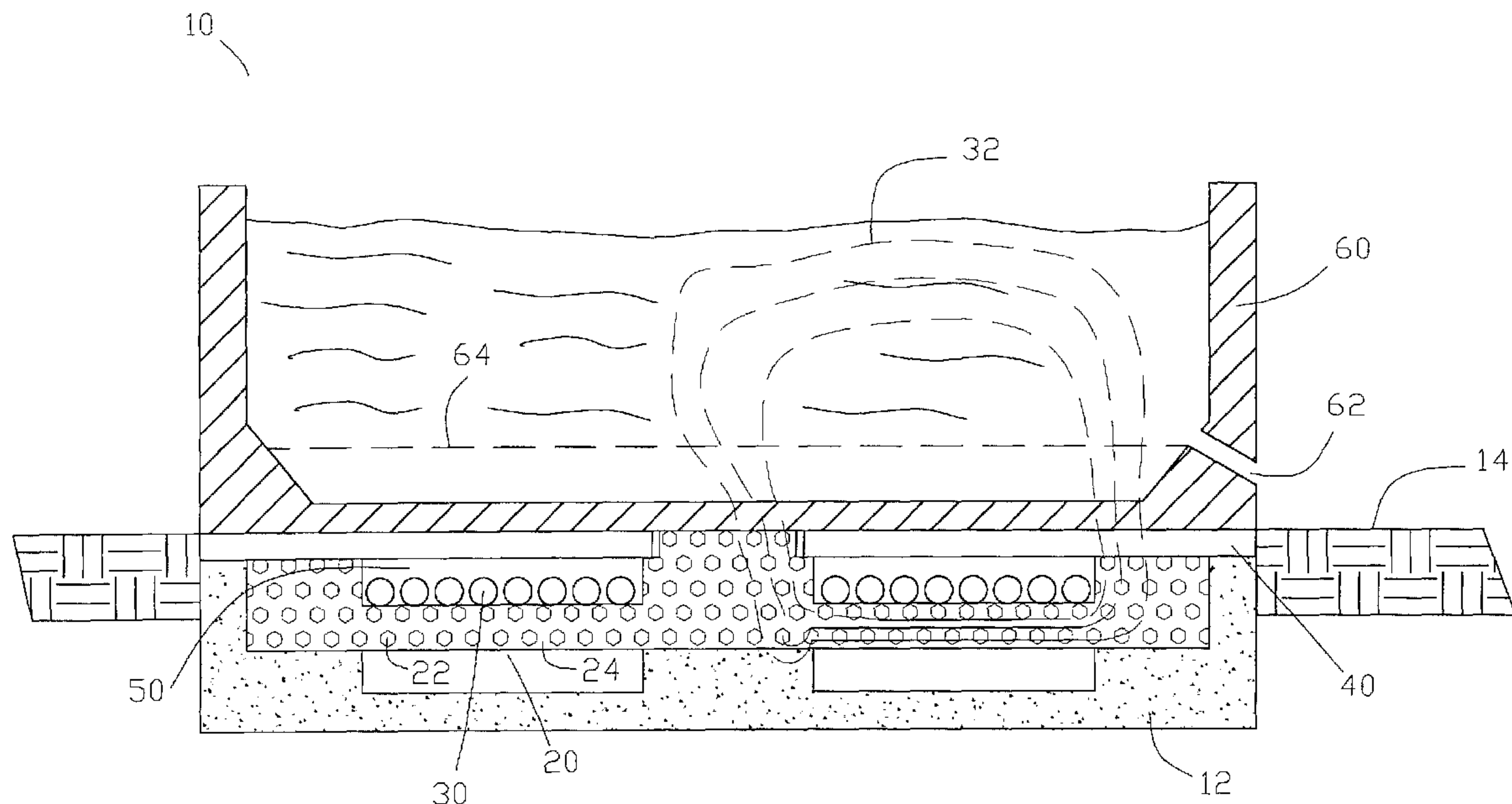




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(54) Title: FURNACE WITH BOTTOM INDUCTION COIL



(57) **Abbrégé/Abstract:**

An induction furnace (10) is provided with a bottom induction coil (30) to melt, heat and/or stir an electrically conductive material placed in the furnace (10). The furnace (10) is particularly useful for electrically conductive materials having a relatively low value of thermal conductivity, such as aluminum or an aluminum alloy.



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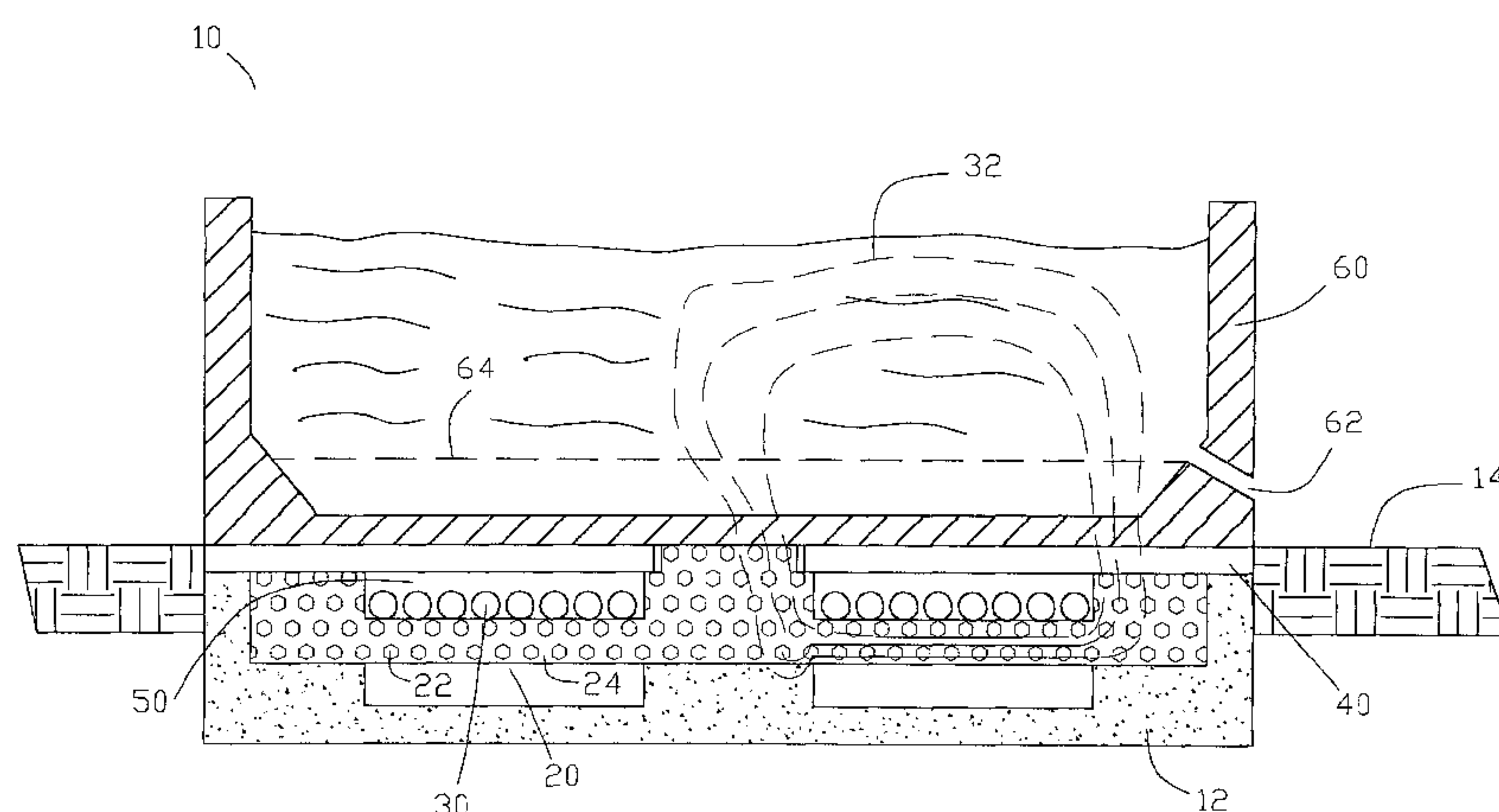
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(54) Title: FURNACE WITH BOTTOM INDUCTION COIL



(57) Abstract: An induction furnace (10) is provided with a bottom induction coil (30) to melt, heat and/or stir an electrically conductive material placed in the furnace (10). The furnace (10) is particularly useful for electrically conductive materials having a relatively low value of thermal conductivity, such as aluminum or an aluminum alloy.



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FURNACE WITH BOTTOM INDUCTION COIL

Cross-reference to Related Applications

[0001] This application claims the benefit of U.S. Provisional Application No. 60/292,679, filed May 22, 2001.

5 Field of the Invention

[0002] The present invention generally relates to electric induction melting, heating and stirring of an electrically conductive material, and in particular to an induction furnace with a bottom induction coil.

