June 9, 1942. M. TAMA ET AL 2,286,024

CORELESS INDUCTION FURNACE FOR MELTING METALS

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Fig. 1.

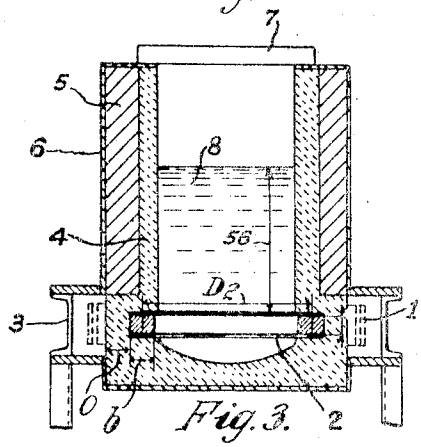


Fig. 2.

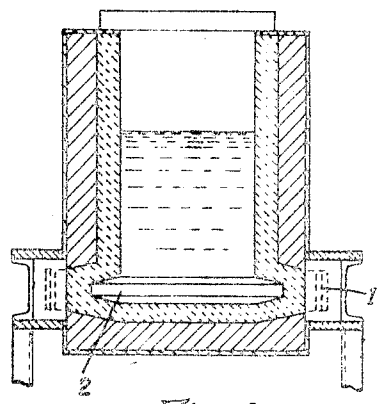


Fig. 3.

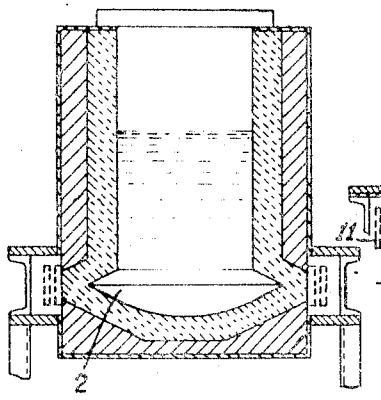


Fig. 4.

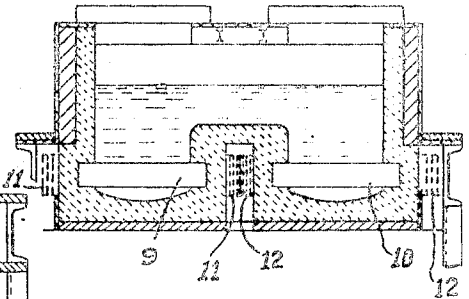


Fig. 6.

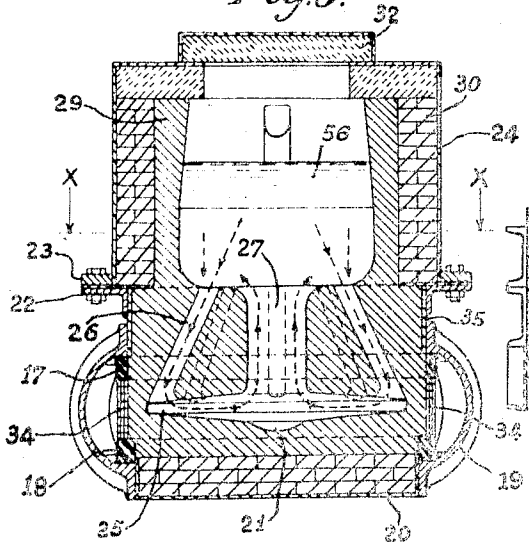
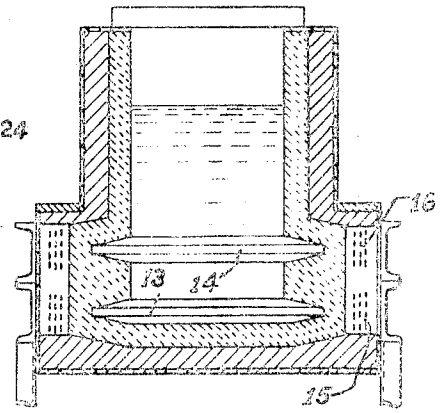


Fig. 5.



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Fig. 7.

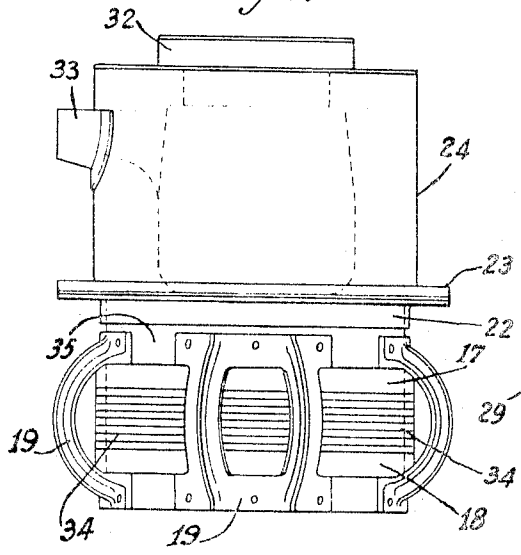
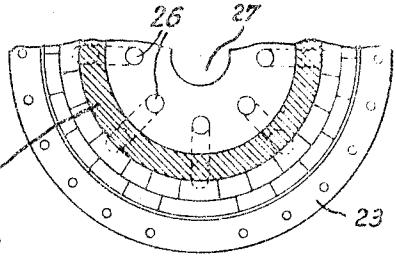


Fig. 8.



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CORELESS INDUCTION FURNACE FOR MELTING METALS

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Fig. 9.

