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1,694,792

E. F. NORTHRUP

HIGH FREQUENCY INDUCTION FURNACE

Original Filed Nov. 29, 1924 2 Sheets-Sheet 1

Fig. 1.

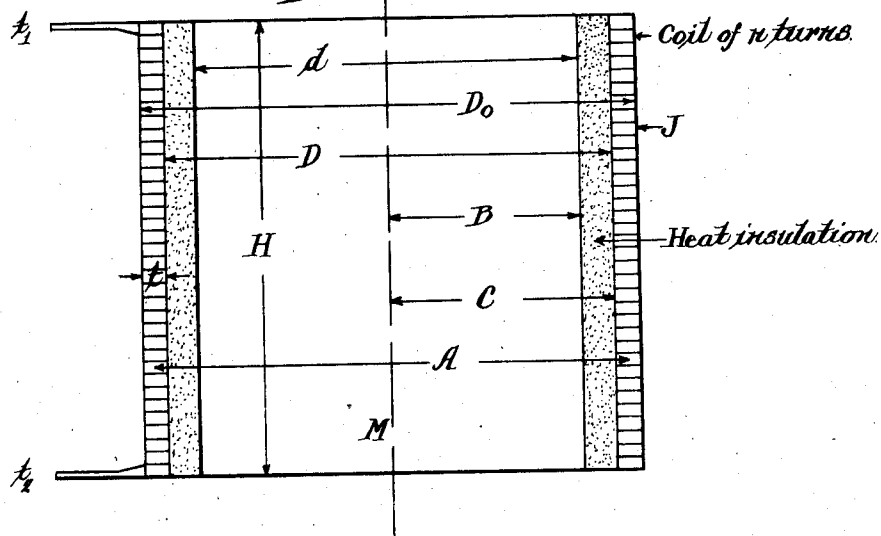


Fig. 2.

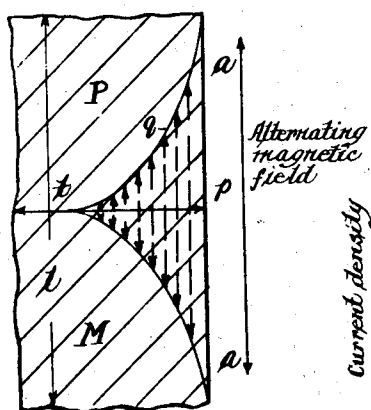
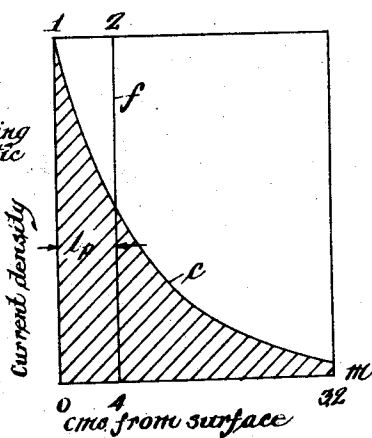


Fig. 3.



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Fig. 5.

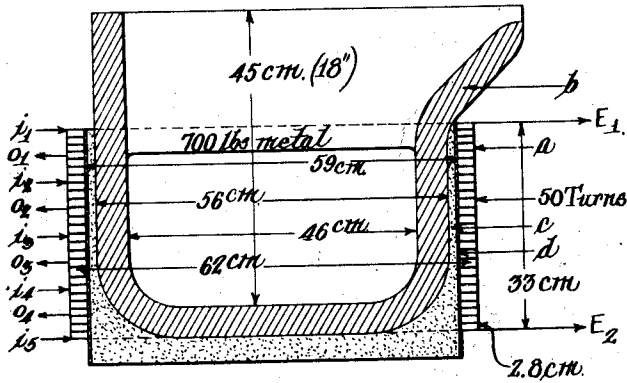


Fig. 4.

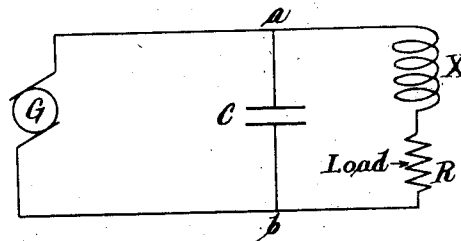
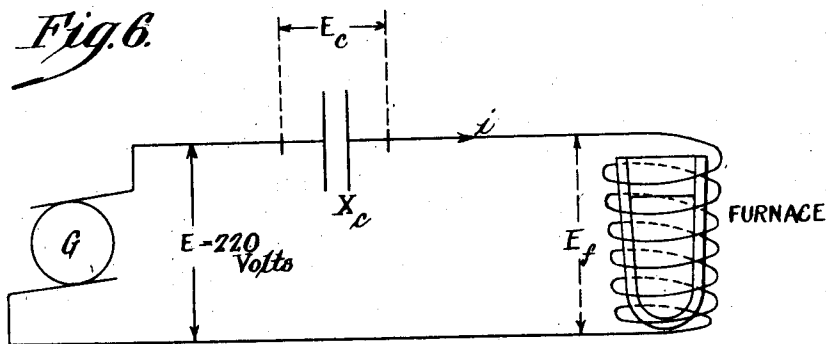


Fig. 6.



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HIGH-FREQUENCY INDUCTION FURNACE.

Application filed November 29, 1924, Serial No 752,835. Renewed July 28, 1928.

My invention relates to inductive heating free from the need for transformer iron and at substantially unity power factor at source of current supply. It has specific reference to certain relations, I have discovered, being chosen between such quantities as; diameter of the charge heated, resistivity of this charge and the internal and external diameters of the inductor.

A further purpose, for reasons of securing economy in equipment costs, is to make practical use of certain broad relations, which I have established by theory and verified by actual practice between certain essential design elements entering into a furnace, by employment of which substantially the same electrical efficiencies may be secured with furnaces widely differing in size.

A further purpose is to maintain the ratio of the resistance of the inductor to its inductance low by use of an edgewise wound coil having a conductor of width definitely related to the diameter of the coil, and, by so doing secure small power losses in the coil itself throughout a considerable range of frequencies.