Background of the Invention

10 [0003] A material with a relatively low value of thermal conductivity, such as aluminum, can be melted and heated in a fossil fuel-fired reverberatory furnace. The salient features of a fossil fuel-fired reverberatory furnace **100** are illustrated in **FIG. 1**. Crucible **110** is configured to accommodate a shallow depth of molten bath **120** of the material. Heat generated by fossil fuel-fired burners **115** disposed above the surface of the bath
15 reverberates in the volume bounded by crucible lid **125**, the surface of the bath, and the side wall of crucible **110**. The heat is transferred by conduction throughout the melt, with the shallow depth of the bath minimizing heat transfer time. To facilitate heat transfer from the upper to the lower regions of the bath, a mechanical stirrer **130** (shown diagrammatically in **FIG. 1**) is used to circulate the bath. If the molten bath is aluminum,
20 the entire bath must be kept at least above the melting point of aluminum, which is nominally 661°C. Material charge can be added to the crucible by removing lid **125** and placing the charge in the crucible. Molten material can be tapped from the crucible at selectively closeable outlet **162**.

[0004] Melting and heating aluminum in a reverberatory furnace is an inefficient process
25 in terms of energy input, time and simplicity of operation. Additionally, mechanical stirrers are high maintenance and high failure items due to submersed operation in the molten bath. The present invention addresses these problems by providing an apparatus for and method of melting, heating and/or stirring aluminum in an efficient manner by

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magnetic field induction heating. The apparatus and method are also of particular value for the melting, heating and/or stirring of other metals besides aluminum and its alloys, and other electrically conductive materials having a relatively low value of thermal conductivity.

5 Summary of the Invention

[0005] In one aspect, the present invention is apparatus for and method of melting, heating and/or stirring an electrically conductive material in an induction furnace having a bottom induction coil. The coil is placed between a bottom support structure and a magnetic flux concentrator so that a magnetic field generated external to the coil, by a
10 current flowing through it, is directed towards the material in the crucible of the furnace to magnetically couple with it and inductively heat the material. The coil may consist of multiple active and passive coil sections. An active coil section is impedance matched to the input of an ac power supply, and the passive coil section forms an inductive/capacitive resonant circuit. Magnetic coupling of the passive coil section with a magnetic field
15 generated by current in the active coil generates a secondary magnetic field. The fields generated by the active coil section and the passive coil section are directed towards the material in the crucible of the furnace to inductively heat the material. These and other aspects of the invention will be apparent from the following description and the appended claims.

20 BRIEF DESCRIPTION OF THE DRAWINGS

[0006] For the purpose of illustrating the invention, there is shown in the drawings a form which is presently preferred; it being understood, however, that this invention is not limited to the precise arrangements and instrumentalities shown.

[0007] FIG. 1 is a cross sectional view of a typical fossil fuel-fired reverberatory
25 furnace.

[0008] FIG. 2 is a graph illustrating the electrical resistivity of aluminum over a temperature range.

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[0009] FIG. 3 is a cross sectional view of one example of the induction furnace of the present invention.

[0010] FIG. 4(a) is a plan view of one example of a bottom support structure for use with an induction furnace of the present invention.

5 [0011] FIG. 4(b) is a cross section elevation view of the bottom support structure of FIG. 4(a) as indicated by section line A-A in FIG. 4(a).

[0012] FIG. 5(a) is a diagram of one arrangement of an induction coil used with the induction furnace of the present invention wherein the coil comprises an active coil section and a passive coil section.

10 [0013] FIG. 5(b) is a diagram of another arrangement of an induction coil used with the induction furnace of the present invention wherein the coil comprises an active coil section and a passive coil section.

[0014] FIG. 6(a) is a diagram of another arrangement of an induction coil used with the induction furnace of the present invention wherein the coil comprises an active coil
15 section and a passive coil section.

[0015] FIG. 6(b) is a diagram of another arrangement of an induction coil used with the induction furnace of the present invention wherein the coil comprises an active coil section and a passive coil section.

[0016] FIG. 7 is a cross sectional view of one application of the induction furnace of the
20 present invention.

[0017] FIG. 8 is a vector diagram illustrating the advantages of an induction coil with an active coil section and a passive coil section for use with the induction furnace of the present invention.

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Detailed Description of the Invention

[0018] FIG. 3, FIG.4(a) and FIG. 4(b) illustrate one example of the induction furnace 10 of the present invention. While aluminum is a preferred electrically conductive material for heating, melting and/or stirring in furnace 10, the choice of material does not limit the scope of the invention. Further the term "aluminum" as used herein, applies to pure aluminum and aluminum alloys without limitation to composition. Furnace foundation 12 can be provided below grade 14, and may be formed from any suitable load bearing material such as concrete.

[0019] Crucible 60 is formed from a suitable refractory material. The crucible can be provided with a plugged or valved outlet 62 that normally opens into the interior of the crucible above a heel line 64 (indicated by dashed line in FIG. 3). Molten aluminum below the heel line, called remnant melt, is left in the crucible when melt above the heel line is tapped through outlet 62 to provide a minimum inductively coupled load for a magnetic field generated by current flowing through induction coil 30. A suitable ac power supply (not shown in the figures) is connected to the coil to provide the current.

[0020] Magnetic flux concentrator 20 is disposed on foundation 12 as shown in FIG. 3. In this non-limiting example of the invention, the flux concentrator is in the shape of a ring with a raised central section and raised outer section that form between them a space within which induction coil 30 is coiled. Preferably, but not necessarily, flux concentrator 20 is formed from a plurality of discrete ferromagnetic elements 22, such as steel pellets, disposed in a non-electrically conductive matrix material 24, such as a composite epoxy material. In this embodiment of the invention, flux concentrator 20 can be manufactured in cast form.

[0021] As shown in FIG. 3, induction coil 30 is disposed below the bottom of the furnace and on top of flux concentrator 20. Coil 30 is generally formed by a spirally wound inductor coil that forms a "pancake" configuration with the inductor coil lying substantially in the same horizontal plane. Coil 30 may optionally be embedded in an electrically non-conductive material, such as an epoxy composition, or disposed within plenum 50 as shown in FIG. 3. Crucible 60 is supported on bottom support structure 40. In this example of the invention, as shown in FIG. 4(a) and FIG. 4(b), bottom support

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structure **40** comprises an inner central ring element **42**, a plurality of transverse support elements **44** and an outer perimeter ring element **46**. Transverse support elements **44**, which may be structural steel I-beams, are connected at one end to inner central ring element **42**, and at the opposing end to outer perimeter ring element **46**. If the transverse support elements **44** are composed of structural steel or other electrically conductive material, the width of each element **44** must be minimized so that they do not create a significant low reluctance path for the magnetic field created by an ac current flow through coil **30**. Further, if elements **44** are ferromagnetic, they must be connected to outer perimeter ring element **46** via a non-electrically conductive element, such as an electrical isolating pad in a bolted connection between element **44** and element **46**, to prevent the formation of a significant low reluctance path among transverse support elements **44** and the outer perimeter ring element. The remaining volume of the disc-shaped bottom support structure **40** may be filled with a non-electrically conductive material, for example, by casting assembled elements **42**, **44** and **46** in a concrete composition to provide a stronger support base for crucible **60**. The configuration of bottom support structure **40** in this example may be of other shapes and configurations as long as the structure provides structural support for the crucible and allows sufficient passage of the magnetic field generated by coil **30** for magnetic coupling with the melt contained in the crucible.

[0022] Representative magnetic flux lines **32** (shown in dashed lines in **FIG. 3**) illustrate (in cross section) for the right side of induction furnace **10** the magnetic field that is created when ac current is supplied to coil **30** from a suitable power supply. The eddy current induced in the molten aluminum produces electromagnetic forces that will effectively stir the molten aluminum without the need for stirring apparatus. Further the frequency of the ac current may be varied to enhance the electromagnetic stirring effect, if desired.

[0023] Induction coil **30** may be formed from either hollow fluid-cooled conductors, or preferably, air-cooled conductors. For air-cooled conductors, Litz wire may be used. In other applications, coil **30** may be of other shapes, such as rectangular in cross section, and may be formed, for example, from a flexible solid conductor, such as copper.