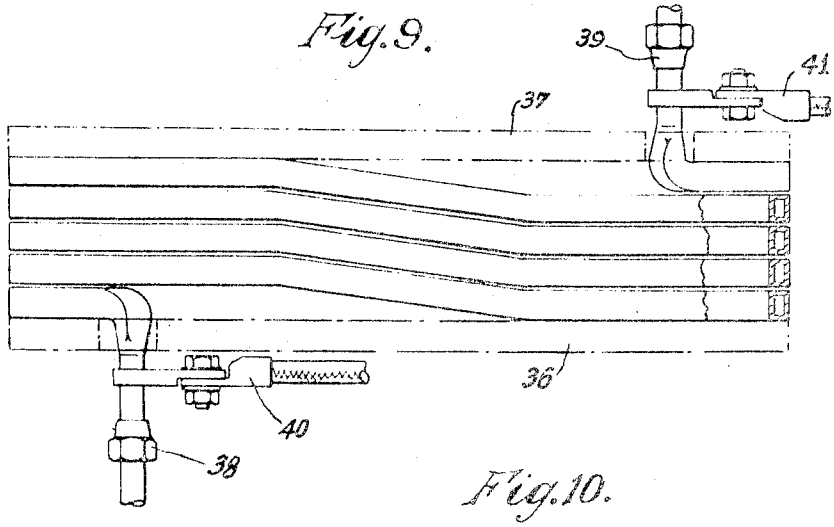


Fig. 10.

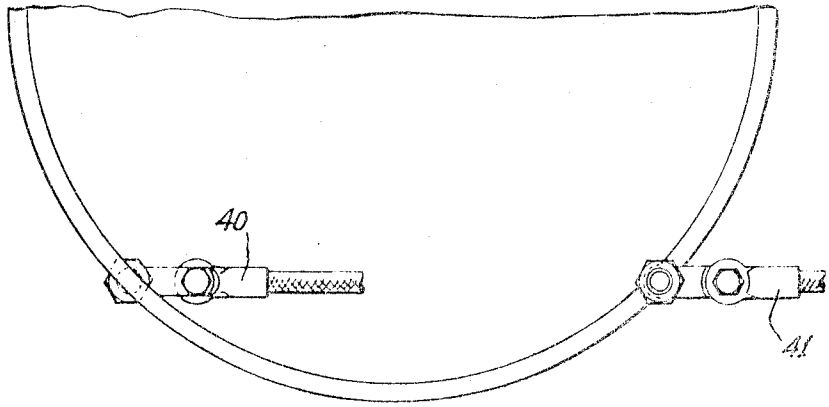


Fig. 11.

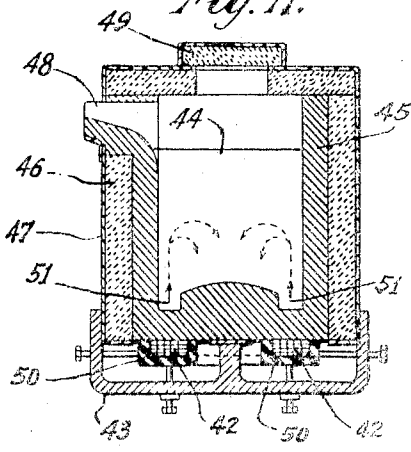
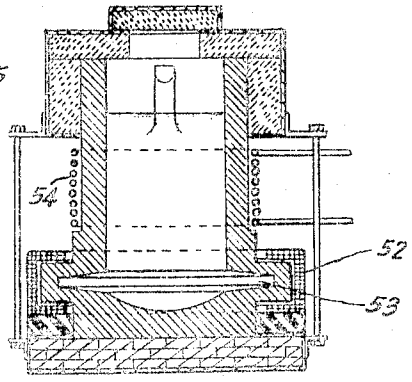


Fig. 12.



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CORELESS INDUCTION FURNACE FOR MELTING METALS

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Fig. 13.

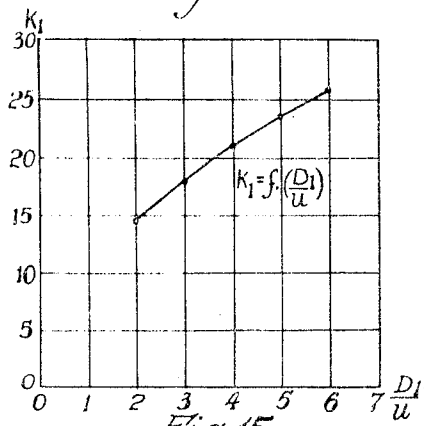


Fig. 14.

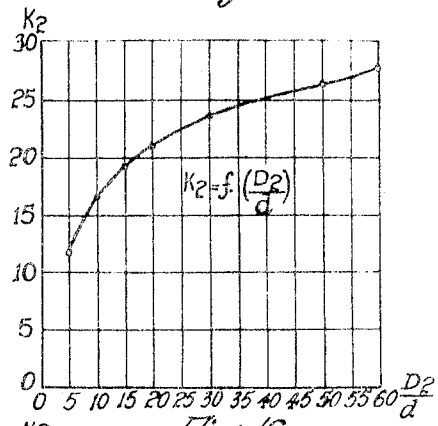


Fig. 15.

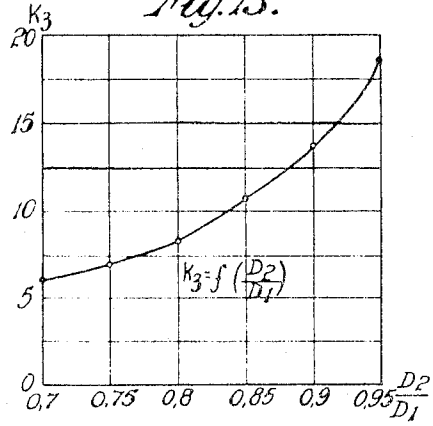


Fig. 16.

