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3,239,783

TEMPERATURE-RESPONSIVE CURRENT CONTROLLING INDUCTOR DEVICE

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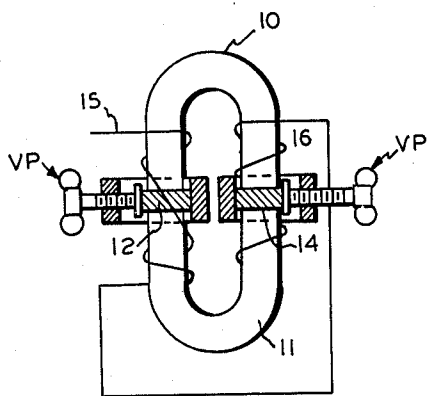


FIG. 1

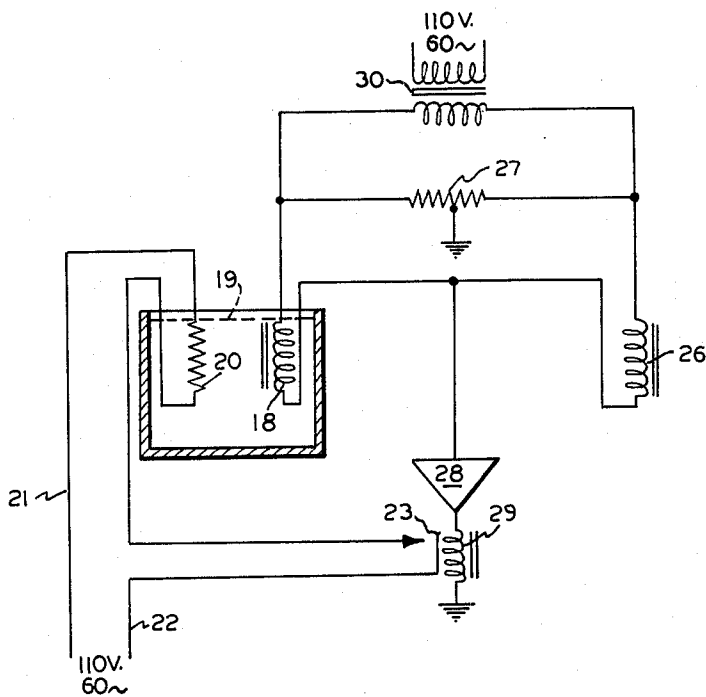


FIG. 2

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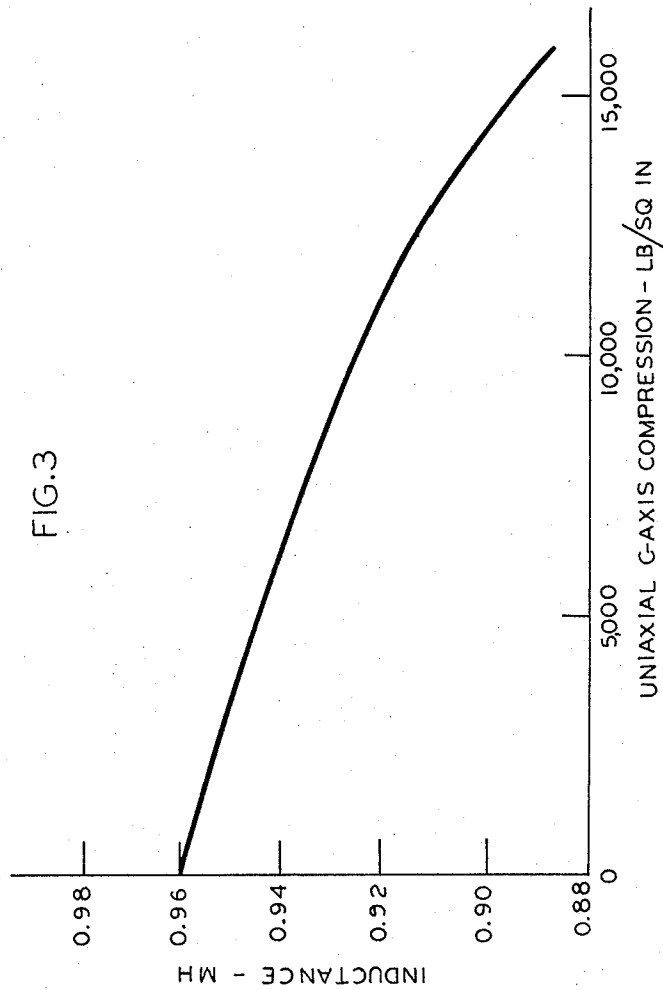
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1