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- [0024]** Induction coil **30** can be composed of one or more separate coil sections that are connected to one or more suitable power supplies. Induction coil **30** may also be composed of two or more separate coil sections wherein one or more of the coil sections are connected to a suitable power supply (active coils) and the remaining coils are passive coils connected to a capacitive element to form a resonant inductive/capacitive (L-C) circuit. Magnetic fields generated by current flow in the one or more active coils will induce secondary current flow in the one or more passive coils. Magnetic fields generated by current flows in the active and passive coil sections are directed towards the melt contained in the crucible and magnetically couple with the melt to inductively heat it.
- [0025]** **FIG. 5(a)** and **FIG. 5(b)** illustrate examples of an induction coil **30** with active coil section **30a** and passive coil section **30b**. Ac current, I_1 , provided from power supply **70** to coil section **30a** through load matching capacitor C_1 creates a magnetic field that induces a current, I_2 , in coil section **30b**, which is series connected with resonant capacitor C_2 to form an L-C resonant circuit.
- [0026]** In **FIG. 6(a)** and **FIG. 6(b)** active coil section **30a** and passive coil section **30b** are planarly interspaced with each other, rather than being disposed planarly interior and exterior to each other as shown in **FIG. 5(a)** and **FIG. 5(b)**. In other examples of the invention, the active and passive coil sections may be disposed in other arrangements such as overlapped active and passive coil sections.
- [0027]** The advantage of active and passive coil sections can be further appreciated from the vector diagram shown in **FIG. 8**. In the figure, with respect to the circuit formed by the active coil circuit, vector **OV** represents current I_1 in active coil section L_{30a} as illustrated in **FIG. 5(a)**, **FIG. 5(b)**, **FIG. 6(a)** and **FIG. 6(b)**. Vector **OA** represents the resistive component of the active coil's voltage, $I_1 R_{30a}$ (R_{30a} not shown in the figures). Vector **AB** represents the inductive component of the active coil's voltage, $\omega L_{30a} I_1$ (where ω equals 2π times f , which is the operating frequency of power supply **70**). Vector **BC** represents the voltage, $\omega M I_2$, induced by the passive coil section L_{30b} onto active coil section L_{30a} . Vector **CD** represents the voltage, $I_1 / \omega C_1$, on series capacitors C_1 connected between the output of power supply **70** and active coil section L_{30a} . Vector **OD** represents the output voltage, V_{ps} , of power supply **70**.

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[0028] With respect to the circuit formed by the passive coil circuit, vector **OW** represents current I_2 in passive coil section L_{30b} that is induced by the magnetic field produced by current I_1 . Vector **OF** represents the resistive component of the passive coil's voltage, $I_2 R_{30b}$ (R_{30b} not shown in the figures). Vector **FE** represents the inductive component of the passive coil's voltage, $\omega L_{30b} I_2$. Vector **EG** represents the voltage, $\omega M I_1$, induced by the active coil section L_{30a} onto passive coil section L_{30b} . Vector **GO** represents the voltage, $I_2 / \omega C_2$, on capacitor C_2 , which is connected across passive coil section L_{30b} .

[0029] The active coil circuit is driven by voltage source, V_{ps} , while the passive coil loop is not connected to an active energy source. Since the active and passive coils are mutually coupled, vector **BC** is added to vector **OB**, which represents the voltage (V'_{furn}) across an active coil section in the absence of a passive capacitive coil circuit, to result in vector **OC**, which is the voltage (V_{furn}) across an active coil section with a passive capacitive coil circuit. The resultant induction furnace voltage, V_{furn} , has a smaller lagging power factor angle, ϕ (counterclockwise angle between the x-axis and vector **OC**), than the conventional furnace as represented by vector **OB** (shown in dashed lines). As illustrated in **FIG. 8**, there is a power factor angle improvement of $\Delta\phi$.

[0030] With active and passive coil sections, the inductive impedance in the passive coil is substantially compensated for by the capacitive impedance (i.e., $\omega L_{30b} \approx 1 / \omega C_2$). The uncompensated resistive component, R_{30b} , in the passive coil circuit is reflected into the active coil circuit by the mutual inductance between the two circuits, and the effective active coil circuit's resistance is increased, thus improving the power factor angle, or efficiency of the coil system.

[0031] Further the power factor angle, Ψ , for the output of the power supply improves by $\Delta\Psi$ as illustrated by the angle between vector **OJ** (the resultant vector (V'_{ps}) of resistive component vector **OA** and capacitive component vector **AJ** in the absence of a passive furnace coil circuit) and vector **OD** (the resultant vector (V_{ps}) of resistive component vector **OH** and capacitive component vector **HD** with the passive furnace coil circuit).

[0032] In **FIG. 3**, plenum **50**, which is bounded by flux concentrator **20** and bottom support structure **40**, provides a gaseous (typically, but not limited to air) flow cavity

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through which cooling air can be provided by a forced air mechanical system (not illustrated in the drawings) to remove heat generated in induction coil 30.

[0033] Normally a lid (not shown in FIG. 3) is provided over the top of furnace 10 to inhibit heat loss from the melt. The lid is removable by means of a mechanical handling system to permit the introduction of additional feedstock into the furnace.

[0034] The following are two exemplar applications of the induction furnace 10 of the present invention. In both applications, induction furnace 10 has an aluminum capacity of 125 thousand tons (MT), a minimum remnant melt of 20 to 25 MT and a productivity rate of 10 MT/hr. A density of 2,370 kg/m³ and energy consumption of 320 kW-hrs/ton was used for molten aluminum. In both applications, the parameters of coil 30 in table 1 apply, as further identified in FIG. 7.

Table 1 – Coil Parameters

Coil Parameter	Value of Parameter
Inner Diameter (D _{in})	2,000 mm
Outer Diameter (D _{out})	6,400 mm
Overall Length of Coil	1,300 mm
Coil Cross Sectional Diameter	50 mm

[0035] Coil 30 in both applications is a circular, insulated power cable suitable for use at 60 Hertz, and at the voltage and current identified below. Magnetic flux concentrator 20 in both applications has an approximate relative magnetic permeability of 4.

[0036] In both sample applications, the molten metal load, which takes on the general cylindrical shape of the interior of crucible 60, is defined by the parameters in table 2.

Table 2 – Load Parameters

Load Parameter	Value of Parameter
Load Diameter (D _{ld})	7,200 mm
Height (h _{bot}) of Bottom Load Zone	300 mm
Height (h _{top}) of Top Load Zone	1,000 mm

The load parameters in this example define a crucible with an interior load volume having a diameter to height ratio of approximately 5.5:1 (7,200 mm / 1,300mm). This provides a reasonable shallow depth of melt for a metal load with a relatively low value of thermal

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resistivity and high electrical resistivity. As illustrated in **FIG. 2**, the electrical resistivity (ρ) rises significantly at and above the melting point of aluminum. A crucible with an internal load volume having a diameter to height ratio approximately in the range from 3:1 to 6:1 is preferable.

5

[0037] In the first application, sufficient heat is supplied by magnetic induction to the molten aluminum load to melt solid aluminum (having an average resistivity of approximately $6 \mu\Omega \cdot \text{cm}$) in the top metal load zone inside of the crucible, and maintain molten aluminum in the bottom load zone of the crucible. In this first application,

10 induction furnace **10** operates as an aluminum melting furnace. 60 Hertz power is supplied from one or more suitable power sources to establish the output characteristics in table 3.

Table 3 – Power Supply Output Characteristics

Electrical Parameter	Value of Parameter
Coil Voltage	2,282 volts
Coil Current	45,498 amperes

15 **[0038]** With this 60 Hertz power applied to coil **30** in the first application, coil operating parameters are as listed in table 4,

Table 4 – Coil Operating Parameters

Coil Operating Parameter	Value of Parameter
Coil Losses	636 kW
Coil Power	3,836 kW
Coil Efficiency	83.4%

and power transferred to the molten aluminum load is as listed in table 5.

20

Table 5 – Power Transferred to Load

Load Power Parameter	Value of Parameter
Bottom Zone Load Power	3,198 kW
Top Zone Load Power	2 kW
Total Load Power	3,200 kW

[0039] In the second application, sufficient heat is supplied by magnetic induction to the molten metal aluminum load (having an average resistivity of approximately

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24.5 $\mu\Omega\bullet\text{cm}$) to maintain molten aluminum in the top and bottom load zones. In this second application, induction furnace **10** operates as a molten aluminum heating furnace. 60 Hertz power is supplied from one or more suitable power sources to establish the output characteristics in table 6.

5

Table 6 – Power Supply Output Characteristics

Electrical Parameter	Value of Parameter
Coil Voltage	2,281 volts
Coil Current	45,464 amperes

[0040] With this 60 Hertz power applied to coil **30** in the second application, coil operating parameters are a listed in table 7,

Table 7 – Coil Operating Parameters

Coil Operating Parameter	Value of Parameter
Coil Losses	634 kW
Coil Power	3,834 kW
Coil Efficiency	83.5%

10

and power transferred to the molten aluminum load is as listed in table 8.

Table 8 – Power Transferred to Load

Load Power Parameter	Value of Parameter
Bottom Zone Load Power	3,196 kW
Top Zone Load Power	4 kW
Total Load Power	3,200 kW

[0041] In both applications, forced cooling air flowing through plenum **50** is used to cool coil **30**. The flow rate of cooling air at an air temperature rise, Δt , equal to 30°C around coil **30** is 970 m³/min for the first application, and 973 m³/min for the second application. Both applications illustrate that induction furnace **10** of the present invention achieves an efficiency greater than 80 percent with induction coil losses low enough so that air cooling, rather than water cooling, can be utilized.

[0042] Additionally in an initial furnace startup when solid aluminum is placed in the bottom load zone of the crucible, induction furnace **10** will melt the solid aluminum much faster than a prior art fossil fuel-fired furnace.

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[0043] The foregoing embodiments do not limit the scope of the disclosed invention. The scope of the disclosed invention is further covered in the appended claims.