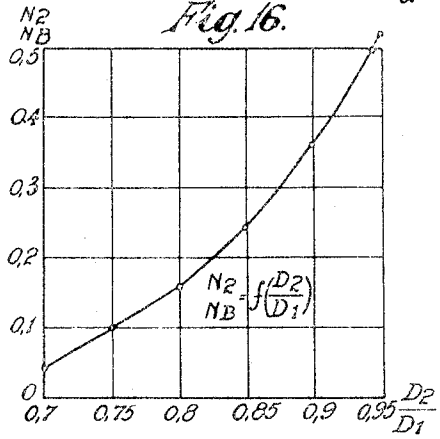
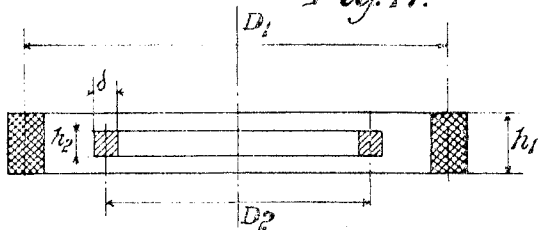


Fig. 17.



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Patented June 9, 1942

2,286,024

UNITED STATES PATENT OFFICE

2,286,024

CORELESS INDUCTION FURNACE FOR MELTING METALS

Manuel Tama and Mario Tama, Morrisville, Pa., assignors to Ajax Electrothermic Corporation, Ajax Park, N. J., a corporation of New Jersey

Application October 25, 1940, Serial No. 362,730
In Germany October 30, 1939

11 Claims. (Cl. 13—26)

This invention relates to a coreless induction furnace for melting metals.

Coreless induction furnaces are very frequently used at the present time for melting metals. In such furnaces the charge, which is usually contained in a cylindrical crucible, is subjected to the alternating magnetic field of a primary coil. The current induced into the charge by the field produces the heat for melting the metal. It is well known that in such furnaces the maximum current density is concentrated at the surface of the charge, while the centre is almost free of current.

The particular advantages of coreless induction furnaces as compared with the induction furnaces having a closed magnetic circuit are:

1. Uniform movement of the molten charge by magnetomotive forces.
2. No overheating of the metal in narrow melting channels.
3. A lining of a very simple shape which can easily be repaired or replaced if necessary.

There are, however, the following drawbacks in the use of known coreless induction furnaces:

1. A much higher frequency than the usual commercial frequencies of 40 to 60 cycles is necessary.
2. The power factor is very low, and consequently expensive condenser sets are needed for compensation.
3. The electrical efficiency of the equipment is comparatively poor owing to large losses in the frequency converting machines and in the primary coil.

In order to avoid the expense of high-frequency generating equipment and the low electric efficiency of the furnace due to the use of such a motor-generator, many attempts have been made to use the ordinary commercial frequencies of 40 to 60 cycles for operating coreless induction furnaces. Such experiments were sometimes successful when metals with a high specific resistance had to be treated. Discouraging results were obtained, however, when trying to melt metals with a low specific resistance, such as aluminum and its alloys. Commercial frequencies have not yet been used on a large scale in coreless induction furnaces, not even for metals of a high specific resistance, for the following reasons:

1. The compensation of the inductive load is very expensive at these frequencies. (The power factor of a low-frequency furnace.)
2. It is necessary to fill the crucible completely with molten metal when starting the furnace, as the skin effect with these frequencies is not sufficient in non-magnetic materials to start melting with solid pieces.
3. The movement of the charge increases with the decrease of frequency. (The melting of light metals becomes almost impossible, the metal being thrown out of the crucible.)
4. The furnace cannot conveniently be adapted for using three-phase current.

The present invention aims at providing a coreless induction furnace which can use the ordinary commercial alternating current frequencies without exhibiting the foregoing drawbacks. The furnace according to this invention is so superior to the furnaces hitherto known, both from a technical as well as an electrical point of view, as to make the coreless induction furnace for commercial low frequencies, for the first time, an economically acceptable proposition. The electrical advantages of the furnace of the present invention, however, are not confined to the low frequencies, important advances in the electrical results when using higher frequencies also being obtained.

The furnace of the present invention is especially suitable for melting light metals such as aluminum, magnesium, and their alloys. Hitherto only induction furnaces of the closed magnetic circuit type have been used for this purpose; the melting channels of these furnaces, however, become obstructed by oxides and other chemical compounds of the metals treated. This results in interruption of the secondary current, and the lining of the secondary channel having to be replaced.

In order to make continuous operation of such a furnace possible, two methods have been proposed. According to one of these methods, the secondary channels are of a comparatively wide cross-section, and the furnace is emptied completely after some hours, and the melting channels are cleaned by means of special tools, generally by flexible chains. The other method makes the secondary channel accessible from outside at its lowest part, where most of the oxides seem to accumulate. Both these methods have several disadvantages. In both cases all the metal has to be removed from the furnace to perform the cleaning operation. This means quite a long interruption of the melting process, absorption of gases by the charge when pouring it out and back into the furnace, and a considerable loss of

temperature. The overall efficiency of such a furnace is, therefore, not very satisfactory, and the production of molten metal is much reduced owing to the cleaning being necessary at frequent intervals.

A furnace built according to the present invention has a secondary channel of such a shape that practically no oxides remain therein. Thus cleaning is only necessary after a long time, and the secondary channel is made so easily accessible that it can be cleaned, in most cases, without emptying the furnace.