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## TEMPERATURE-RESPONSIVE CURRENT CONTROLLING INDUCTOR DEVICE

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5 Claims. (Cl. 336—179)

This application is a continuation-in-part of my co-pending earlier filed application Serial No. 19,399, filed April 1, 1960, now abandoned.

This invention relates to an improved temperature-pressure-responsive control device, and particularly to an improved temperature-responsive inductor device comprising a core element consisting at least in part of a substance which displays, in addition to normal Curie point or Néel point behavior, an abrupt change from a non-magnetic to a magnetic state under high magnetizing forces accompanying a first-order transition from one solid state phase to a second solid state phase, and an inductive electrical winding in operative association with the core element.

Permeability variation with temperature has hitherto been employed in a general way to effect temperature compensation by the utilization of magnetic materials in the vicinity of their Curie points as taught in U.S. Patent 1,761,764. However, the particular temperature response characteristics of devices utilizing Curie point phenomena have proved to be limited as to both the location of the operative temperature region and the extent of this region and such devices have not had much acceptance in the art.

Accordingly, it is an object of this invention to provide an improved temperature-pressure-responsive inductor device having highly desirable particular temperature response characteristics under high magnetic field conditions.

Another object of this invention is to provide such an improved temperature-pressure-responsive inductor device which is especially well adapted for use in conjunction with conventional magnetic materials to effect a highly effective precise temperature-responsive flux control within a magnetic path.

Other objects of this invention are to provide such an improved temperature-responsive inductor device yielding a variable compound control function in a selectable predetermined temperature range with the resistance parameter of a circuit, and a temperature-responsive inductor device of this improved type which is, in addition, economical, durable and dependable in service. The manner in which these and other objects of this invention are attained will become clear from the following description and the drawings, in which:

FIGURE 1 is a partially schematic representation in side elevation of a preferred embodiment of temperature-responsive inductor according to this invention,

FIGURE 2 is a schematic representation of a temperature control circuit utilizing an inductor of the type detailed in FIGURE 1, and

FIGURE 3 is a typical inductance-compression plot for a device of the type of FIGURE 1 showing the effect of C-axis compression on the core element.

Generally, the temperature-pressure-responsive inductor device of this invention comprises in combination a core element which comprises a substance which displays an abrupt change from a non-magnetic to a magnetic state at a temperature below its Curie or Néel point accompanying a first-order transition from one solid state phase to a second solid state phase and an electrical conductor or winding positioned around, or in inductive relation to, said core element. In addition the device further comprises a

2

means cooperating with the core element for applying a force to vary the pressure to which the said substance is subjected.

The substances employed as the temperature-responsive elements, or cores, in the inductor devices of this invention are possessed of the characteristic of abruptly changing in a controllable manner their saturation magnetizations with changing temperature from a non-magnetic to a magnetic state in the course of the first order transition from one solid state phase to the second solid state phase. It is preferred that this change be from an anti-ferromagnetic state on the one hand to a ferromagnetic or ferri-magnetic state on the other. This characteristic is in addition to normal Curie point or Néel point behavior of these substances. Moreover, in the inductor devices of this invention, the first-order transition is such that it can be induced to occur at preselected temperatures, within limits, by the application of compressive force to the core material by a suitable means, as a result of which there occurs an alteration in the temperature response which is, for the antimonides hereinafter described, of a magnitude of about 2° C. per 15,000 lbs./sq. in. of compression in the direction of increasing temperature. This not only affords a means for small scale changes in characteristics as an aid in calibration by the use of conventional devices such as pressure-loading set screws or the like, but also makes possible a response based on combined temperature-pressure interaction provided, of course, that the contribution allocable to each agency is identifiable. It has been found that the first order transitions of these substances can also be induced at preselected temperatures within limits solely by the imposition of a magnetic field.