A further purpose is to make use of the relation which I have discovered between the electrical efficiency of a furnace and the width of the conductor when edgewise wound in a single layer primary and the inside diameter of the winding, this width of the conductor, edgewise wound, and the coil diameter being definitely related.

A further purpose is to employ certain relations in actual constructions between diameter of charge, diameter of coil, resistivity of charge and ampere turns in coil to secure absorption of power in charge at highest efficiency.

A further purpose is to employ for the construction of the single-layer inductor coil an edgewise wound conductor meeting the following specifications and for the following purposes; a copper tube is flattened between rollers to an extent that the opening between the flattened side walls is approxi-

mately equal to the wall thickness of the tube. A continuous length of such tube is edgewise wound to form a single-layer helical coil or solenoid, the separation between the turns being just sufficient to give electrical insulation when filled in with an insulating cement. The width of this copper tubing when flattened is made approximately one twentieth of the inside diameter of the coil when wound, the width of the flattened copper tubing thus being chosen as a definite function of the coil diameter. The coil of flattened copper tubing is provided with one or more water inlets and an equal number plus or minus one of water outlets for the purpose of passing water through the coil, the flow of water under low pressure being kept sufficient by the provision made of multiple inlets and outlets. The purposes of the construction described are: (1) to keep the resistance of coils of large diameter low by using flattened tubing of an appropriate width and (2) to keep the inductor cool and thereby its resistance down by means of a cooling fluid which is made to flow through it.

Further purposes will appear in the specification and in the claims.

I have preferred to illustrate my invention diagrammatically, not attempting to show actual structure even where crucibles are illustrated.

Figure 1 is a diagrammatic view to aid illustrating the principles involved in ironless inductive heating.

Figure 2 is a diagrammatic view showing the distribution and intensity of magnetic field induced in a conducting mass.

Figure 3 is a diagrammatic view showing current densities beneath the surface of a conductor.

Figure 4 is a diagrammatic view intended to illustrate the conditions present for unity power factor.

Figure 5 is a vertical section of a crucible furnace illustrating features of my invention.

Figure 6 is a diagrammatic view showing a condenser in series as applied to my invention.

In the drawings similar numerals indicate like parts.

Since the descriptions and purposes of specific constructions to be given can be fully understood only when knowledge is had of certain general principles of ironless inductive heating discovered by me, I shall first explain these principles in broad outline.

General description of phenomena of ironless inductive heating.

A typical construction for ironless inductive heating is shown diagrammatically in Figure 1. M is a solid cylindrical mass to be heated by electrical currents induced in it. J is an inductor. It consists of a single-layer coil (of edgewise wound, hollow, flattened copper tubing) through which both water and electric current flow. J may have any number of turns n which can be wound in a single layer in a length of space H. Heat insulation h is packed between J and M.

An alternating E. M. F. E is applied to the terminals t_1, t_2 of coil J. An alternating magnetic flux or field is set up on the inside of the coil J. Most of this magnetic flux passes (approximately in the direction of the length of the coil) through the mass M but some of the flux passes through the insulation h between coil J and cylindrical mass M. Only that portion of the total magnetic flux which passes through the mass M can induce electric currents in the mass.

If the magnetic field were perfectly uniform over the cross section of the coil taken at right angles to its axis, then the proportion of the total flux to pass through the mass M would be $\frac{s}{S}$ of the whole flux, where small s is the area of the cross section of the mass and S is the area of the cross section of the inside of the coil. The magnetic field, however, fans out near the ends of the coil and the proportion of flux which threads the mass is somewhat less than $\frac{s}{S}$. For a coil whose

length about equals its diameter and for proportions similar to those shown in Figure 1 we can write $C = \frac{s}{S} 0.8$ as approximately representing the fraction of the total flux which threads the mass M. The constant C is called the coupling factor between coil and mass.

In Figure 1, $C = \frac{d^2}{D^2} \times .8 =$, with the proportions shown, $\frac{44^2}{50^2} \times .8 = .62$ approximately and the coupling in this case is said to be 62 per cent.

When the alternating current in the coil J

risks from zero to a maximum, the flux through the mass M, which also rises from zero to a maximum, develops large electric currents in the mass. These currents, which in general flow circumferentially round the mass in its interior, develop heat. The current density of these currents is, however, greatest at the surface of the mass and the density less and less as the axis of the mass is approached. If the mass has a good conductivity and if its diameter is sufficient the currents which are set up in the mass by the alternating magnetic flux completely die out, or the current density becomes zero before the axis of the mass is reached. In this case all the electromagnetic energy which is associated with the flux which enters the mass, becomes changed over into heat energy in the substance of the mass. In this way a quantity of heat is given to the mass each time the current in J, which gives rise to the flux, makes an alternation.

Hence it is evident that a current of certain magnitude in J which makes 1200 alternations a second will put in one second ten times as much heat into the mass as would a current of equal value which makes but 120 alternations in a second. In other words, for a fixed number of ampere turns of the coil J, the rate of heating of the mass is proportional to the frequency of the current employed. Herein lies the advantages of high frequency current for rapid heating of a conducting mass—which advantages I have described in my Patents Nos. 1,286,394-5, dated December 3, 1918; 1,328,336, January 20, 1920 and others.

The tendency for the circumferentially flowing currents set up in the mass M to concentrate toward the circumference of the mass is more pronounced as the frequency of the current is increased and as the electrical conductivity of the material is higher. It is evident, therefore, that if the mass has a small diameter, and if its resistivity is high, currents of very high frequency must be used, if all the electromagnetic energy is to become converted into heat energy before the inflowing energy reaches the axis of the mass of small diameter. In fact, rapid and effective heating in this manner of, say, a rod of graphite of 1" diameter can only be accomplished by using a current of at least 5000 to 20,000 cycles.