A furnace according to the present invention can very well be adapted to the melting of steel. Hitherto, high-frequency coreless induction furnaces have been used for melting steel. These are quite suitable, but for the reasons hereintofore set forth, are expensive and the efficiency is comparatively low. Nevertheless, many such furnaces have been built for the melting of steel, as only with these furnaces was it possible to use a simple and durable refractory lining. It is especially difficult to make the refractory lining, with basic linings consisting of magnesite. The main reason for using a coreless furnace for melting steel instead of the closed magnetic circuit type induction furnace, is because it has been impossible to produce a refractory lining of such a complicated shape as the secondary channel of the iron-core furnace. Magnesite linings are subject to considerable expansion and contraction with changes of the temperature, and thus the complicated melting channels were thereby easily destroyed.

The present invention enables the employment of a lining which is almost as simple as that of the high-frequency furnace hitherto known, whilst using ordinary alternating current frequencies. Moreover, furnaces for melting steel are often built for very high power. This can only be achieved conveniently, if three-phase current can be employed. The present invention also allows the use of polyphase current which was hitherto impossible with a coreless furnace. It is possible to use with one furnace designed according to the present invention a power of 500 to 1000 kw. employing three-phase current of ordinary alternating current frequency.

With the foregoing and other objects in view, the present invention provides a coreless induction furnace for melting metals having a groove like extension of the crucible (secondary groove), situated in such a way with respect to the primary coil as to embrace as many of the flux lines of the primary coil as possible.

While the coreless furnaces hitherto known had a cylindrical crucible in which the secondary current could flow on the entire surface of the cylinder, provision is made by the present invention, for the current to flow in a special secondary groove, similar in some respects to the secondary channel of an iron core furnace, but with the important difference that the channel is always open towards the metal container on one side. In such a groove the current flows mainly in those portions in proximity to the primary coil.

By varying the height of the secondary groove it is possible to change the resistance and self-inductance of the thus formed secondary. The secondary groove should be placed as close as possible to the primary coil, in order to embrace as many flux lines as possible, i. e. the coupling should be as close as possible. However, some restrictions are imposed by the minimum wall thickness of the refractory material, which is necessary between the molten metal and the primary coil in order to prevent the metal from breaking through.

The secondary groove of the furnace is best dimensioned when its inductive resistance is about equal to its ohmic resistance. The theory hereinafter explained will permit the size of the secondary groove which will give the best efficiency and power factor to be determined. The introduction of the secondary groove allows the electrical behavior of the furnace to be much more controlled than was possible with the simple cylindrical crucible where, with a given diameter and height of the crucible, the depth of penetration determined the ohmic and inductive resistance of the secondary.

While the primary coil of the coreless furnaces hitherto known were usually of the one-layer type and had a length at least equal to its diameter, electrical reasons, as hereinafter explained, call for a secondary channel of very small height, which consequently necessitates a comparatively short coil, having a length varying between one fifth and one fifteenth of its diameter, and generally consisting of more than one layer. This type of coil usually gives the best magnetic coupling with the secondary. For the sake of brevity, a furnace according to the present invention will hereinafter be referred to as a "short coil furnace," and a furnace of the type hitherto employed as a "long coil furnace," although these are not the only features in which such furnaces differ.

The secondary groove may be of a rectangular, trapezoidal or triangular cross-section, and in all such cases it is advisable to round off the edges in order to avoid cracking of the refractory material. The trapezoidal cross-section appears to be the most convenient, the short side of the trapezoid being situated as close as possible to the primary coil.

A further feature of the invention resides in the fact that the primary coil and the secondary groove pertaining thereto are situated at the lowest part of the crucible. By virtue of this arrangement, the following advantages are achieved:

1. It is possible to start the melting operation always with a charge of liquid metal and with the normal power. As the entire power of the furnace is produced in the secondary groove, one can always be assured that the short coil furnace absorbs the entire power, even if it be started with only a small charge, which only fills the secondary groove. With a long coil furnace it is necessary to fill up the entire crucible, if the whole power is to be used. A short coil furnace can be filled and partly emptied during the melting process, but the power consumption remains entirely constant; such furnace is always operating at its rated power input.
2. The movement of the charge caused by electrodynamic forces is produced at the lowest part of the furnace. In cases where this movement is very pronounced, the height of the crucible is chosen so as to counteract this movement by hydrostatic pressure, and to have the metal surface where a movement generally is not desired, at sufficient distance from the space where the movement is originated.

3. The short coil furnaces can be easily adapted to polyphase current by placing two or three secondary grooves either beside each other concentrically one above the other, at the bottom of the furnace.

In order to enable the invention to be more readily understood, reference is made to the accompanying drawings which illustrate diagrammatically and by way of example, various embodiments thereof, and in which:

Figs. 1 to 5 are vertical cross sections of five different embodiments;

Figs. 6, 7 and 8 are respectively a vertical cross section, an elevation and a horizontal cross section along the line x—x of Fig. 6, of a further embodiment;

Figs. 9 and 10 show an embodiment of the coil in elevation and plan respectively;

Figs. 11 and 12 are vertical cross-sectional views of still another embodiment;

Figs. 13 to 16 are diagrams which serve to illustrate the theoretical explanation hereinafter set forth; and

Fig. 17 is a sketch of the primary coil and an annular shaped body, which, for the purpose of calculation, may replace the charge of the furnace. It is also referred to in the theoretical explanation.

In said drawings, like parts are denoted by like reference characters.