A first-order transition is always accompanied by a change in internal energy in the substance undergoing the transition, and this change is manifested by a latent heat which, for the state in which the internal energy content is lowered, becomes available as a sensible heat for transfer by conduction and the other modes of heat transfer to an environment with respect to which a positive thermal gradient exists. Conversely, where the state past the transition point is such that the internal energy content is elevated, the substance seeks to absorb heat from its environment and will, accordingly, remove heat from an environment with respect to which a negative thermal gradient exists.

A first order transition, also known as a transition of the first kind, is one in which a discontinuity occurs in the first derivatives of the Gibbs free energy. For example, there are discontinuities in the first derivative with respect to temperature, i.e., entropy, with respect to pressure, i.e., in volume, and for a magnetic material with respect to magnetic field, i.e., in magnetization.

A second-order transition is one in which the second derivative of the free energy function is discontinuous but the first derivative is continuous. In other words, at a second-order transition energy, volume, and in a magnetic substance magnetization change continuously but the temperature derivatives of these quantities have singularities. The Curie point in a magnetic material is an example of a second-order transition.

Further discussion of first and second order transitions is found in Swalin, "Thermodynamics of Solids," John Wiley & Sons, Inc., New York, 1962, pp. 72-73 and in "Phase Transformations in Solids" (Symposium at Cornell University, August 23-28, 1948), John Wiley & Sons, Inc., New York, 1951, Chap. I, by L. Tisza, pp. 1 and 2. Quotations from these references are given below.

Swalin:

"If a transition occurs with a discontinuity in . . . first derivatives of the free energy, it is called a *first order transition*."

"If . . . a transformation is discontinuous in its second derivatives of the free energy function, it would be identified as second order."

"The transformation from the ferromagnetic to the paramagnetic state is considered as an example of a second order transition."

Tisza:

"It is well known that there are two kinds of phase transitions: the first kind, called also of first order, in which energy, volume, and crystal structure change discontinuously; the second kind, frequently called . . . Curie points . . . , in which energy and volume change continuously, but the temperature derivatives of these quantities have singularities."

As defined in the "International Dictionary of Physics and Electronics"—Van Nostrand, second edition copyrighted in 1961, the Néel temperature is the transition temperature for an antiferromagnetic material, at which maximal values of magnetic susceptibility, specific heat, and thermal expansion coefficient occur.

The improved devices of this invention utilize the latent heat condition developed in their core elements in their improved functioning, as will be discussed more fully hereinafter.

Among compositions useful in devices and methods of this invention are compositions as more fully described in U.S. Patent No. 3,126,347, filed March 22, 1962 by T. J. Swoboda.

Iron-rhodium alloys and iron-rhodium alloys containing up to 20 atom percent of at least one other element are also useful in devices of this invention. Suitable alloys include those described by Fallot, *Revue Scientifique* 77, 498 (1939); Kouvel et al., *General Electric Research Report* No. 61-RL-2870M; and U.S. Patents 3,140,941, 3,140,942, 3,144,325, 3,144,324.

Still other compositions useful in the present invention are described in U.S. Patents 3,126,345 and 3,126,346, filed October 31, 1960, in the name of T. A. Bither and T. J. Swoboda respectively.

It is desirable in inductors that the low temperature ferromagnetic transition produce a large change in induction. The temperature at which the transition occurs is, of course, affected by changes in composition of the magnetic phase and can be adjusted to suit a particular device. The most useful compositions exhibit a saturation induction below the lower ferromagnetic temperature, which is not more than about  $\frac{1}{40}$  of the maximum saturation induction above this temperature. This variation can be made to occur within a limited temperature range as low as 2° C. in extent.

