section and wound with enough turns of wire to bring the inductance up to 600 to 1000 microhenries so as to permit obtaining resonance with the variable Q meter capacitance of 450 micromicrofarads. The Q meter is resonated at the desired frequency and a reading of Q and the required resonant capacitance are noted. This permits calculation

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[1] W. Esmarch, "Zur Theorie der kernlosen Induktionsöfen," *Wiss. Veröffent. Siemens-Konzern*, vol. 10, pp. 172–196; 1931.

[2] H. B. Dwight and M. M. Bagai, "Calculations for coreless induction furnaces," *Elec. Eng.*, vol. 54, pp. 312–315; March, 1935.

[3] G. H. Brown, "Efficiency of induction heating coils," *Electronics*, vol. 17, pp. 124–129, 382–385; August, 1944.

[4] Bureau of Standards Circular No. 74, Radio Instruments and Measurements, 1938.

of L_M, ωL_M, and R_M, where the subscript M refers to the model. The load is then inserted. (If the load is magnetic at room temperature, but not at the desired temperature, an identical load of nonmagnetic metal should be used.) The Q meter is reresonated and the new values of Q and capacitance are noted. Again L_M', $\omega L_M'$, and R_M' are calculated. The original values are subtracted giving $\Delta\omega L_M$ and ΔR_M. The theory shows that

$$\frac{\Delta\omega L_M}{\omega L_M} = K^2 \frac{Q_M{}^2}{1 + Q_M{}^2} \tag{4}$$

and that

$$Q_M = \frac{\Delta\omega L_M}{\Delta R_M} \cdot \tag{5}$$

Equation (5) gives Q_M which is inserted in (4). Equation (4) can be solved for the coupling coefficient K. Knowing the resistivity of the actual load at the desired temperature and the resistivity of the load used during the test above, we find that the true Q of the load is

$$Q_2 = Q_M \sqrt{\frac{\rho_M}{\rho_2}} \tag{6}$$

where ρ_M is the model load resistivity and ρ_2 the actual load resistivity. Equation (6) assumes that the depth of penetration is less than about one fifth of the radius of the load. Finally, the measured ωL_M must be reduced by the ratio of the square of the inductor turns to the square of the model turns, so as to get the true inductor reactance ωL_1. All values are then known for (2) and (3).

Both of the above methods have been used with good results. One example will be given. The load and inductor were those shown in Fig. 4. A model of the inductor was made by winding 91 turns on a coil form. The model had the same length as the inductor, but the diameter was 3.75 inches (95 millimeters) instead of 3.5 inches (89 millimeters). This requires a later correction in K. The model connected to a Boonton Q meter, gave at 300 kilocycles a Q of 180 and a resonant capacitance of 272 micromicrofarads. By a second measurement at 600 kilocycles, it was found that the model had 7 micromicrofarads stray capacitance. Therefore the corrected capacitance was 279 micromicrofarads. From the usual formula connecting L, C, and f, the inductance of the model was 1010 microhenries and its reactance was 1905 ohms at 300 kilocycles. Thus the model had a resistance of $1905/180 = 10.6$ ohms.

Next, the anode of Type 813 tube was inserted in the model and it was found that at 300 kilocycles the Q was 29 and the resonant capacitance was 286 micromicrofarads. Repeating the calculations above the new model reactance was 1810 ohms and the new resistance was $1810/29 = 62.4$ ohms. The change in reactance was, thus, $1905 - 1810 = 95$ ohms, and the change in resistance was $62.4 - 10.6 = 51.8$ ohms. Applying (5) we find that

$$Q_M = \frac{95}{51.8} = 1.83.$$

In this case, since an actual anode and not a model was used, $Q_M = Q_2$. However, the anode was not at operating temperature, so the correction of (6) is still necessary. The ratio of hot-to-cold resistance in this case was 0.85. Therefore the hot

$$Q_2 = 1.83\sqrt{\frac{1}{0.85}} = 1.99.$$

Applying (4), we obtain

$$\frac{95}{1905} = K^2 \cdot \frac{1.83^2}{1 + 1.83^2} \cdot$$

From this equation

$$K = 0.25.$$

This value needs revision, due to the fact that the inductor model had too large a diameter. As an approximation, K is inversely proportional to diameter. Thus the corrected K became

$$0.25 \times \frac{3.75}{3.5} = 0.268.$$

The reactance of the model inductor was then reduced by the square of the number of turns in order to get the reactance ωL_1 of the actual inductor, which had 4.5 turns. We obtain

$$\omega L_1 = 1905 \times \left(\frac{4.5}{91}\right)^2 = 4.63 \text{ ohms.}$$

The power required in the anode was calculated by assuming that the temperature was 1100 degrees centigrade and the radiation coefficient was 0.8, and by allowing 5 per cent for end effects. This gave 1200 watts.

Now applying (2) and (3), we obtain

$$I = \frac{1}{0.268}\sqrt{\frac{1200(1 + 1.99^2)}{4.63 \times 1.99}} = 95 \text{ amperes}$$

and

$$E = 95 \times 4.63\left(1 - 0.268^2 \cdot \frac{1.99^2}{1 + 1.99^2}\right) = 415 \text{ volts.}$$

Actual measurements on an exhausting machine gave $I = 87$ amperes, $E = 365$ volts at a frequency of 308 kilocycles and with an anode temperature of 1100 degrees centigrade. This comparison shows that satisfactory results can be obtained by this method.

Additional References

(1) T. P. Kinn, "R-F generator characteristics for induction heating," *Radio-Elec. Eng.*, vol. 4, pp. 20–22, 28–30; January, 1945.
(2) R. M. Baker and C. J. Madsen, "High-frequency induction heating of conductors and nonconductors," *Elec. Eng.*, vol. 64, p. 64; February, 1945.
(3) F. W. Curtis, "High-Frequency Induction Heating," McGraw-Hill Book Company, New York, N. Y., 1944.