In the embodiment of a single phase furnace shown in Fig. 1, 1 indicates the primary coil and 2 the groove-like extension or secondary groove. The primary coil and the secondary groove are situated concentrically, the secondary groove being inside the primary coil. The primary coil is of the multi-layer type, each layer consisting of copper strips, the larger dimension of which extends in the direction of the coil axis and the smaller dimension of which extends in the direction of the charge. The height of the coil 1 is somewhat larger than the height of the groove like extension 2. The primary coil 1 is air cooled. The equipment necessary for cooling the coil is not shown in the drawings, such details of the construction being known to all experts. Usually one or more ventilators will be arranged in order to blow air through the space between the casing 3 and the primary coil. It is, however, also possible to employ water cooled coils hereinafter described. The space 8 above the groove shaped extension 2 is filled with the charged metal. The crucible which can either be rammed of refractory material or be made of shaped bricks, is indicated by 5, the heat insulating layer by 6, the metal casing of the crucible by 6 and the cover by 7. In Fig. 1 the groove-like extension 2 is rectangularly shaped, in Fig. 2 a trapezoid and in Fig. 3 triangle shaped.

Figs. 4 and 5 show two further modifications of the short coil furnaces built on the same lines as those described with reference to Figs. 1 to 3, but adapted to two phase operation.

In the embodiment shown in Fig. 4, two secondary grooves 9 and 10 and two corresponding primary coils 11 and 12 are situated side by side at the bottom of the furnace, whereas in the embodiment shown in Fig. 5 two secondary grooves 13 and 14 and two primary coils 15 and 16 are placed one above the other.

Figs. 6, 7 and 8 show a further embodiment of the short coil furnace. In this embodiment also the groove-like extension is concentrically placed within the primary coil 34; the latter is supported at its ends by means of rings 17 and 18 made of fire-proof insulating material, and is pressed together by screws or keys (not shown). The entire coil and aforementioned insulating rings are supported and held together by segmental parts 19 which are screwed to the casing 35 and to the bottom 20. All screw connections are well insulated in order to avoid losses by currents in accidental secondary circuits formed by the supporting means. For the same reason the casing 20 and the flanges 22 and 23 are split so as not to form a closed secondary circuit. This does not apply to the casing 24 which is situated sufficiently far away from the main magnetic field. All supporting means, as far as they are metal parts, should preferably be of non-magnetic material of high resistivity, such as austenitic stainless steel.

The groove like extension 25 has the same shape as the grooves shown in the foregoing embodiments and is shown as trapezoidal shaped. In addition there are provided several tubes 26 in the lining which form a direct connection between the secondary groove and the metal 28 contained in the furnace, as is clearly shown in Fig. 8 which is a cross-section in the plane x—x of Fig. 6, the segments 19 (Fig. 9) having been omitted for the sake of simplicity. With this arrangement there is also provided a further cylindrical space 27 which is filled with metal when starting the furnace. This space being comparatively small, the furnace can be commenced operating with a small quantity of metal. In Fig. 6 the arrows show the motion of the metal within the tube like openings 26 and the secondary groove 25. A sump 21 is provided underneath the groove like extension.

The furnace is provided with a crucible 33, an insulating layer 30, a casing 24, a cover 32 and a pouring nose 33 shown in Fig. 7. The water cooled coil 34 is easily accessible from outside. The coil which will hereinafter be more fully described consists of two or three layers of copper tubes having a special cross section.

Figs. 9 and 10 show details of the short coil in elevation and in plan. Only one layer of the coil is shown in the drawings. The primary coil is made of copper tube of rectangular-cross-section, the large side of the rectangle being in the direction of the coil axis.

The coil is wound in such a way that the end windings lie in a plane at right angles with the coil axis. This is done in order to enable the coil to be pressed together by two simple insulating rings 36 and 37. The coil thus pressed together is a solid piece and a base for the refractory lining which can be pressed into it. Each layer of the coil will generally have its own water connections 38 and 39 and connecting cables 40 and 41, the latter being connected either to the current supply or to the next coil layer. The separate cooling of each layer gives a much more efficient cooling system.

Fig. 11 shows another embodiment of the invention in which the flat primary coil 42 supported by ring 50 has more or less the same diameter as the groove-like extension 51 and is situated concentrically below this channel. The opening of the channel is in the direction of the coil axis.

The primary coil is supported by a frame 43 preferably of non-magnetic material of high specific resistance. In this figure the metal is indicated by 44, the crucible by 45, the heat insu-

lating layer by 46, the casing by 47, the pouring nose by 48 and the cover by 49.

A further embodiment of the invention is shown in Fig. 12 in which the primary coil 52 is not wound as a simple short cylindrical coil, but has a U-shaped cross-section surrounding the groove-like extension 53. The coil is composed of two flat portions and one cylindrical portion. All portions are, of course, wound in the same direction. While the construction of such a coil is more complicated than that of an ordinary cylindrical one, stray fields are reduced considerably by its use.

Another feature of this furnace is a second long coil 54. This furnace represents a combination of the short coil furnace and the known long coil furnace. The coil 54 can be operated either at the commercial frequency or at a higher frequency.

The height 56 of the metal bath in the crucible must be so chosen as to allow only so much stirring movement originated by the electromagnetic movement at the bottom of the secondary groove to be transferred to the surface of the bath as is necessary for carrying-out the metallurgical process in the furnace. When melting light metals the pressure head of the molten metal must be greater than when melting heavy metals. The height should be chosen so as to prevent any undesired oxidation of the liquid metal on the surface of the metal bath due to the stirring movement in said bath.

It is known that a mutual repulsion takes place between primary coil and secondary groove. The metal heated in the groove-like extension (see Fig. 6) is thus repelled towards the center and flows into the cylindrical space 27. The space from which the metal is moved now receives cold metal coming from the upper parts of the furnace through the ducts 26 and flowing in the direction indicated by the arrows in order to prevent overheating of the metal. An abrupt reversal of the direction of flow of the metal does not take place, nor are there "dead spots," where the metal might remain for some time or reverse its direction. This embodiment of the invention is extremely advantageous when melting light metal alloys, because the oxides and other chemical compounds are continuously washed away by the moving metal and are carried towards the center, there to sink to the sump of the furnace 21, which is provided for the accumulation of such oxides.