For the inductor devices of this invention, a composition exhibiting a very sharp increase in induction is desired. The range of temperature over which the desired increase in saturation induction occurs is sharply limited by preparing the composition in single crystal form or by quenching and annealing as taught by W. W. Gilbert in U.S. patent application Serial No. 120,679, filed June 29, 1961, now U.S. Patent No. 3,196,055, issued July 20, 1965. This process generally involves melting a composition which exhibits an increase in saturation induction with rise in temperature over a wide temperature interval or the ingredients requisite for the formation of such a composition, quenching the molten composition to a temperature below its solidification temperature, annealing at a higher temperature below the solidification temperature and cooling slowly. Optionally a chalcogen-reactive reagent, e.g., Al, may be added to the molten composition prior to quenching.

Permeability,  $\mu$ , is defined as  $B/H$ , where  $B$ =magnetic flux density and  $H$ =magnetic field intensity. Saturation magnetization is that constant value of resulting intrinsic induction in a ferromagnetic substance which is approached asymptotically when an increasing magnetizing force is applied to the substance. Considering as an ex-

ample the quaternary antimonides hereinbefore mentioned, the material, below transition temperature, is essentially non-magnetic with a permeability substantially constant at about unity. As the material is heated, the magnetization of the material, and its permeability abruptly increases 20-30 times, or even higher.

Examination has revealed that the crystal symmetry is not changed when materials useful as inductor core materials according to this invention traverse the first order solid-phase-to-solid-phase transition.

In an inductor device provided with a core element of magnetic material and a winding, the inductance,  $L$ , can be expressed as follows:

$$L=KN^2\mu$$

where

$L$ =inductance in henries,

$N$ =number of turns of conductor surrounding the core element,

$\mu$ =permeability of the magnetic core element, and

$K$ =a constant depending upon the geometry of the inductor device.

The magnetic antimonides described in the patents hereinbefore referred to are magnetically anisotropic and thus have a preferred direction of magnetization which is substantially along the  $c$ -axis of single crystal material at temperatures above about -20° C., shifting gradually to the  $a$  plane at temperatures somewhat below this level, and lying substantially entirely in the  $a$  plane below about -50° C. It is, accordingly, advantageous to utilize these materials with orientation within the core element such that the direction of the flux lines coincides substantially with the preferred direction of magnetization corresponding to the temperature of use. The described orientation can be readily accomplished by techniques known in the art, such as, for example, by aligning antimonide particles within a strong magnetic field and thereafter cementing them into a unitary mass with a suitable cement. However, it is preferred to utilize single crystals shaped to preselected dimensions by the use of "crystal pullers" or similar apparatus, since these possess the highest permeability values.

Referring to FIGURE 1, there is shown a preferred embodiment of an improved inductor device adapted to obtain temperature response according to this invention. The core element in this instance consists of two horseshoe pieces of silicon iron strip core 10 and 11 having a rectangular cross section measuring  $\frac{1}{2}$ " x  $\frac{3}{4}$ ", between the opposed ends of which are inserted, in physical contact therewith, two pieces of antimonide composition 12 and 14 having a thickness of  $\frac{1}{10}$ ". The antimonide insert material had the following analysis expressed in atom ratios:

|           |      |
|-----------|------|
| Chromium  | 0.4  |
| Manganese | 7.6  |
| Antimony  | 3.99 |
| Indium    | 0.01 |

The winding for the improved inductor device was conveniently distributed as two 1000-turn series-wound coils 15 and 16 each disposed over straight-run portions of the horseshoe pieces and over inserts 12 and 14, although the winding disposition is not critical. Thus, if open accessibility of inserts 12 and 14 to the outside environment is desirable to obtain enhanced heat transfer, the windings can be reserved to other regions. As shown in FIGURE 1 the pieces 12 and 14 are engaged by an adjustable device VP for applying a predetermined force or pressure on the pieces.