If on the other hand the mass M has the low resistivity of an alloy like brass, and if its diameter is several inches, the electromagnetic energy will all become converted into heat before the axis is reached even though the frequency of the current is much reduced; say to 500 or even less cycles per second. But in this case, we must greatly increase the ampere turns of the inductor to secure with reduced frequency the same heating effect as we may obtain with a higher frequency and

fewer ampere turns. If, however, we employ a large current through the coil to secure the needed large number of ampere turns the conductor must have an increased cross section to carry this large current with the same power waste in the coil, as a smaller current at higher frequency produces. For this reason the width of the conductor is made great and the conductor is then edgewise wound to secure the necessary number of turns and total weight of copper in the coil.

It becomes increasingly costly to produce alternators for generating high frequency current as the required frequency is greater. Hence, it becomes of economic importance to use no higher high-frequency current than need be. We have analyzed these matters, made verifying experiments and equipments and reached conclusions upon selection of frequency and proportioning of furnace parts, which are quite new to the scientific and engineering world and to which we make claim for patent protection.

We now describe and define these relations, and give the essential electrical features of a furnace of any size and we describe by way of illustration a particular furnace designed to melt 600 lbs. an hour of red brass when operated with about 80 kilowatts.

Principles on which furnace proportions are based.

The "depth of penetration" of current induced in a conducting mass by an alternating magnetic field of frequency N has been defined and determined by Steinmetz. (See Chapters VI and VII "Transient Electric Phenomena".)

In Figures 2 is shown a cross section of a mass of great length l and large thickness t . $a-a$ is the free surface of this mass assumed to have great extent in the direction vertical to the plane of the paper. To the right of the surface $a-a$ is an alternating magnetic field having the direction shown by the line p . The lines of force of this alternating field reach into the mass M as indicated by the dotted lines q , the field growing less and less intense as we move into the mass toward the left. Since the field is alternating, electric currents are induced in the mass. The direction of flow of these currents in the mass is at right angles to the plane of the paper. The amperes per square cm. or the current density are greatest at the surface $a-a$ of the mass and as we move into the mass this current density grows less and less by a definite law. The line c given in Figure 3 shows the decrease in the current density as we move into the mass toward the left from surface $a-a$ of Figure 2.

If we draw a vertical line 2-4, Figure 3, such that the area inclosed by the rectangle 0-1-2-4-0 is equal to the area. The lines c and c' given in Figure 3 show the decrease

in the mean squares and instantaneous values, respectively of current density as we move into the mass toward the left from surface $a-a$ of Figure 2.

If we draw a vertical line 2-4, Figure 3, such that the area inclosed by the rectangle 0-1-2-4-0 is equal to the area (shown shaded) under the curve c' , then the width 1-2 of this rectangle is defined as the "depth of penetration" of the current into the mass M . Otherwise stated, 1-2 is the effective penetration of the alternating current into the mass which, having the constant density which exists at the surface, would give the same total current as exists in the mass.

Steinmetz has shown (p. 383 "Theory and Calculation of Transient Electric Phenomena and Oscillations") that we may quantitatively express the depth of penetration for non-magnetic material by the expression—

$$1_p = 5030 \sqrt{\frac{\rho}{N}} \quad (1)$$

where ρ is the resistivity of the material and N is the frequency of the alternating inducing field.

This formula applies to a mass having a plane surface. If the surface $a-a$ is concave the depth of penetration is less and if the surface is convex the depth of penetration is somewhat greater. When an inductor which creates the alternating magnetic field surrounds a cylindrical mass of moderate diameter, then the surface of the mass is convex and for our purpose we may take

$$1_p = 6000 \sqrt{\frac{\rho}{N}} \quad (2)$$

By referring to curve c' Figure 3 we note that if we move into the mass a depth four times the depth of penetration we find the actual value of the current density has become $\frac{1}{20}$ and its heating effect

$$\left(\frac{1}{20}\right)^2 = \frac{1}{400}$$

of what it is at the surface of the mass. Hence, we may assert that when we have moved four times the depth of penetration into the mass we find the heating effect of the current in the mass has become negligible and the electromagnetic energy of the alternating magnetic field has become practically all converted into heat energy. Hence, it follows that when we are inducing currents in a cylindrical mass by means of an alternating field produced by a solenoidal coil surrounding the cylinder, the diameter D of this cylinder should be about eight times the depth of penetration for substantially com-

plete conversion of the electromagnetic energy into heat energy. Or we should make

$$D \geq 81_p = 4800 \sqrt{\frac{\rho}{N}}$$

or in round figures write

$$D \geq 5 \times 10^4 \sqrt{\frac{\rho}{N}} \quad (3)$$

Thus if we are heating a cylinder of molten brass, the resistivity of which is

$$\rho = 40 \times 10^{-6}$$

and if we use a frequency of 360 cycles, we should make the diameter of this cylinder at least

$$D = 5 \times 10^4 \sqrt{40 \times 10^{-6} \times \frac{1}{360}} = 16.7 \text{ cms.}$$

or say, 6 3/4". The mass may have a greater diameter than this, but for complete conversion of electromagnetic energy into heat energy should not have a much less diameter.

As another example, assume we wish to heat to the best advantage a rod of Acheson graphite 0.5 cm. in diameter, what frequency should we use? The resistivity of graphite is about 7×10^{-4} ohm. By Formula (3)

$$0.5 = 5 \times 10^4 \sqrt{\frac{7 \times 10^{-4}}{N}}$$

Thus

$$N = 7 \times 10^6$$

or seven million cycles per second.

It thus appears that we may use to advantage such wide range of frequency as seven million cycles to three hundred and sixty cycles or less according to the diameter and resistivity of the material to be heated.