The continuous supply of cold metal through the ducts 26 (Fig. 6) to the most heated part of the secondary groove renders it possible to apply much more power than with the previously described types, so that a furnace in accordance with the present invention can work with much more power than a furnace having a secondary groove of the same dimensions but without the ducts 26.

An important characteristic of the invention is the phenomenon of displacement of the current which will cause the current to flow almost entirely in the groove-like extension if the height of the channel is sufficiently large. Therefore, in the furnace an electrodynamic force is set up which causes the metal to be repelled from the primary coil, and an upward movement of metal will occur as for instance indicated by arrows in the embodiment of the invention shown in Fig. 11.

In the modification illustrated in Fig. 12 the second coil 54 serves the purpose of increasing the power of the furnace. If it is operated at high frequency the furnace can be charged entirely with small pieces of metal, which will partly be melted by currents induced from the coil 54. One piece after the other will sink into the sump of metal which is heated by the short coil and the remainder of the melting will be done by low frequency.

The long coil may, however, be used to produce additional movement of the metal. For this purpose it is preferably supplied with alternating current of a low frequency, and the movement of the metal can be controlled by the power applied to said second coil.

The depth of the secondary groove shown in Fig. 12 as being half the difference between the diameter of the secondary groove 53 and the crucible should not be too small. In practice, this depth will be chosen greater than double the depth of penetration of the current, but not more than three to four times such depth.

Since one of the main advantages of the present invention is an improvement of the electrical efficiency and power factor, it is necessary to explain the theory of the coreless induction furnace precisely. A practical theory on the rather complicated matter has been developed by Professor Esmarch (Wissenschaftliche Veroeffentlichungen aus dem Siemens Konzern, vol. X) and his rather simple calculation has proved to be in accordance with the results of many experiments. Although this theory was based on the long coil furnace, the same principle can be applied to a short coil furnace with a special secondary channel, according to the present invention.

The basic idea of Professor Esmarch's theory is this: The current is supposed to flow in a layer of the thickness δ on the surface of the charge, and no current is supposed to flow in the inner layers. δ is called the "depth of penetration," i. e. if the current density were uniform in the layer of the thickness δ, and the current in this layer equal to the real total current, the heat produced by this current in said layer is equal to the heat produced in reality by currents distributed according to an exponential function.

For an infinitely long cylindrical body of a diameter which is large as compared with δ, the depth of penetration has mathematically been proved by Steinmetz to be:

$$\delta = 5030\sqrt{\frac{\rho}{\mu . f}} \text{cm.}$$

This formula is approximately exact for the shapes of coreless induction furnaces hitherto built. Conditions in a short coil furnace seem to be somewhat different. Experiments seem to prove that a coefficient slightly larger than 5030 is correct. However, the basic idea of imagining the current uniformly distributed in a layer of the thickness δ, can be used with good results for the calculation of the short coil furnace. While the task of determining the exact depth of penetration is such a secondary groove remains for mathematicians, a calculation based on the Steinmetz formula will not be far wrong. The Steinmetz formula was first suggested by Dr. E. F. Northrup, who is responsible for the development of the high frequency furnace, for the calculation of such furnaces.

In Professor Esmarch's theory the real charge of the furnace is replaced by an electrically equal body, having the shape of a tube of the same outer diameter and same height as the charge,

and of the wall thickness δ. The known theory of a two-coil system is then applied to this electrically equal body. For a short coil furnace the electrically equal body has the shape of a ring of square cross-section, the height of the channel h being more or less of the same size as the depth of penetration.

In the thus defined two coil system electrically equal to the real charge and primary coil (Fig. 17), the following expressions will be used for the purpose of calculation:

L_1 = Self inductance of primary coil in henrys
L_2 = Self inductance of secondary body, in henrys
M = Mutual inductance of both coils, in henrys
R_1 = Resistance of primary coil, in ohms
R_2 = Resistance of secondary body, in ohms
U_1 = Voltage at primary coil terminals, in volts
I_1 = Primary current, in amperes
N_1 = Total power input, in watts
N_2 = Power dissipated in secondary body, in watts
N_V = Power loss in primary coil, in watts
N_B = Inductive load, in voltamperes
D_1 = Average diameter of primary coil, in centimeters
D_2 = Average diameter of secondary body (outer diameter minus depth of penetration) in centimeters
h_1 = Height of primary coil, in centimeters
h_2 = Height of secondary body, in centimeters
w = Circumference of primary coil cross-section in centimeters
d = Diameter of a circle having the same area as the cross-section of the secondary body in centimeters
w = Number of turns of primary coil
ρ = Specific resistance of metal in the charge in ohms per centimeter
f = Frequency in cycles
$\omega = 2\pi f$
$j = \sqrt{-1}$

Using these terms, the well known equation of a two coil system is:

$$U_1 = J_1[(R_1 - p^2R_2) - jw(L_1 - p^2L_2)] \quad (1)$$

where p, the quotient of secondary and primary current, is given by:

$$p^2 = \frac{\omega^2 M^2}{2L_2^2 + R_2^2} \quad (2)$$

The power dissipated in the secondary body, i. e. in the charge, is calculated by:

$$N_2 = J_1^2 p^2 R_2 \quad (3)$$

and the inductive load is:

$$N_B = J_1^2 \omega (L_1 - p^2 L_2) \quad (4)$$

The important difference between a short coil furnace according to the present invention and the long coil furnace is the following: In the latter, the resistance of the secondary body is small as compared with its reactance ωL_2. Professor Esmarch, for the purpose of calculating the long coil furnace, neglected the term R_2 in the expression for p given above (2), and wrote:

$$p = \frac{M}{L} \quad (5)$$

In the furnace according to the present invention, however, the resistance of the secondary will be of a value comparable to its reactance ωL_2, and, therefore, the exact Formulae 2, 3 and 4 will have to be used for its calculation.