The inductance v. temperature characteristic of the inductor device of FIGURE 1 was determined utilizing a controlled temperature oil bath and a General Radio Type 1650-A impedance bridge with bridge supply voltage furnished from a 60 c. 110 volt outlet. This characteristic showed a temperature response which indicates that this

5

particular inductor device was suited to temperature measurement within the range of approximately 40–60° C. It is possible to make up antimonide compositions of different analyses which display transitions within different preselected temperature regions, so that a wide range of temperature responses are available for specific uses.

Referring to FIGURE 2, there is shown the circuit for a bridge-type temperature controller incorporating the temperature-responsive inductor device of FIGURE 1, indicated generally at 18. The inductor device is disposed within an oil bath 19 which it is desired to maintain at a given temperature by operation of a heater 20 immersed in the oil and supplied with current through 110 v., 60 c. leads 21 and 22 in circuit with relay-operated switch 23.

Inductor device 18 is connected in bridge circuit with an inductor 26 which is identical with 18, except provided with air gaps substituted for the antimonide inserts. The bridge circuit was completed on one side by potentiometric balance resistor 27 and had connected in the other a phase-sensitive amplifier 28 (typically a single-stage transistor amplifier with 60 c. A.C. applied to the collector) which powered the relay coil 29 of switch 23 by connection therethrough to ground. Finally, the bridge was powered from the secondary winding of a step-down (12 v. secondary) transformer 30, the primary winding of which was connected with the usual 110 v. 60 c. mains.

With a suitable calibration plot of temperature versus potentiometer setting for the apparatus of FIGURE 2 it is possible to select any given temperature within the response range of the apparatus by appropriate setting of the tap of resistor 27.

A series of operating tests were run on the oil bath temperature controller throughout the range 35–50° C. and it was found that the apparatus was effective in controlling the oil temperature within  $\pm 0.25^\circ$  C. of the set point.

It is believed that the latent heat phenomenon associated with the core element of the inductor devices of this invention is advantageous and useful in arrangements as discussed above under conditions in which a delay is desired in energization and deenergization of a device such as a heater to prevent chattering of control switches and an undue amount of on-and-off cycling of the heater under sharply varying temperature conditions.

An additional use for the inductor device of this invention is as a control reactor functioning as an on-off switching unit, such as by connecting the inductor in series with a resistor in an alternating current circuit, thereby effecting self-contained temperature control. In such a circuit, with negligible capacitance present, the absolute value of current

$$i = \frac{E}{\sqrt{R^2 + \omega^2 L^2}}$$

where

$E$  = applied voltage,  
 $R$  = circuit resistance,  
 $L$  = circuit inductance, and  
 $\omega$  = angular frequency.

Utilizing an antimonide temperature-responsive inductor such as 18 in series with a resistor as described, it is seen that, as the temperature of the inductor increases,  $L$  will increase abruptly, and the current will decrease abruptly. Also, since the heating effect of an electrical heater is  $W = i^2 R$ , the heat generation of the resistor increases as temperature decreases. Such a circuit, then, contains the basic elements of a control reactor.

In operation, the described reactor was employed to control the temperature of a small oil bath, the complete inductor-resistor circuit being immersed in the oil together with a fixed heater in series circuit therewith furnishing approximately 2 watts. Conditions were such that a stable temperature of 40.8° C. was maintained

6

with the cover of the bath closed. Heat loss was then increased by removing the cover, whereupon the temperature of the oil started to drop. The inductor-resistor control circuit automatically compensated by increasing the current supplied to the resistance heater, whereupon the temperature stabilized at 38° C. A separate test made in the same environment without the controller gave a temperature drop to 32° C. before thermal equilibrium was attained.

