US 20120031109A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2012/0031109 A1**

Vetrovec (43) **Pub. Date: Feb. 9, 2012**

(54) **MAGNETOCALORIC REFRIGERATOR**

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(21) Appl. No.: **13/134,427**

(22) Filed: **Jun. 7, 2011**

Related U.S. Application Data

(60) Provisional application No. 61/397,246, filed on Jun. 7, 2010, provisional application No. 61/397,175, filed on Jun. 7, 2010.

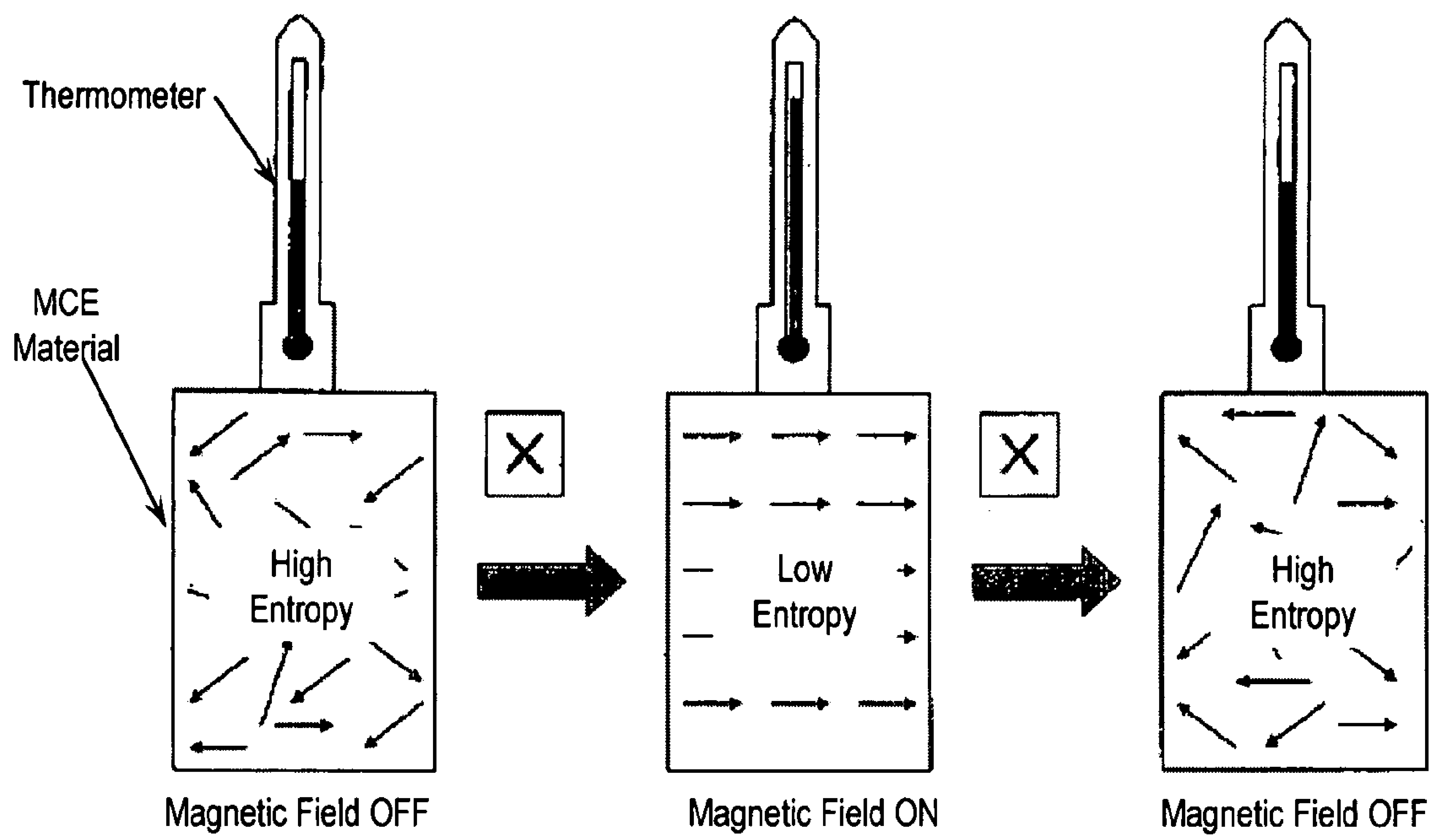
Publication Classification

(51) **Int. Cl.**
F25B 21/00 (2006.01)

(52) **U.S. Cl.** **62/3.1**

(57) **ABSTRACT**

The invention is for an apparatus and method for a refrigerator and a heat pump based on the magnetocaloric effect (MCE) offering a simpler, lighter, robust, more compact, environmentally compatible, and energy efficient alternative to traditional vapor-compression devices. The subject magnetocaloric apparatus alternately exposes a suitable magnetocaloric material to strong and weak magnetic field while switching heat to and from the material by a mechanical commutator using a thin layer of suitable thermal interface fluid to enhance heat transfer. The invention may be practiced with multiple magnetocaloric stages to attain large differences in temperature. Key applications include thermal management of electronics, as well as industrial and home refrigeration, heating, and air conditioning. The invention offers a simpler, lighter, compact, and robust apparatus compared to magnetocaloric devices of prior art.