The inductor coil will in general be made by winding the conductor in a coil having a single layer. The advantage obtained by using a single layer instead of a multiple layer winding has been pointed out by me in my various theoretical treatments of inductive heating. To secure with a single layer winding a coil of many turns and low resistance, edgewise winding of flat conductor is used. This flat conductor is hollow so water may be passed through it to keep it cool and its resistance low. One half the axial section of the inductor when so wound will occupy a certain area, the length of which is H (Figure 1) and the width of which is t (Figure 1). A certain proportion of the area tH is not filled with copper, but is necessarily occupied by space for the water flow and by insulation between inductor turns. The easiest way to take account of this when making a calculation of the ohmic resistance of the coil is to assume that the resistivity of the copper is increased and that the copper then fills the entire area tH . Thus if one half the area tH is occupied by non-

conducting material we would assume that the resistivity of the copper is doubled. Thus taking the resistivity of copper at the working temperature, as

$$\rho = 2 \times 10^{-6}$$

and assuming that copper occupies but one half the area tH , we would call

$$\rho = 4 \times 10^{-6}$$

and then treat the cross section tH as if entirely occupied by conductor material.

The selection of the width of the inductor is to a certain extent arbitrary for a furnace of a given size, but to give a satisfactory electrical efficiency we have chosen this width such that the coil resistance is low enough to give not over 10% to 20% loss in the coil of the total power supplied to the furnace. To accomplish this result with a particular furnace we have found that the width t of the edgewise wound conductor should be approximately one-twentieth of the inside diameter of the coil. Having made this selection for a particular furnace we have found that the same ratio, $\frac{\text{width of conductor}}{\text{diameter of coil}}$, should be approximately maintained for a furnace of any size.

The ratio, diameter of mass M to inside diameter of coil (Figure 1) should be made large as possible, for this ratio determines the coupling and this in turn the operating power factor of the furnace. On the other hand, sufficient space, $C-B$ (Figure 1), must be allowed for heat insulation, and if a nonconducting crucible is used an additional space is required for the thickness of the crucible wall. Experience shows that this insulation space must be greater for very high temperature melts than for melts made at medium temperature. It does not in general, however, need to be greater for a furnace of large diameter than for one of small diameter. Consequently in a very large furnace the ratio $\frac{\text{inside diameter of coil}}{\text{diameter of melt}}$ may be made larger than for a small one, and thus we obtain for a large furnace a better coupling and a consequent better power factor. For purposes of calculation, however, we will arbitrarily choose the ratio $\frac{B}{C} = 0.8$ and main-

tain this ratio for furnaces of widely different sizes. With this ratio the coupling will be about 51%. The height of the inductor may with advantage be chosen about equal to its inside diameter. This leads to simplicity in making calculations and is usually a good proportion for operating conditions.

With the above general discussion in mind we summarize as follows the proportions we have found good by theory and verified by practice and on which we seek patent protec-

tion as being the first to discover the character and value of such proportions.

Coupling factor.

5 We have pointed out that this factor, C is approximately the ratio, cross section of diameter of melt divided by cross section of coil, times the arbitrary constant 0.8. Or we call

$$10 \quad C = \frac{d^2}{D^2} 0.8$$

and we have found it practical to make

$$15 \quad C = 0.5 \text{ to } 0.7.$$

Resistance of inductor.

Assume that the inductor has one turn and fills the space of length H and width t (Figure 1) less the amount of space used for water flow and insulation. If the inductor were copper and filled the whole space the resistance of this one turn (see Figure 1) would be

$$25 \quad r_1 = \frac{\pi A}{H t} \rho \quad (4)$$

where A is mean diameter of the one turn coil and

$$\rho = 2 \times 10^{-8} \text{ ohm.}$$

30 is the specific resistance of copper at the working temperature. Since, however, a certain proportion of the area, $H t$, is not occupied by copper, but by water and insulation (between turns when there are several turns) we take the specific resistance to be greater (see page 13). Let

$$\rho' = p\rho = 2\rho$$

as representing an average case such as occurs in practice. Then the resistance of one turn is

$$40 \quad r' = \frac{\pi A}{H t} \rho' \quad (5)$$

45 As pointed out (page 4) we have found it advantageous to maintain the ratio width of flattened conductor diameter of coil about the same, whatever the size of the furnace. We have found one-twentieth a suitable value for this ratio. If then we write $\frac{A}{t} = k$, a constant, where $k=20$ for good practice, we have

$$55 \quad r_1 = \frac{\pi \rho' k}{H} \quad (6)$$

If the same space, $H t$, is filled with n turns, the resistance will be n^2 times as great as if the space were filled with one turn; hence the resistance of a coil of n turns may be written,

$$60 \quad r = \frac{n^2 \pi \rho' k}{H} \quad (7)$$

65 Or we conclude that it is necessary and good

practice in order to preserve the same proportionate power loss in the coil of a furnace of any size to so wind our single layer coil that its resistance is

$$70 \quad r \propto \frac{n^2}{H} \quad (8)$$

That is, we should choose the width of the edgewise wound conductor such that the resistance of the coil will decrease with the linear dimension of the coil. 75

Self induction of empty inductor.

When the inductor is empty, namely, the mass M not in it (Figure 1) its self-induction is

$$80 \quad L \propto n^2 D \quad (9)$$

where n is the number of turns in the coil and D is the inside diameter. In the Bulletin of the Bureau of Standards, vol. 8, No. 7, January 1, 1922, pp. 117, 118, 194, is given a simple formula and table for rapidly calculating the self-induction of any single layer solenoid. 85 90

Relation of frequency, diameter and resistivity of any mass to be heated.

We have shown (page 11) that the diameter of the mass to be heated should not be less than

$$D = 5 \times 10^4 \sqrt{\frac{\rho}{N}} \quad 100$$

where ρ is the resistivity of the mass and N the frequency employed. Thus we should maintain

$$105 \quad D \propto \rho^{1/2} N^{-1/2} \quad (10)$$

By this we see that the diameter of the melt should be varied directly as the square root of the resistivity of the melt and inversely as the square root of the frequency used.

Reactance of the inductor. 110

The reactance of the inductor with no mass in it is

$$x = 2\pi N L \quad (11)$$

By Relation (10) we should maintain 115

$$N \propto \frac{\rho}{D^2}$$

Hence

$$x \propto \frac{\rho L}{D^2} \quad (12)^a \quad 120$$

and by Relation (9)

$$L \propto n^2 D \quad 125$$

Hence

$$x \propto \frac{n^2 \rho}{D} \quad (12)$$

In other words, we should vary the reactance of our empty coil directly as the resistivity 130

of our melt and inversely as the diameter or linear dimensions of the melt.