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Claims

1. An induction furnace for heating an electrically conductive material, comprising:
 - a crucible to contain the electrically conductive material;
 - a bottom support structure to support the bottom of the crucible;
 - 5 a magnetic flux concentrator disposed below the bottom support structure; and
 - an at least one induction coil disposed between the bottom support structure and the magnetic flux concentrator, whereby a magnetic field generated by a flow of an ac current through the at least one induction coil penetrates the electrically conductive material to induce an eddy current in the electrically conductive material that heats the electrically
 - 10 conductive material.
2. The induction furnace of claim 1 wherein the magnetic flux concentrator comprises a plurality of discrete ferromagnetic elements disposed in a non-electrically conductive material.
3. The induction furnace of claim 1 wherein the crucible has a circular bottom and the
- 15 magnetic flux concentrator comprises an inner central ring element, an outer perimeter ring element, and a plurality of transverse elements, the plurality of transverse elements spaced radially between and connected to the inner central ring element and the outer perimeter ring element whereby the magnetic field passes through at least the openings between the plurality of transverse elements.
- 20 4. The induction furnace of claim 1 wherein the at least one induction coil comprises:
 - an at least one active induction coil section, each of the at least one active induction coil section connected to an ac power supply; and
 - an at least one passive induction coil section connected to a capacitor to form a resonant circuit, whereby the magnetic field generated in the at least one active induction coil
 - 25 section magnetically couples with the at least one passive induction coil section to induce a secondary current flow through the at least one passive induction section to generate a secondary magnetic field that penetrates the electrically conductive material to induce an eddy current in the electrically conductive material that heats the electrically conductive material.

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5. The induction furnace of claim 4 wherein the at least one active induction coil section and the at least one passive induction coil section are disposed interior and exterior to each other.

6. The induction furnace of claim 4 wherein the at least one active induction coil section and the at least one passive induction coil section are interspaced with each other.

5 7. The induction furnace of claim 1 further comprising a plenum formed between the magnetic flux concentrator and the bottom support structure for the flow of a cooling medium to cool the at least one induction coil.

8. The induction furnace of claim 1 wherein the crucible forms a substantially cylindrical volume for containing the electrically conductive material, the substantially cylindrical
10 volume having a diameter to height ratio in the range of approximately 3:1 to 6:1.

9. An induction furnace for heating an electrically conductive material, comprising:

a crucible to contain the electrically conductive material;

a bottom support structure to support the bottom of the crucible, the bottom support structure having passages therein for the transmission of an electromagnetic field;

15 a magnetic flux concentrator disposed below the bottom support structure; and

an at least one induction coil disposed between the bottom support structure and the magnetic flux concentrator, the at least one induction coil formed from an at least one active coil section and an at least one passive coil section whereby a magnetic field generated by a flow of current through the at least one induction coil penetrates the electrically conductive
20 material to induce an eddy current in the electrically conductive material that heats the electrically conductive material.

10. A method of heating an electrically conductive material comprising the steps:

supporting a crucible on a bottom support structure;

placing the electrically conductive material in the crucible;

25 generating a magnetic field from the flow of a current through an at least one induction coil disposed below the bottom support structure;

directing the magnetic field towards the bottom of the crucible; and

magnetically coupling the magnetic field with the electrically conductive material in the crucible to inductively heat the electrically conductive material.

30 11. The method of claim 10 wherein the step of directing the magnetic field towards the

- 14 -

bottom of the crucible includes placing a magnetic flux concentrator below the at least one induction coil.

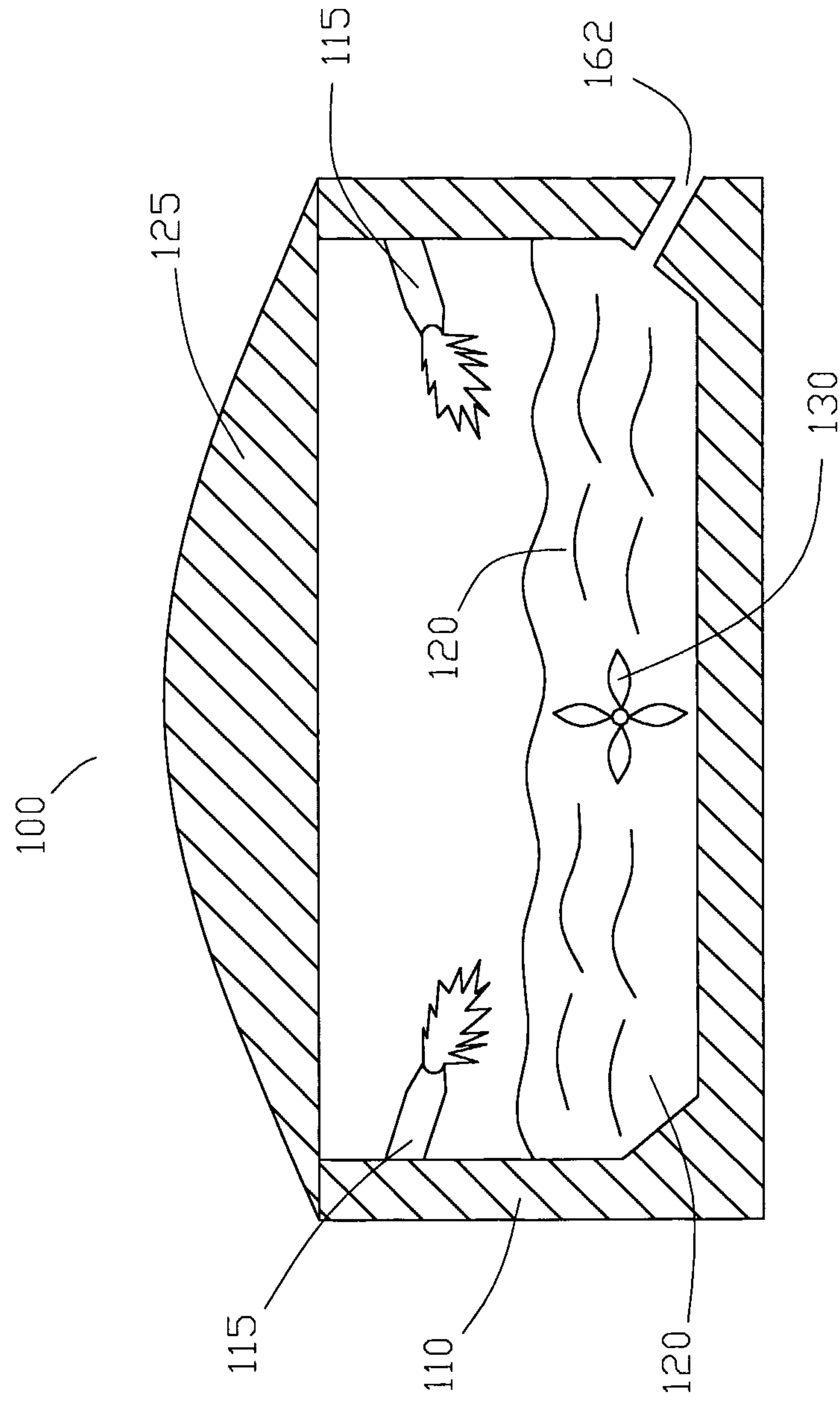
12. The method of claim **10** wherein the frequency of the current is adjusted to electromagnetically stir the electrically conductive material.

5 13. The method of claim **10** further comprising the steps of:

inducing a secondary current in an at least one passive coil section of the at least one induction coil by magnetically coupling the at least one passive coil section to an at least one active coil section of the at least one induction coil, the at least one active coil section connected to a source of ac current, the secondary current generating a secondary magnetic
10 field exterior to the at least one passive coil section; and

magnetically coupling the secondary magnetic field with the electrically conductive material in the crucible to inductively heat the material.