In the diagrams shown in Figs. 13 to 15, coefficients are given which enable the self-inductance and mutual inductance in question to be calculated approximately.

Fig. 13 represents Korndorfer's formula for coils with a rectangular cross-section. It can be used for determining the self-inductance L_1 of the primary coil according to:

$$L_1 = k_1 . D_1 . w^2 . 10^{-9} \quad (6)$$

Figure 15 shows a function discovered by Rayleigh and Niven, for the calculation of the self-inductance of a circular ring of circular cross-section.

The diameter of the ring being D_2 and the cross-section's diameter being d, the self-inductance can be determined by the equation:

$$L_2 = k_2 . D_2 . 10^{-9} \quad (7)$$

This formula can be used for the approximate calculation of the self-inductance L_2 of the secondary body, the cross-section of said body being replaced, for that purpose, by a circular cross-section of equal circumference.

Figure 15 shows a relation found by Havelock, between the mutual inductance of two circular rings of wire situated in the same plane, and the quotient of the diameters of both rings. This relation can be used approximately for the determination of the mutual inductance in the two coil system discussed, which is determined by:

$$M = k_3 . D_1 . w . 10^{-9} \quad (8)$$

The use of this formula will only lead to good results, if the height h_1 of the primary coil is not larger than the difference of the diameters D_1 and D_2. Should the coil be made longer than that, the coefficient k_3 will have a lower value than shown in the diagram. It is desirable, however, to obtain as high a mutual inductance as possible, and a coil of a greater height than the limit given above will therefore rarely be used.

The main fact learned from these diagrams when trying them on examples is: A variation of the height of the secondary body H_2 between zero and the value of h_1 will not affect the mutual inductance and only slightly affect the self-inductance of the secondary. The resistance of the secondary, however, varies inversely proportionally to the height h_2.

In the equation:

$$N_2 = p^2 . J_1^2 . R_2 - \frac{\omega^2 . M^2}{\omega^2 . L_2^2 + R_2^2} . J_1^2 R_2 \quad (9)$$

it is, therefore, possible to consider, for a certain purpose, M and L_2 as being constant, when R_2 is varied by varying the height of the secondary body H_2 within the foregoing limits. Presuming this and writing:

$$m = \frac{R_2}{L_2} \quad (10)$$

whereby the power dissipated in the secondary body becomes:

$$N_2 = J_1^2 . \frac{\omega M^2}{L_2} . \frac{m}{1 + m^2} \quad (11)$$

there is obtained the maximum of power dissipated in the secondary at a given current in the primary by choosing h_2 so as to give the maximum of the function:

$$f = \frac{m}{1 + m^2} \quad (12)$$

which represents only the variables taken out

of Equation 11. Differential calculus shows the maximum to be at:

$$m=1 \tag{13}$$

meaning:

$$R_2=\omega L_2 \tag{14}$$

i. e. the height h_2 of the secondary must be chosen so as to obtain a resistance of the secondary equal to its reactance ωL_2, to give the maximum of power dissipated in the secondary for a given primary current, in other words the best efficiency of the furnace. The inductive load in a short coil furnace is given in Equation 4. In all practical cases the value of p^2L_2 will only attain about 30% of the value of L_1. Varying the height of the secondary within the limits given above will, therefore, only mean a slight variation of the inductive load N_2 at a given primary current. This means that at the height h_2 for which the power N_2 attains a maximum for a given primary current, the value of

$$\frac{N_2}{N_B}$$

(which is approximately equal in practical furnaces to the power factor cos. ϕ) will reach its maximum as well.

Thus both the efficiency and the power factor call for a design in the secondary channel that will give a resistance R_2 equal to ωL_2.

In considering a furnace in which this condition is exactly fulfilled, the following simplified expressions can be used for the determination of the power N_2 and the inductive load N_B:

$$N_2=\frac{M^2}{2L_2^2}\cdot J_1^2\omega L_2=\frac{\omega N^2}{2L_2}\cdot J_1^2 \tag{15}$$

$$N_B=J_1^2.\omega\left(L_1-\frac{M^2}{2L_2}\right) \tag{16}$$

The expression

$$\frac{N_2}{N_B}$$

approximately equal to the power factor, in a practical furnace becomes:

$$\frac{N_2}{N_B}=\frac{\omega M^2}{2L_2\omega\left(L_1-\frac{M^2}{2L_2}\right)}=\frac{M^2}{2L_1.L_2-M^2} \tag{17}$$

The power factor depends solely upon the self-inductances and mutual inductances, always on condition that the secondary channel meets the above mentioned requirement.

Equation 17 can be transformed, using Equations 6, 7 and 8, into:

$$\frac{N_2}{N_B}=\frac{M^2}{(2L_1L_2-N^2)}=\frac{D_1^2.k_3^2.w^2}{2D_1D_2k_1k_2w^2-D_1^2k_3^2w^2} \tag{18}$$

$$\frac{N_2}{N_B}=\frac{k_3^2k_1.k_2-k_3^2}{2\frac{D_2}{D_1}} \tag{19}$$

The last equation contains neither the number of turns nor the diameter itself, but only the quotient of the diameters D_1 and D_2. It has hereinbefore been explained that it is impossible to vary k_2 very much by varying the height of the secondary channel within the known limits. Neither can k_1 be varied very much by changing the dimensions of the primary coil. k_3, however, the coefficient of mutual inductances, is very much dependent on the quotient of the diameters D_1 and D_2. This leads to the conclusion that the maximum power factor attainable in a short coil furnace, by choosing the height h_2 of the secondary according to Condition 14 will be chiefly determined by the quotient of the diameters D_1 and D_2.