Power absorbed by mass.

5 If the conversion of electromagnetic into heat energy is complete before the axis of the mass is reached, then the absorbed power

$$P = 2NW_1 = CLNI^2$$

10 where N is the frequency and W_1 , equal to $\frac{1}{2}CLI^2$

is the energy developed every time the current rises to its maximum value I .

15 If the current be of sine form and i the effective value of the current,

$$I^2 = 2i^2$$

and

$$P = 2CLNi^2$$

20 or, since the reactance

$$x = 2\pi NL$$

we have the absorption of power by a mass in a coil (Figure 1) may be found to a fair degree of approximation from the expression

$$\left(P = \frac{Cx^2}{\pi} i^2\right) \text{-----} (13)$$

30 where C is the coupling, x the reactance of the coil (empty), and i the current carried by the coil.

Relation (13) is only true provided Relation (3) is maintained. Since

$$35 \quad x \propto \frac{n^2 \rho}{D}$$

(Equation 12) the absorbed power is

$$40 \quad P \propto \frac{C\rho}{D} (in)^2 \text{-----} (14)$$

The number of ampere turns (in) to use depends upon the power to be absorbed and converted into heat and the number of turns to use depends upon the voltage available.

45 It is also easy to show that we should wind the coil with a number of turns chosen proportional to the available voltage E .

50 *Power factor.*

Since power is the product of volt-amperes multiplied by a certain factor F , called the power factor, or in symbols

$$55 \quad P = EiF \text{-----} (15)$$

we can always predict the rate of heating performance of any furnace provided we measure or calculate the power factor.

60 It is valuable therefore to find if possible an expression which will enable us to calculate, if only approximately, the power factor. It is only possible to derive such an expression when the material to be heated is non-magnetic. It is possible to obtain (as I have 65 done) a very exact expression for the single

case in which the secondary consists of a cylindrical shell of non-magnetic material having a very thin wall. However, if the secondary is a cylindrical mass of solid or liquid material which is non-magnetic and if 70 the diameter of the mass is related to the frequency and its resistivity according to Equation 3, then the following expression is quite approximately true. It is

$$75 \quad F = \frac{0.45 C}{\sqrt{C^4 + 2 - 2C^2}} \text{-----} (16)$$

Here

$$80 \quad C = \frac{d^2}{D^2} 0.8$$

is the coupling factor. By the above we note that the power factor depends only on the coupling.

If the coupling is unity, $C=1$ and $F=0.45$ 85 which shows that the power factor cannot exceed 45%. For $C=0$, $F=0$. For $C=0.6$, $F=0.226$, or 22.6%. This formula (16) obtained by theory has been confirmed by actual tests. In one test 540 cycles were used, and 90 in another 315. In these tests made May 24, 1924 experiment gave power factors 0.282, 0.305, and 0.315. The power factor calculated by Equation 16 was 0.314. In this case the coupling $C=0.76$ and the power used was 95 about 25 kw.

Electrical efficiency.

The electrical efficiency of the furnace is evidently the ratio of the power absorbed by 100 the mass divided by the total power supplied to the furnace terminals.

Let P be the power delivered to the melt. Let i^2r be the power wasted in the inductor where i is the current carried by the inductor and r is the alternating current resistance of the inductor. The expression for the electrical efficiency of the furnace then becomes

$$110 \quad E_t = \frac{P}{P + i^2r} \text{-----} (17)$$

If the furnace is rightly proportioned in the manner described above this electrical efficiency will be approximately the same for 115 furnaces of different sizes. We may show this to be true as follows: By Equation (14),

$$P \propto \frac{i^2 n^2}{D} \text{ or } P = \frac{ai^2 n^2}{D}$$

where a is a constant. By Equation (8) 120

$$r \propto \frac{n^2}{H}$$

or since we assume the height of the coil H to be maintained proportional to its diameter 125 D we can say that

$$r = \frac{bn^2}{D}$$

where small b is another constant. Putting 130

these values for P and r in Equation (17) we have

$$E_1 = \frac{\frac{a^2 n^2}{D}}{\frac{a^2 n^2}{D} + \frac{b n^2}{D}} = \frac{a}{a+b} \quad (18)$$

Since a and b are both constant quantities we conclude that furnaces of different heights and corresponding diameters will have the same electrical efficiency—which efficiency we can readily arrange to exceed 80%.

Power factor correction.

My invention contemplates the correction of the low power factor of the furnace by means of static condensers used in series with the coil or connected in shunt with the coil, or by using a synchronous converter with over-excited field. This would usually be connected in shunt to the furnace inductor. I consider, however, that for power factor correction of high frequency furnaces that static condensers constitute the cheaper and more practical device. The generator which supplies high frequency current to the furnace will then deliver its current to a loaded furnace (that is, one absorbing its full rated power) substantially in phase with the generator voltage. In other words, the generator is only called upon to supply the in-phase component of the kv-a. taken by the furnace, or the "work current". The out-of-phase component of the kv-a. or "reactive component" is then supplied by the condensers or by the synchronous converter if this is used.

If I did not employ a phase correcting device, the low power factor at which my furnace operates would necessitate the use of a generator having a prohibitively large kv-a. rating, but because I use a phase correcting device the kv-a. rating of my generator need be little if any greater than the kw. rating of my furnace.

Since the cost per kv-a. of condensers is much less than the cost per kv-a. of the generator, there is a substantial saving in cost when the reactive component of the kv-a. is carried by condensers instead of being carried by a greatly over-size generator. I shall make this important economic feature of my invention still more clear by expressing the matter in the following way:—

If a generator feeds a receiver circuit having both resistance R and reactance X , it must have a sufficient kv-a. capacity to supply both the reactive component and the power component of the load.

If, on the other hand, the reactive component of the load is wholly carried by a shunted negative reactance X_c , the generator needs to have only sufficient kv-a. capacity to carry the power component of the load. In

this case the kv-a. rating and the kw. rating of the generator are the same.