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PRIOR ART
FIG. 1

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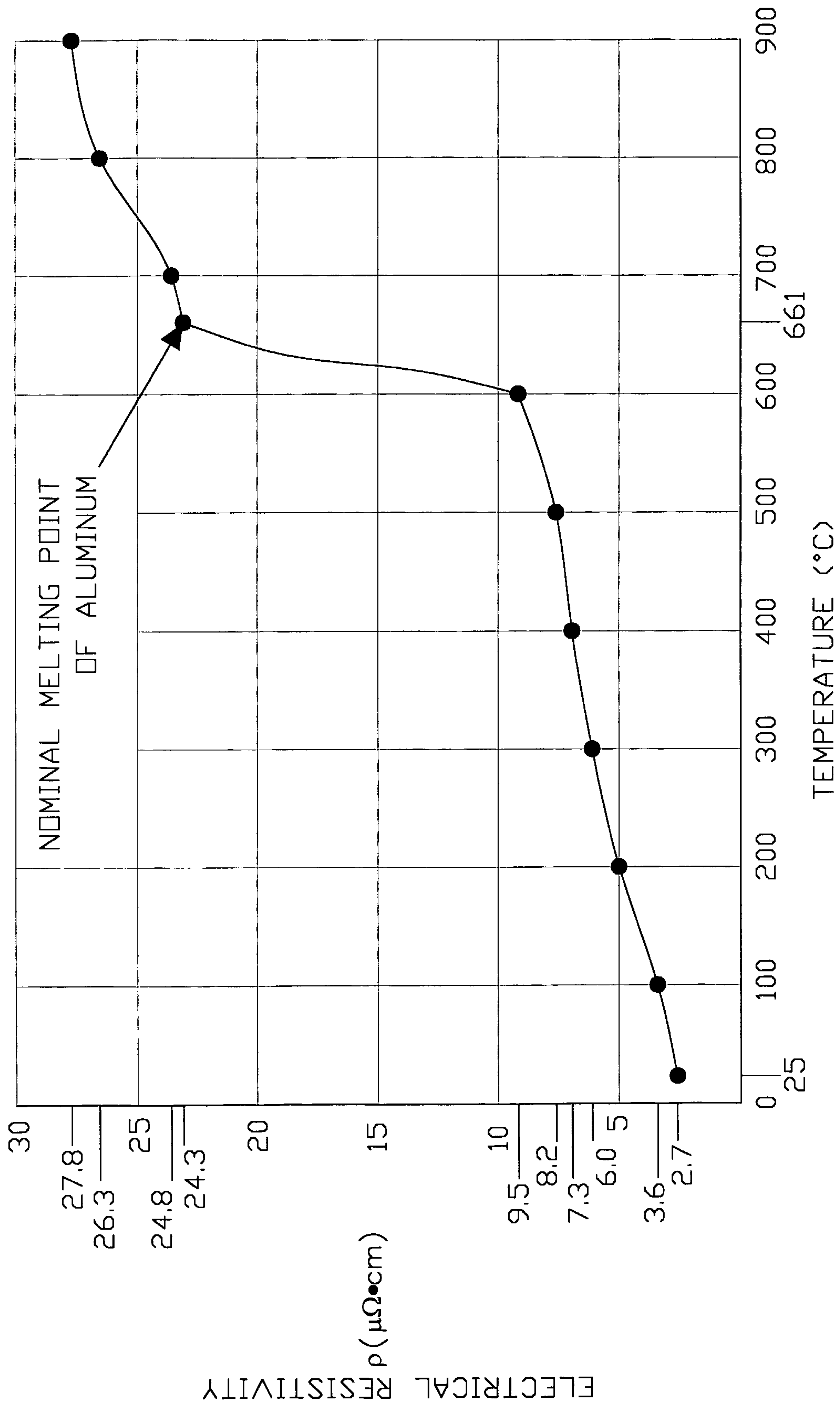


FIG. 2

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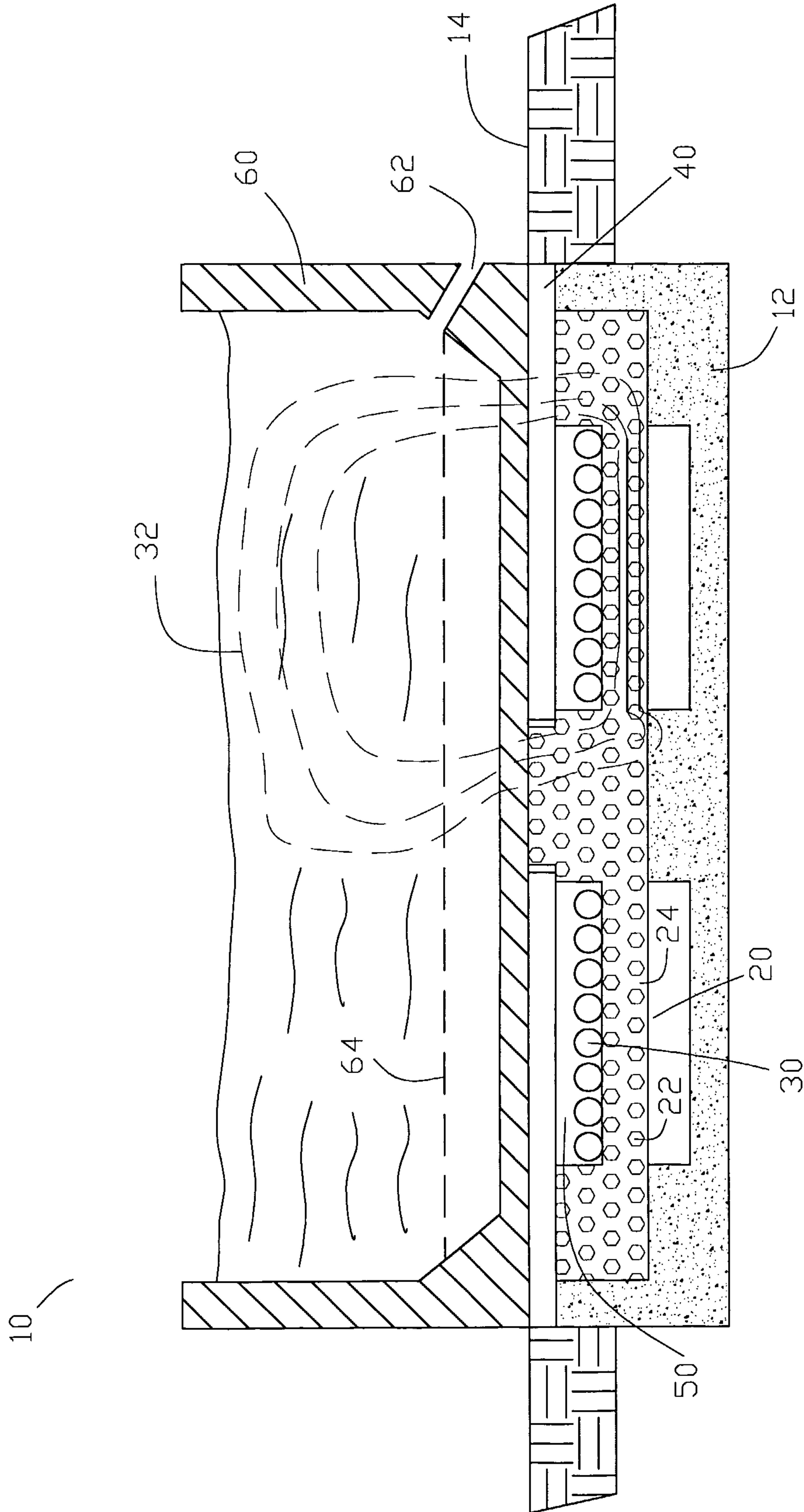