In order to illustrate the variation of the inductance with pressure on a core element of this invention, a single crystal of a chromium-modified manganese antimonide was cleaved and cut to give a sample approximately the shape of a  $\frac{1}{4}$  inch cube. The sample was cemented with epoxy resin between two pyrophyllite plates oriented such that the cleavage planes (001) were parallel to the pyrophyllite plates. A thermocouple was attached to the sample and 250 turns of No. 32 B and S enameled copper wire was randomly wound around the sample. The inductance of the coil was measured with an impedance bridge using a 1000 cycle power source. The sandwich was placed on a proving ring between the platens of a press. The press load was determined from the deflection of the proving ring. The sandwich was wrapped with a heating tape.

At no load the sample was cooled through the transition which had a midpoint of 42° C. The inductance dropped from 0.99 mh. at 74° C. to 0.70 mh. at 0° C. The sample was then isothermally compressed at 54° C. to give the following results which are shown graphically in FIGURE 3

| Uniaxial C-axis compression, |                 |
|------------------------------|-----------------|
| lb./sq. inc.                 | Inductance, mh. |
| 0                            | 0.96            |
| 4,500                        | 0.945           |
| 10,100                       | 0.92            |
| 15,000                       | 0.89            |

The selected applications hereinbefore described illustrate the control principles involved; however, it will be understood that the improved temperature-responsive inductor devices according to this invention have very wide applications. Thus, the inductor devices of this invention can be employed, for example, as high-temperature safety device to abruptly reduce or terminate circuit current with increasing temperature, or as a current cut-off device in which the controlled current flows through a heater winding on the temperature-sensitive inductor device.

From the foregoing, it will be apparent that this invention may be modified in numerous respects by those skilled in the art without departure from its essential spirit, and it is intended to be limited only by the appended claims.

I claim:

1. An improved temperature-responsive current controlling inductor device comprising in combination, a magnetic core element, an inductive electrical winding substantially surrounding said core element, said core element comprising a portion formed of a substance having a given crystalline structure and a normal Curie point with usual Curie point behavior, said substance also displaying, in addition to Curie point behavior, an abrupt change in internal energy and in saturation magnetization accompanying and related to a first-order transition from one solid state phase to a second solid state phase, said crystalline structure remaining unchanged during such a transition and during such changes in internal energy and magnetization, said substance displaying its abrupt change as an increase in internal energy and in saturation magnetization in response to increased heat input at a given constant temperature point between absolute zero and its Curie point, the inductance of said device increasing sharply to control current in said winding when said device is subjected to an increased heat

input which causes said substance to pass through its said first order transition.

2. An improved temperature-responsive current controlling inductor device comprising in combination, a magnetic core element, an inductive electrical winding substantially surrounding said core element, said core element comprising a portion formed of a substance having a given crystalline structure and a normal Néel point with normal Néel point behavior, said substance also displaying, in addition to Néel point behavior, an abrupt change in internal energy and in saturation magnetization accompanying, and related to a first-order transition from one solid state phase to a second solid state phase, said crystalline structure remaining unchanged during such a transition and during such changes in internal energy and magnetization, said substance displaying its abrupt change as an increase in internal energy and as a decrease in saturation magnetization in response to increased heat input at a given constant temperature point between absolute zero and its Néel point, the inductance of said device decreasing sharply to control current in said winding when said device is subjected to an increased heat input which causes said substance to pass through its said first-order transition.

3. The improved inductor device of claim 1 which further comprises an electrical power source operatively connected to said winding to subject said core element to a magnetic field, and an adjustable means cooperating with said core element to apply a preselected level of pressure to the portion of said core element formed of said substance and adjustably control the given constant temperature point at which said abrupt change occurs.

4. The improved inductor device of claim 1 in which said substance comprises a magnetically anisotropic crystalline structure with a preferred direction of magnetization, said substance of said portion of said core so oriented within said core and relative to said winding that the direction of flux lines produced by said winding when energized coincides substantially with the preferred direction of magnetization of the crystalline structure.

5. The improved inductor device of claim 2 in which said substance comprises a magnetically anisotropic crystalline structure with a preferred direction of magnetization, said substance of said portion of said core so oriented within said core and relative to said winding that the direction of flux lines produced by said winding when energized coincides substantially with the preferred direction of magnetization of the crystalline structure.

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