Assuming the cost of the generator in this second case proportional to its kv-a. rating it will also be proportional to its power output. Thus, we can write

$$S_g = AW$$

where A is a constant and W is the power output expressed in kilowatts.

Where, for example, we have a circuit and load as indicated by diagram, Figure 4, it is easy to show that the kv-a. rating of the condenser C necessary to raise the power factor f taken at the terminals $a-b$ of the load to 100% it given by the expression

$$KVA = \frac{W\sqrt{1-f^2}}{f} \quad (18)^a$$

where W is the power expressed in kilowatts delivered to the load, and f the power factor of the load.

The cost of condensers is (in general) proportional to their kv-a. rating. Hence, we may write for condenser cost

$$S_c = \frac{KW\sqrt{1-f^2}}{f} \quad (18)^b$$

The total cost of the equipment for supplying power W to the load is the sum of the generator cost and the condenser cost. In a formula we have

$$S = W\left(A + \frac{K\sqrt{1-f^2}}{f}\right) \quad (18)^c$$

To illustrate—From quotations given by a large electric company on a motor generator set in which the generator is rated at 250 kv-a. and which delivers 360 cycles the total cost (for motor and generator) is at the rate of \$27.87 per kv-a. From prices paid for condensers in actual service we can take the cost of these at \$3.66 per kv-a.

Let uncorrected power-factor f of furnace be 0.4 then $A=27.87$, $K=3.66$, and we obtain

$$S = W\left(27.87 + \frac{3.66\sqrt{1-.16}}{.4}\right) = 36.25 W.$$

Thus, if 250 kw. are delivered, electrical equipment cost would be \$9062.00. We see that if the generator is operated at its full load rating of 250 kv-a. it will deliver 250 kw. because it operates at unity power factor and the total equipment cost for 250 kw. delivered to a furnace will be \$9062.00.

In high frequency generation of electrical power the cost per kv-a. for the generator will always be much greater than the cost per kv-a. for the static condensers to give complete power factor correction. It is therefore a great saving of cost to correct the low power factor of a high frequency induction furnace with static condensers. In fact, to attempt to supply power to such furnace at

high frequency without correcting the power factor is wholly impracticable from economic considerations.

I am the first to point out this important consideration connected with ironless inductive heating, and I consider that the combined use of condensers and high frequency generation of power for ironless inductive heating constitutes an original and an important feature of my system of inductive heating.

Since, however, my present application relates more particularly to the proportioning of furnace elements to secure high efficiency and substantially the same efficiency and the same power factor regardless of the nature of the conductive material heated and the frequency available I will not dwell at more length upon methods I have employed for phase correction and for securing unity power factor. I here make reference to my Patent No. 1,286,395 and the description on page 8 of one of my methods of phase correction.

Having now explained the general principles of the furnace design and having pointed out the necessary proportionment of furnace parts and selection of frequency that I have discovered as being necessary and good for efficient furnace operation I shall illustrate these matters by giving in outline the design of an actual furnace which I have had constructed for the melting of metals, chiefly nonferrous, in 600 pound charges.

Example showing application of principles.

In order to make clear that the principles above can be practically applied, but without restriction or limitation thereby, I give below an application of use to a specific case, namely the design of a 600 pound 80 kw. metal melting ironless induction furnace.

Figure 5 is a vertical cross section of an actually constructed and operated furnace designed more particularly for melting and pouring brass, bronze, etc. in about 600 pound lots. The furnace will, however, melt ferrous metals. a is the coil, b the crucible, c asbestos-magnesia heat insulation, d is a cylinder of micanite about 1/16 inch thick which lines the inside of the coil. The purpose of this is to electrically insulate the coil from the hot crucible.

Figure 5 does not show the furnace housing nor the mechanism for lifting and pouring the furnace. Water inlets and outlets are shown diagrammatically. There are five inlets i_1, i_2, i_3, i_4, i_5 , and four outlets o_1, o_2, o_3, o_4 . The electrical terminals of the coil are indicated at e_1 and e_2 .

It was determined by a rough preliminary calculation that the coil should be wound with 50 turns and that to make a coil of sufficiently low resistance the conductor should consist of flattened copper tubing 13/16" O.

D., and of wall thickness 0.046" (0.117 cms.). The tubing is flattened to 0.2" and edgewise wound, about four turns per inch of winding.

In order to predict the performance of this furnace its constants are first calculated as follows:

The inductance of the coil (when empty) is given by the formula

$$L = \pi n^2 Q \cdot 10^{-9} \text{ henry} \quad (19)$$

Where a is the inside radius of the coil, n the number of its turns, and Q is a constant, the value of which constant Q is given on page 194, Table IV, Bulletin of the Bureau of Standards, Vol. VIII, No. 1, January 1, 1912. Substitute in Equation 19 the dimensions of the coil, as given in Figure 5, and calling $n=50$, the number of turns, and taking from the table $Q=19.5$ we find the inductance of the coil is

$$L = 1.44 \times 10^{-3} \text{ henry} \quad (20)$$

The reactance of the coil (when empty) is given by the formula

$$x = 2\pi N L \quad (21)$$

where N is the frequency used.

Since it was planned to operate this furnace with 540 cycles we place $N=540$ and we find

$$x = 4.88 \text{ ohms} \quad (22)$$

The current for operating furnace was in this case obtained from a 100 kv-a., 220 volt, 540 cycle generator driven by a steam turbine.

The resistance of the coil.