FIG. 3

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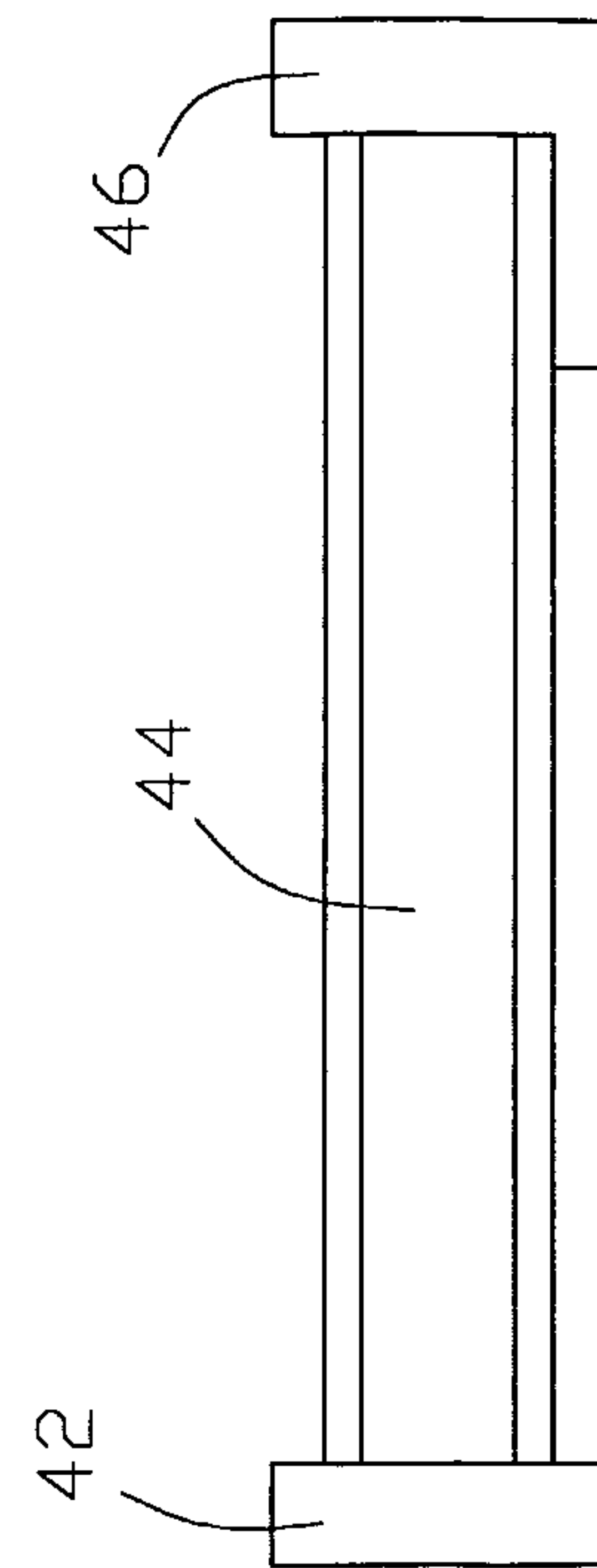
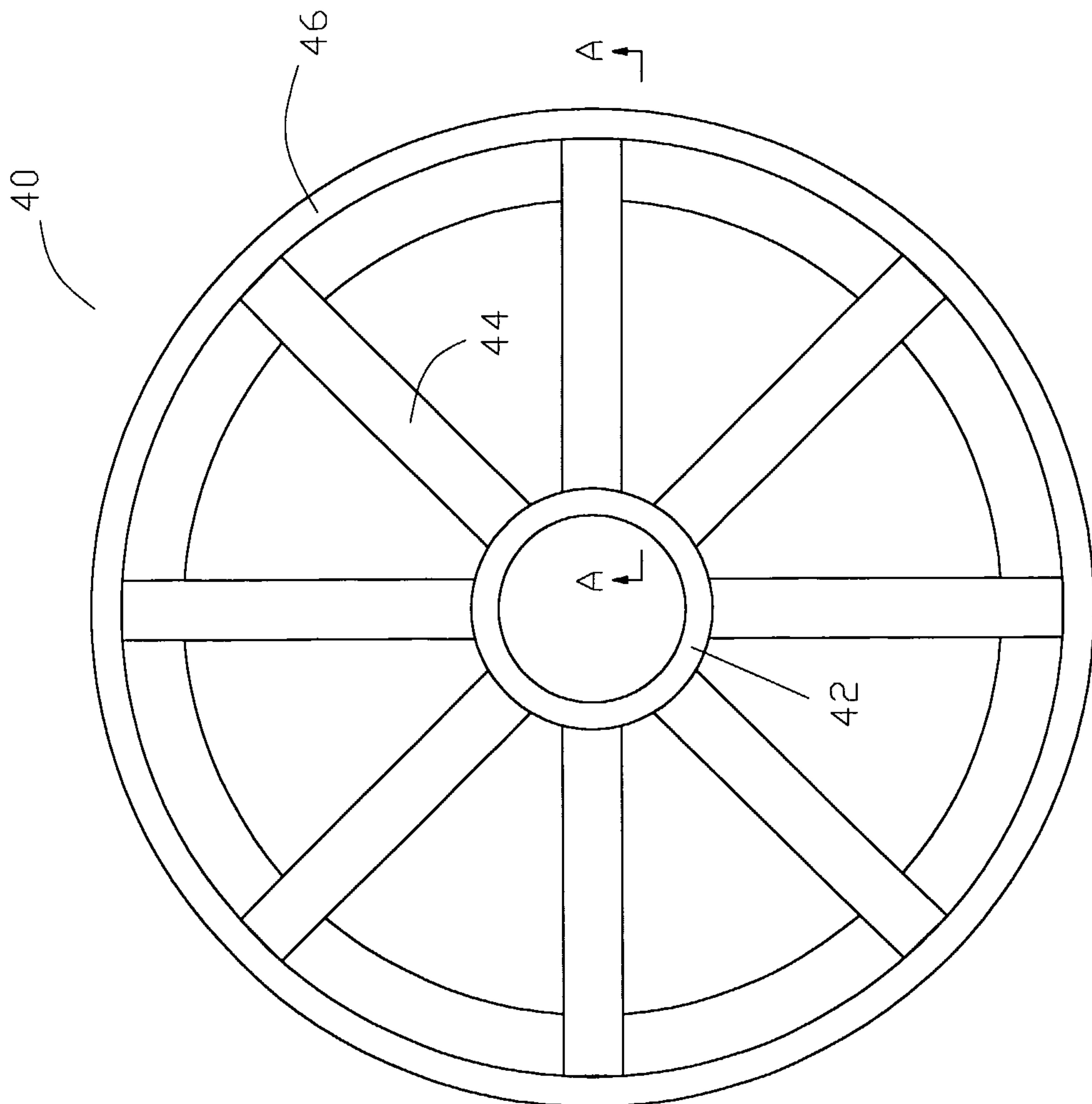


FIG. 4(b)

FIG. 4(a)

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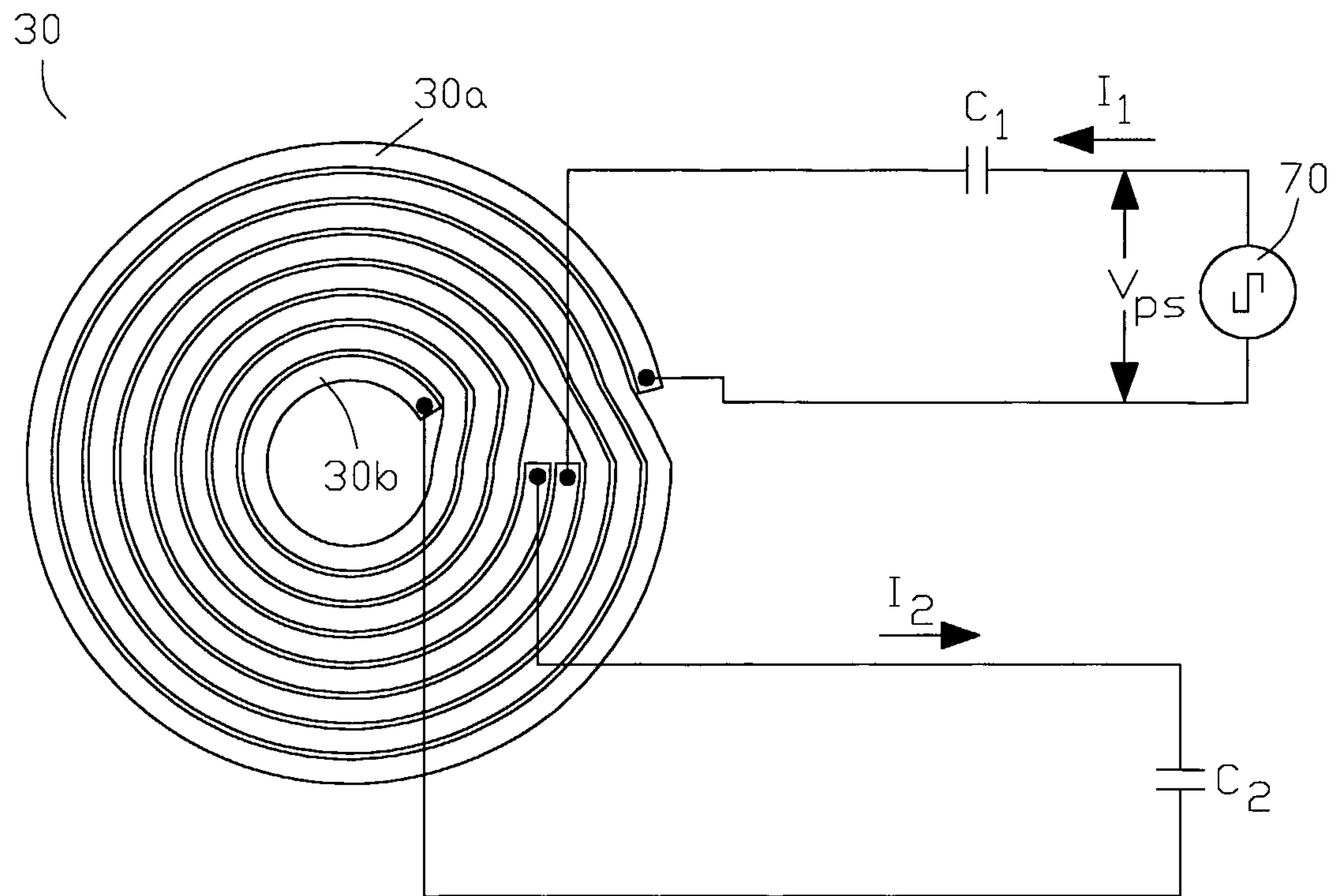


FIG. 5(a)