Assuming practical average values for k_1 and k_2, the diagram in Fig. 16 shows the best power factor attainable in a short coil furnace plotted against the quotient of D_1 and D_2. It should be noted that this is independent of the furnace diameter, the frequency and the specific resistance of the material. If Condition 14 is met, a furnace with a given quotient

$$\frac{D_1}{D_2}$$

will have approximately the power factor shown in this diagram.

It will be seen from the same that a short coil furnace under practical conditions will have a far better power factor than the coreless furnaces hitherto known.

$$\frac{D_2}{D_1}$$

in practical cases will have a value lying between 0.8 and 0.92. A power factor of 0.16 to 0.4 can thus be obtained. The best long coil furnaces have a power factor of about 0.1.

Generally speaking, in a short coil furnace the power N_2 disispated in the charge will be far superior to the secondary power of a long coil furnace of the same diameter and the same ampere turns. With a furnace according to the present invention it will therefore be possible to obtain electrical efficiencies of 80 to 90%.

The results of the foregoing theory have been confirmed by experiments. The maximum efficiency and power factor was obtained at heights of the secondary-channel very close to the calculated values.

Condition 14 also leads to the fact, that the height h_2 giving the maximum efficiency and power factor is dependent on the frequency and the specific resistance of the material only. Calculations assuming the Steinmetz formula to be correct for a short coil furnace lead to a formula:

$$h_2=\frac{1100}{k_2}\sqrt{\frac{\rho}{f}} \tag{20}$$

k_2 for practical cases will have a value between 22 and 27 (see Fig. 14). As a rough formula for determining the height of the secondary channel we may, therefore, write:

$$h_2=44\sqrt{\frac{\rho}{f}} \tag{21}$$

This formula does not apply of course, to the furnace shown in Fig. 11. In this furnace the width of the secondary channel must be determined to fulfill Condition 14 by a complete calculation.

In all the embodiments shown only the main parts of the furnaces have been shown, which are necessary to characterize the present invention. Other details of such furnaces, as are known to any expert, will be mentioned only for the sake of completeness; for example all such furnaces should be provided with a tilting device, in order to pour out the metal. The furnace can be tilted either about the axis of the pouring nose or about the center of gravity of the furnace. However, the metal could also be removed by means of a syphon. The cooling and the supporting of the coil can be performed by any of the known methods. Water cooling and air cooling devices have been shown in the foregoing embodiments.

It must be noted that usually the coil will have to support the refractory lining of the crucible. The coil, therefore, must be designed strong enough to be able to exert a sufficient resistance to the hydrostatic pressure of the metal charge.

It will be convenient always to leave a certain amount of liquid metal, i. e. a sump, at the bottom of the furnace. It is usually practical to start the first melting operation on liquid metal as well.

In some cases it will be of advantage to use external iron yokes in the way these yokes are used in other coreless furnaces. This will be particularly convenient in the case of a multiphase furnace, in order to separate the magnetic fields of the coils connected to different phases.

When operating this furnace it will generally be useful to employ a tapped transformer in order to control the power input in various steps. This will also be necessary, because the secondary channel will be worn out by long use, thereby causing a change in the furnace impedance. This change should be compensated by varying the tension of the primary coil, which may obviously be tapped as well.

Condensers will have to be connected in parallel to the furnace, to improve the power factor.

Having now particularly described and ascertained the nature of our said invention and in what manner the same is to be performed, we declare that what we claim is:

1. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall communicating with the inner space of the crucible, a primary coil situated at the extremity of said annular groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of said groove.

2. A coreless induction furnace for melting metals comprising a crucible, at least one annular groove in the bottom section of the crucible wall communicating with the inner space of the said crucible, a multilayer primary coil situated at the extremity of each annular groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of said groove.

3. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall communicating with the inner space of the said crucible, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, said coil being constructed as a short coil having a height approximately varying between ⅛ and 1/15 of its diameter thus being shaped to induce current substantially only in the metal in the extremity of said groove.

4. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of said groove, a plurality of lateral ducts and a central channel connecting the said groove with the inner space of the crucible.

5. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of the said groove, a plurality of lateral ducts and a central channel connecting the said groove with the inner space of the crucible.

6. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall communicating with the inner space of the said crucible, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the primary coil, said primary coil having a U-shaped cross section and embracing the end of the groove with its flanges for the purpose of concentrating the induced current in the metal in the extremity of the groove.

7. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall communicating with the inner space of the said crucible, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of said groove and an additional long coil surrounding the upper part of the crucible above the said groove.

8. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall communicating with the inner space of the said crucible, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of said groove, said groove and said primary coil having substantially the same diameter.

9. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall communicating with the inner space of the said crucible, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove

the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of said groove and being constructed as an annular flat coil located below the said groove.

10. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall communicating with the inner space of the said crucible, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of said groove, the height of the metal column in the crucible being controlled in such a manner as to counteract by its pressure head the metal movement created in the vicinity of the groove to such an extent as to prevent surface oxidation.

11. A coreless induction furnace for melting metals comprising a crucible, an annular groove in the bottom section of the crucible wall communicating with the inner space of the said crucible, a primary coil situated at the extremity of said groove, in a position corresponding generally to an extension of the length of said groove the free opening of same into the inner space of the crucible being directed away from the location of the said primary coil, the latter being shaped to induce current substantially only in the metal in the extremity of said groove and a sump below the said groove for the accumulation of solid impurities.

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