The resistance of one turn of solid copper which fills the space 2.8 cm. wide by 33 cm. long is

$$r_1 = \frac{\pi 62\rho}{2.8 \times 33}$$

The double wall thickness of the flattened copper tube is 0.234 cm. There are 50 turns, hence space used by copper is

$$0.234 \times 50 = 11.7 \text{ cms.}$$

The length of the space in which the copper is wound is 33 cms. Hence we call

$$\rho' = \frac{33\rho}{11.7}$$

or we take $\rho' = 2.82\rho$. Now the resistivity of copper at the working temperature of the coil is about

$$\rho = 2 \times 10^{-6}$$

Since, however, the current through the coil is of high frequency there will be some "skin effect" which will apparently increase its resistance. To determine accurately the

amount of this increase a measurement of the alternating current resistance must be made at the frequency used. In one case we found the D. C. resistance increased three times using a frequency of 540 cycles. On the present design we estimate the specific resistance for 540 cycles at

$$\rho = 2.7 \times 10^{-6} \text{ ohm.}$$

We now have

$$r_1 = \frac{3.14 \times 62}{2.8 \times 33} 2.82 \times 2.7 \times 10^{-6} = 16.04 \times 10^{-6} \text{ ohm.}$$

But there are fifty turns and the resistance is proportional to the square of the number of turns, (Equation 7) hence the resistance of the coil of fifty turns is

$$r_{50} = 16.04 \times 50^2 \times 10^{-6} = 0.0401.$$

Call

$$r_{50} = 0.40 \text{ ohm} \text{ ----- (23)}$$

$$F = \frac{0.45 \times .5}{\sqrt{.5^4 + 2 - 2 \times 0.5^2}} = \frac{0.225}{\sqrt{2.0625 - 0.5}} = 0.18 \text{ or } 18\% \text{ ----- (25)}$$

The power.

The total power which this furnace will absorb will be

$$P = E_r i F \text{ ----- (26)}$$

Or as we have found $F = 0.18$

$$P = E_r i 0.18 \text{ watts ----- (27)}$$

where E_r is the volts at furnace terminals and i the current through the furnace coil.

The particular alternator used to furnish current for this furnace is rated at 100 kv-a. and supplied a maximum of 460 amperes at 220 volts.

In this case we prefer to correct the power factor by connecting condensers in series with the generator and furnace as shown in Figure 6. With the series connection the same current passes through furnace coil and through the condensers.

The reason for connecting the condensers in series instead of in shunt with the furnace inductor is found in the fact that the voltage of the generator is low, only 220 to 250 volts. By selecting the correct negative reactance x_c to connect in series with the furnace, we are able to bring the current not only into exact phase with the generator voltage E but we are further able to raise the voltage E_r at the terminals of the furnace so that sufficient current will flow through the furnace coil to cause the furnace to absorb its full rated power. The voltage drop E_r over the furnace is ahead of the current in phase, in this case leading the current by $79^\circ, 38'$. The voltage drop over the negative reactance x_c is 90° in phase behind the current. These two voltages can be combined vectorially to give the resultant voltage which the alternator supplies. The furnace coil has when empty the positive reactance x which we found to equal

The coupling factor C.

We estimate

$$C = \frac{\frac{46}{59}^2}{2} \times 0.8 = 0.5 \text{ (nearly) ----- (24)}$$

The power factor of this crucible furnace when the crucible (assumed to be of non-conducting material) is filled with metal near to the level of the top of the coil may be found by Formula (16). Thus

4.88 ohms (Equation 22) but when the crucible is full of metal the reactance of the furnace as a whole is different and is less than x . If we call X the reactance of the loaded furnace, then to secure unity power factor at the generator we must make the negative reactance

$$x_c = X \text{ ----- (28)}$$

It can be shown that the equivalent furnace reactance X may be determined with a fair degree of approximation to be

$$X = \frac{x(2 - C^2)}{2} \text{ ----- (29)}$$

Since we have taken $C = 0.5$ and $x = 4.88$ we find $X = 4.27$ ohms. By placing $x_c = X = 4.27$ we secure unity power factor at generator terminals when the furnace is loaded and the generator will feed into the circuit as if this consisted of pure ohmic resistance. The current which will then flow will be

$$i = \frac{E}{R} \text{ ----- (30)}$$

where E is the generator voltage and R is the equivalent resistance of the furnace.

It can also be shown that

$$R = \frac{2r \times C^2 x}{2} \text{ ----- (31)}$$

where small r is the ohmic resistance of the coil which in this case we have taken as 0.04 ohm (Equation 23). Thus

$$R = 0.65 \text{ ohm ----- (32)}$$

The power supplied by the generator will be supplied now at unity power factor and it will be

$$P = \frac{E^2}{R} = \frac{E^2}{0.65} \text{ ----- (33)}$$

If we wish to deliver 80 kw. to the furnace we must write

$$E^2 = 0.65 \times 80000 \text{ ----- (34)}$$

5 which gives

$$E = 228 \text{ volts ----- (35)}$$

Since

$$10 \quad x_c = \frac{10^6}{2\pi N C_{n-1}} = 4.27 \text{ ----- (36)}$$

we find

$$C_{n-1} = \frac{10^6}{6.28 \times 540 \times 4.27} = 69 \text{ microfarad. (37)}$$

as the capacity which must be used. The current which will flow is 15

$$i = \frac{E}{R} = \frac{228}{0.65} = 350.7 \text{ amps. --- (38)} \quad 20$$

The voltage E_c (Figure 6) at the terminals of the condensers is

$$E_c = ix_c = 350.7 \times 4.27 = 1497 \text{ volts --- (39)} \quad 25$$

The voltage E_t at the terminals of the furnace is

$$E_t = i\sqrt{R^2 + X^2} = 350\sqrt{0.65^2 + 4.27^2} = 1511 \text{ volts ----- (40)}$$

It is the vectorial addition of 1497 and 1511 which gives $E = 228$. 30

In the furnace design we have given above it should be noted that we have made use of the principles and the proportioning of parts for which we seek patent protection; 35

1. We have shown that the diameter of our mass heated should be

$$40 \quad D \cong 5 \times 10^4 \sqrt{\frac{\rho}{N}} \text{ ----- (41)}$$

Since for molten brass $\rho = 40 \times 10^{-6}$ and since our frequency is $N = 540$ we should make the diameter of our mass at least 13 cms. and we have made it 46 cms. 45

2. We have used an edgewise wound single layer coil, as explained.

3. We have made the width of our inductor divided by the inside diameter of our coil

$$50 \quad \frac{2.8}{59} = .047 +$$

which is near to the ratio 1/20 which is explained as being desirable to have.