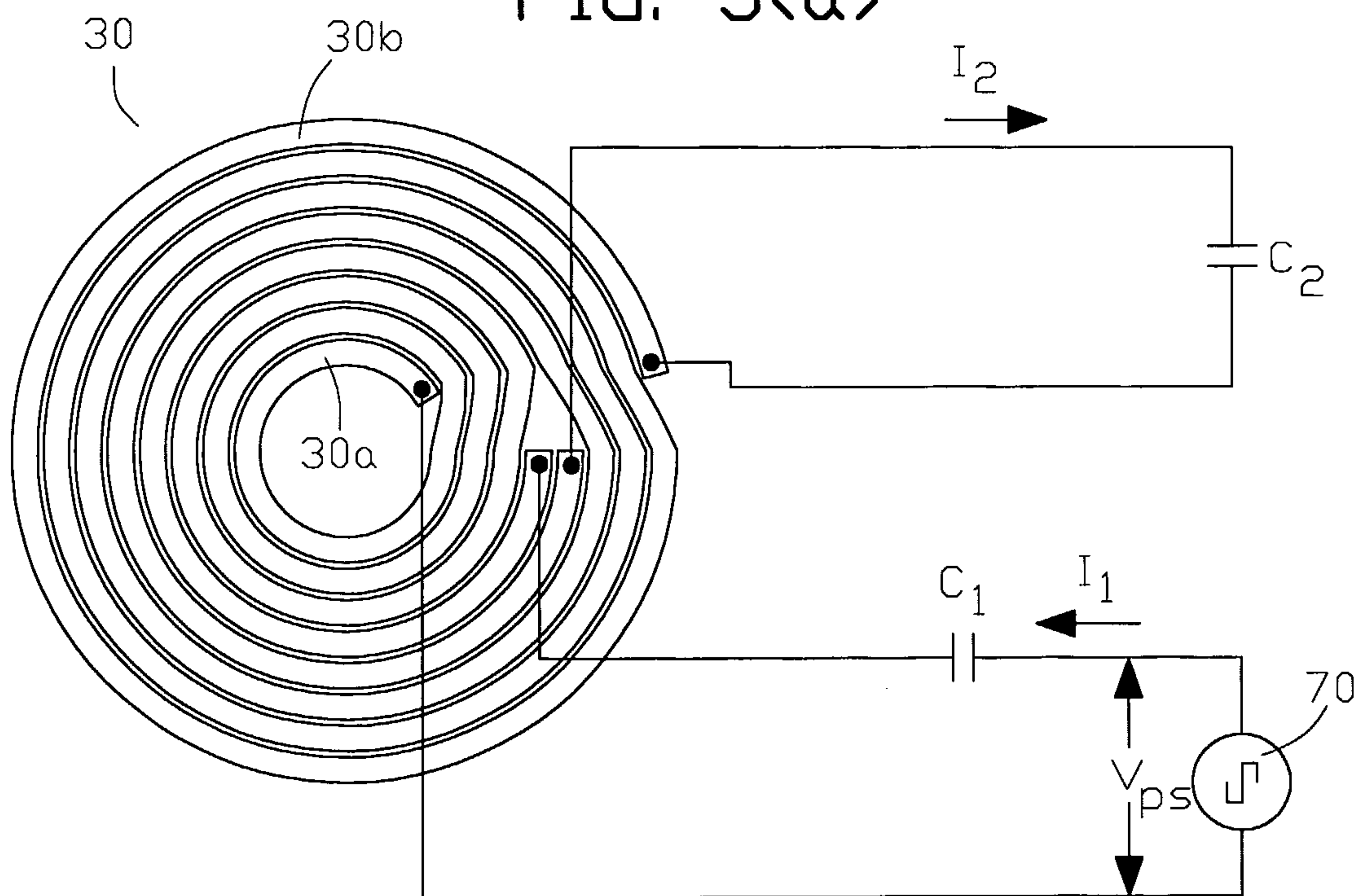
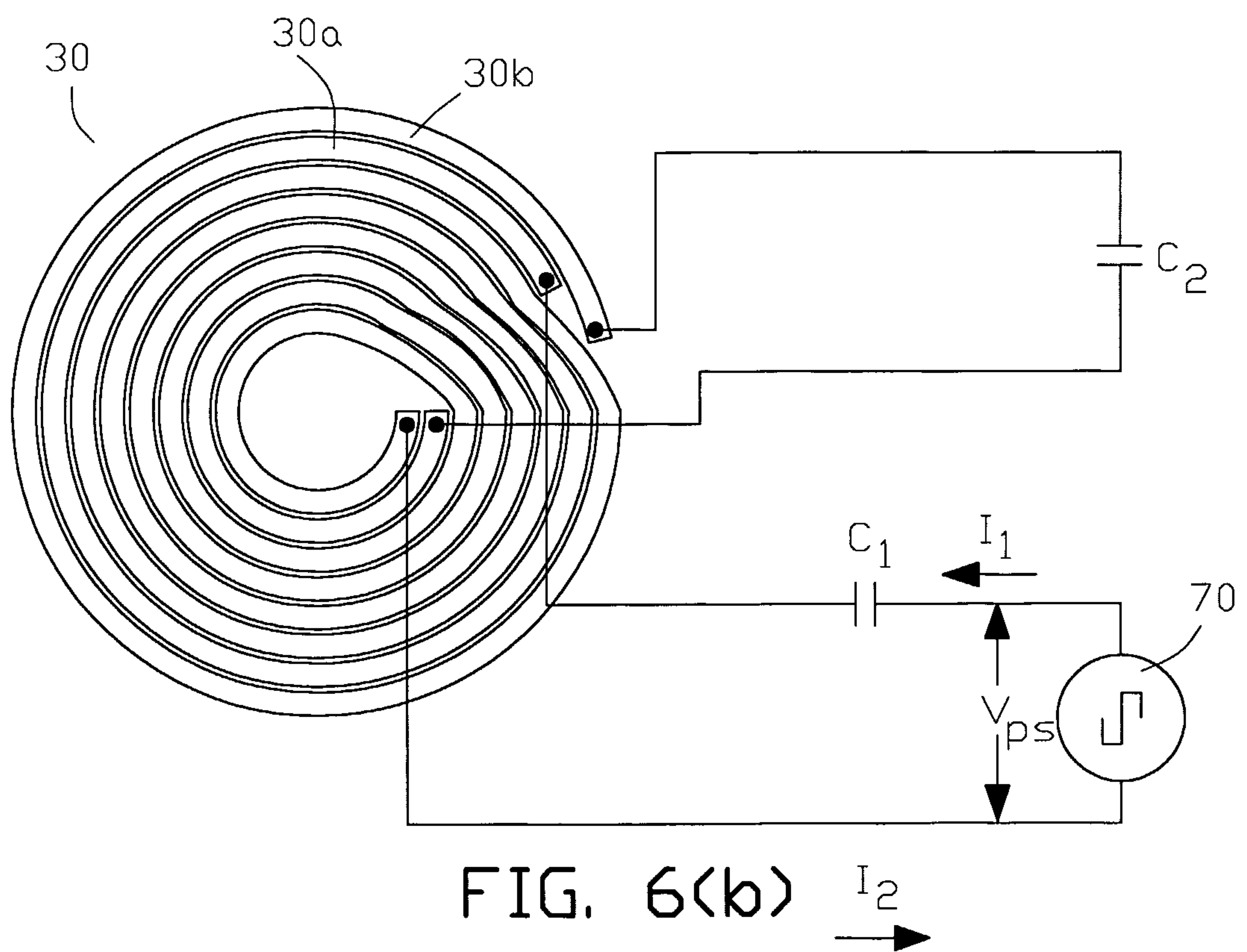
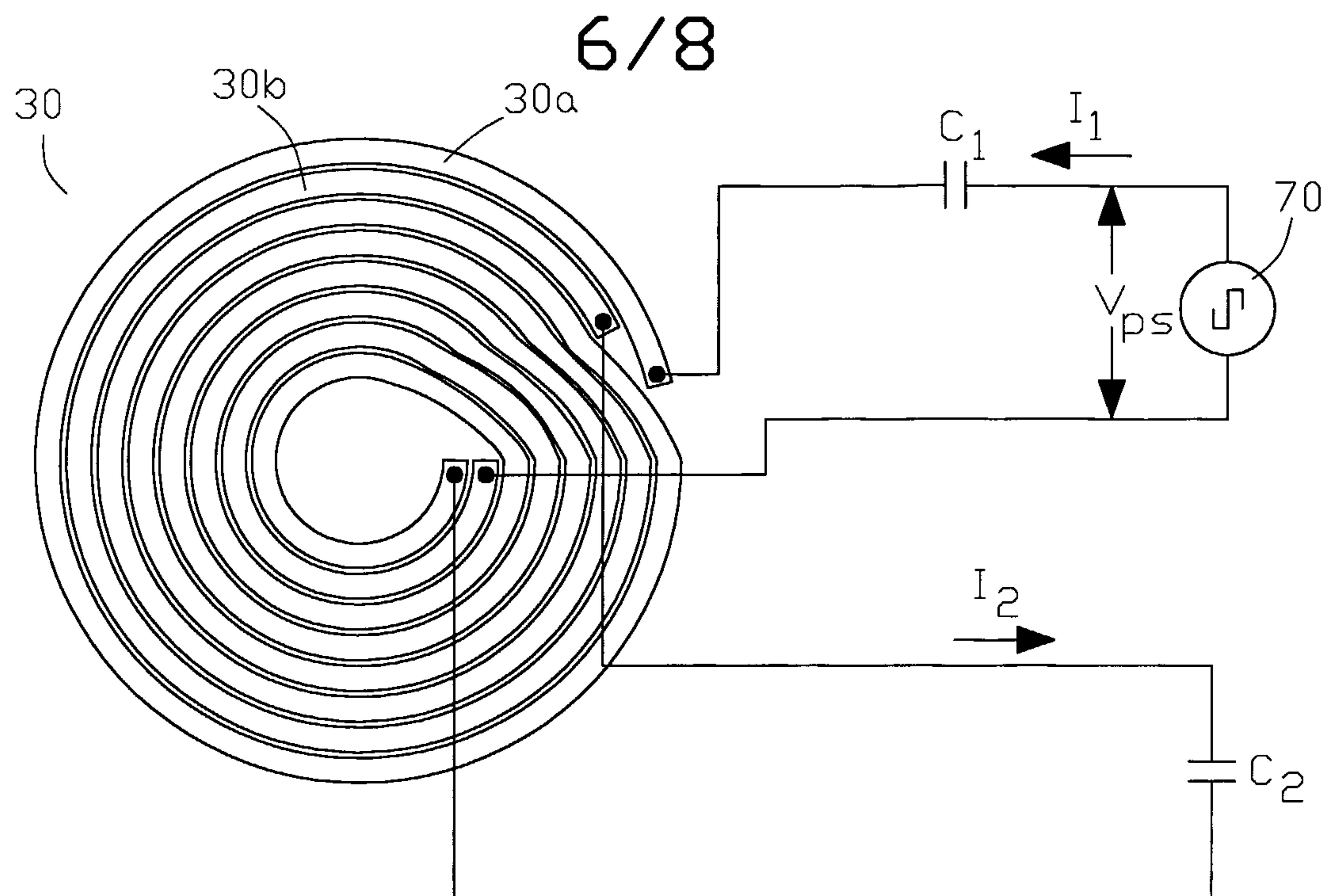


FIG. 5(b)



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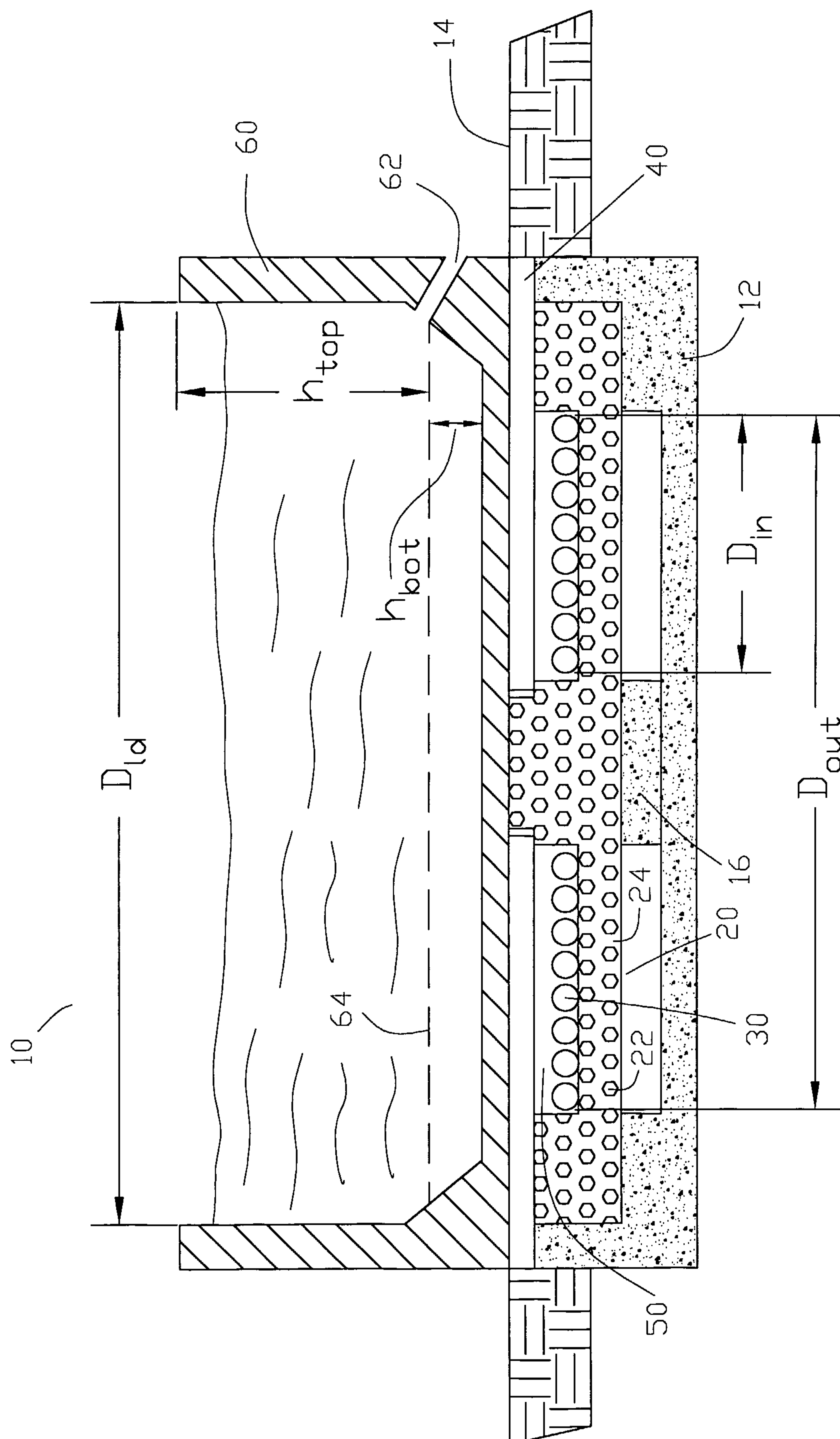


FIG. 7

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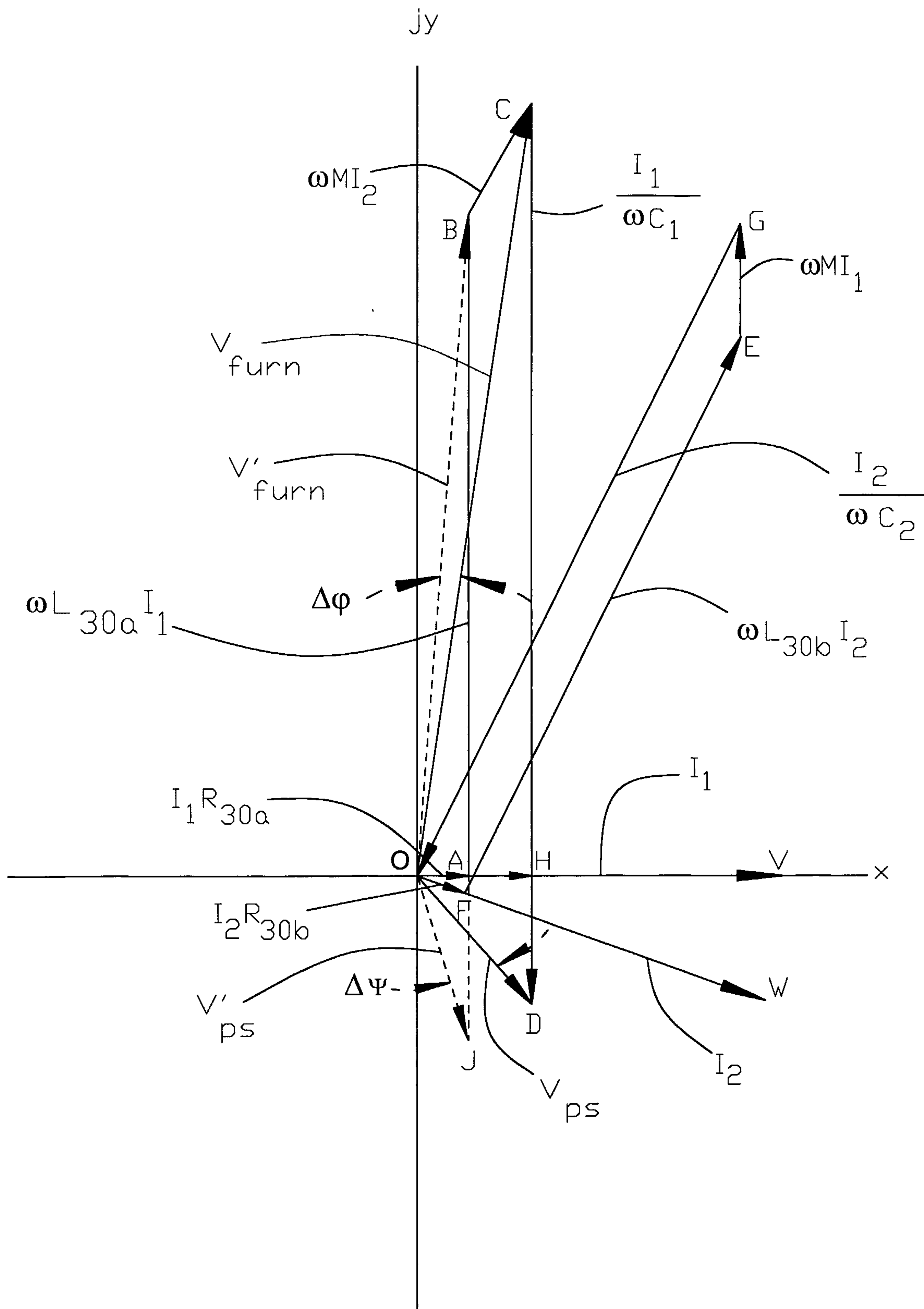


FIG. 8