4. We have used a flattened copper tubing of wall thickness 0.046 and have left an opening in this between side walls of about 0.046. This approximates the proportion stated as being desirable. 55

5. We have provided for the circulation of water in the coil and used multiple inlets and outlets. 60

6. The electrical efficiency of our furnace calculates out as follows, Formula (17), 65

$$E_t = \frac{8 \times 10^4}{8 \times 10^4 + 350^2 \times 0.04} = 0.94 + \text{--- (42)}$$

and hence is above 90%. After the above calculations were made the A. C. resistance of this coil under the conditions used was found to be about three times its D. C. resistance and the efficiency proved to be slightly less than 90%. By maintaining the furnace 70

proportions and the relation given Equation 3, which we have shown to be necessary we will have the same electrical efficiency if the furnace be doubled or halved in size or changed in some other proportion (Equation 14) provided there is a corresponding change in the frequency-resistivity ratio 75 80

so as to maintain the same value for $\frac{BN^{1/2}}{\rho^{1/2}}$

7. We have used condensers in series with the generator and inductor and which we have chosen of such value as to give complete power factor correction to our furnace when loaded. We may add here that when the furnace is not loaded there will be a sufficient excess of positive reactance to prevent the rise of current in the circuit to exceed that of the rated capacity of the generator. If our generator has been built to give a higher voltage, say 1200 volts, we could then with advantage have used our condensers joined in parallel to the furnace coil. 85 90 95

Thus by our descriptions and by the example of the design of a particular furnace we have made clear the important features and elements of our invention. 100

It is evident that the breadth of this invention is such that there can be a considerable variation in the proportions given and in the method of applying the principles set forth and the greatest possible variation in the details of design without departing from the spirit and intent of this invention. 105

Having thus described my invention what I claim as new and desire to secure by Letters Patent is:— 110

1. In inductive heating free from transformer iron, the novelty which consists in providing a single layer of inductor of greater conductor depth than thickness having a depth radially bearing a definite proportion to the diameter of the charge to make the loss of power in the inductor substantially independent of the size of the inductor. 115

2. In inductive heating free from trans- 120

former iron to secure highest efficiency and power factor and keep down the frequency the novelty which consists in proportioning the diameter of the charge to the diameter of the coil and the resistivity of the charge.

3. In inductive heating free from transformer iron to secure highest efficiency and power factor and keep down the frequency the novelty which consists in proportioning the ampere turns in the coil to diameter of the charge, the diameter of the coil and the resistivity of the charge substantially the same in furnaces of different size.

4. In inductive heating free from transformer iron, the novelty which consists in varying the diameter of the melt directly as the square root of the resistivity of the melt.

5. The method of maintaining efficiencies substantially constant for furnaces of different sizes, which consists in maintaining the same relations between the heights and diameters of the materials treated and the heights and radial depths of the coil windings.

6. In inductive heating free from transformer iron utilizing a single layer coil of flattened hollow copper tubing, the novelty which consists in maintaining the same percentage of power loss in the coil with different sizes of furnace and regardless of the frequency.

7. In inductive heating free from transformer iron utilizing a single layer coil of flattened hollow copper tubing, the novelty which consists in maintaining the same percentage of power loss in the coil with different sizes of furnace and regardless of the frequency by maintaining the ratio between the square of the number of turns and the linear dimensions of the inductor coil.

8. In inductive heating free from transformer iron utilizing a single layer coil of flattened hollow copper tubing, the novelty which consists in maintaining the same percentage of power loss in the coil with different sizes of furnace and regardless of the frequency by choosing the radial depth of the flattened tubing as a proportion of the diameter of the mass.

9. In inductive heating free from transformer iron, the process of determining the reactance of the inductors for furnaces for different metals and sizes which consists in varying the reactance of the inductor directly as the resistivity of the material and inversely as the lineal dimensions of the melt.

10. In ironless inductive heating by a coil surrounding a continuous cylindrical conducting mass, the novelty which consists in selecting the total number of turns in the inductor in direct proportion to the applied voltage selected.

11. In ironless inductive heating by an in-

ductor surrounding a cylindrical charge, the novelty which consists in proportioning the furnace dimensions and frequency for resistivity of given charge such that the electrical efficiency of the furnaces of different size shall be substantially independent of the sizes of the furnaces.

12. An ironless induction furnace consisting of a solenoidal coil having a single layer and surrounding an approximate cylinder of conducting material to be heated in which the ratio of diameter of conducting material to inside diameter of coil is maintained between the limits of nine to ten and five to ten, and in which the depth of insulation between the inductor coil and the work or crucible is limited substantially to the depth of heat insulation required, combined with static condensers to correct the power factor at generator terminals to substantially unity.

13. The combination of an alternating current generator, an edgewise wound flattened tube, artificially cooled, wound in a single layer coil about the mass to be heated by ironless induction and having radial width of flattened tube chosen to be in the limits one to eight to one to twenty-five of the inside diameter of the inductor, the insulation within the inductor being restricted in depth to substantially the heat insulation needed, and condensers connected in series with the inductor and generator for the purpose and chosen of sufficient capacity to bring the power factor of the combination near unity at source of current supply.

14. The combination of an alternating current generator, an edgewise wound flattened tube artificially cooled, wound in a single layer coil about the mass to be heated by ironless induction and having a radial width of flattened tube chosen to be in the limits one to eight to one to twenty-five of the inside diameter of the inductor, the insulation within the inductor being restricted in depth to substantially the heat insulation needed, and condensers connected in parallel to the inductor for the purpose and chosen of sufficient capacity to bring the power factor of the combination near unity at source of current supply.

15. The combination of an alternating current generator, an ironless inductive heater operated with current of higher frequency than normal with condensers connected in series with the generator and heater, the negative reactance of which is equal to the equivalent positive reactance of the heater thereby giving a higher voltage at the heater terminals than the supply voltage and bringing the power factor at the source of current supply to near unity.

EDWIN F. NORTHRUP.