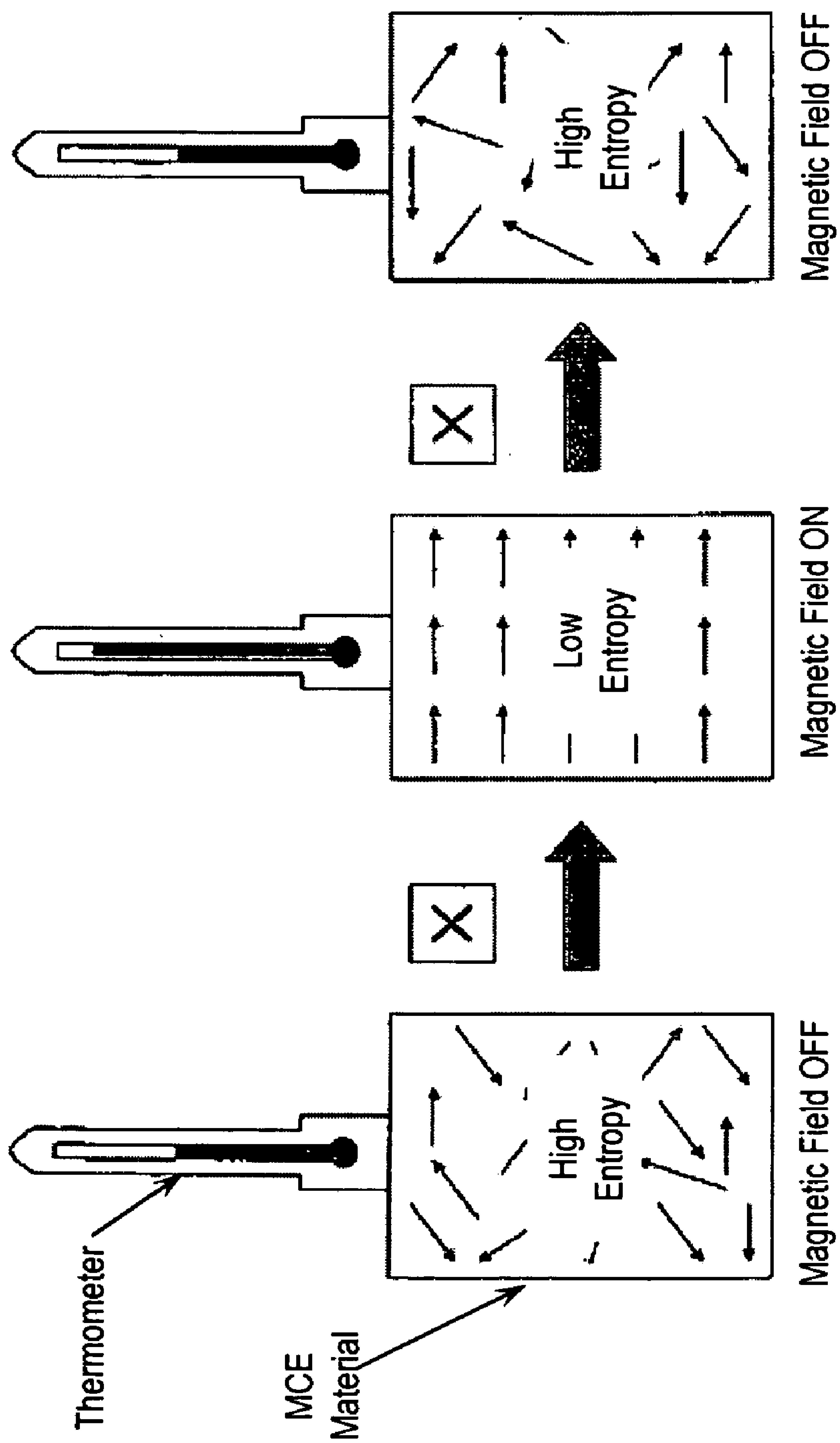

Thermometer
MCE Material
High Entropy
Magnetic Field OFF
Low Entropy
Magnetic Field ON
High Entropy
Magnetic Field OFF

FIG. 1

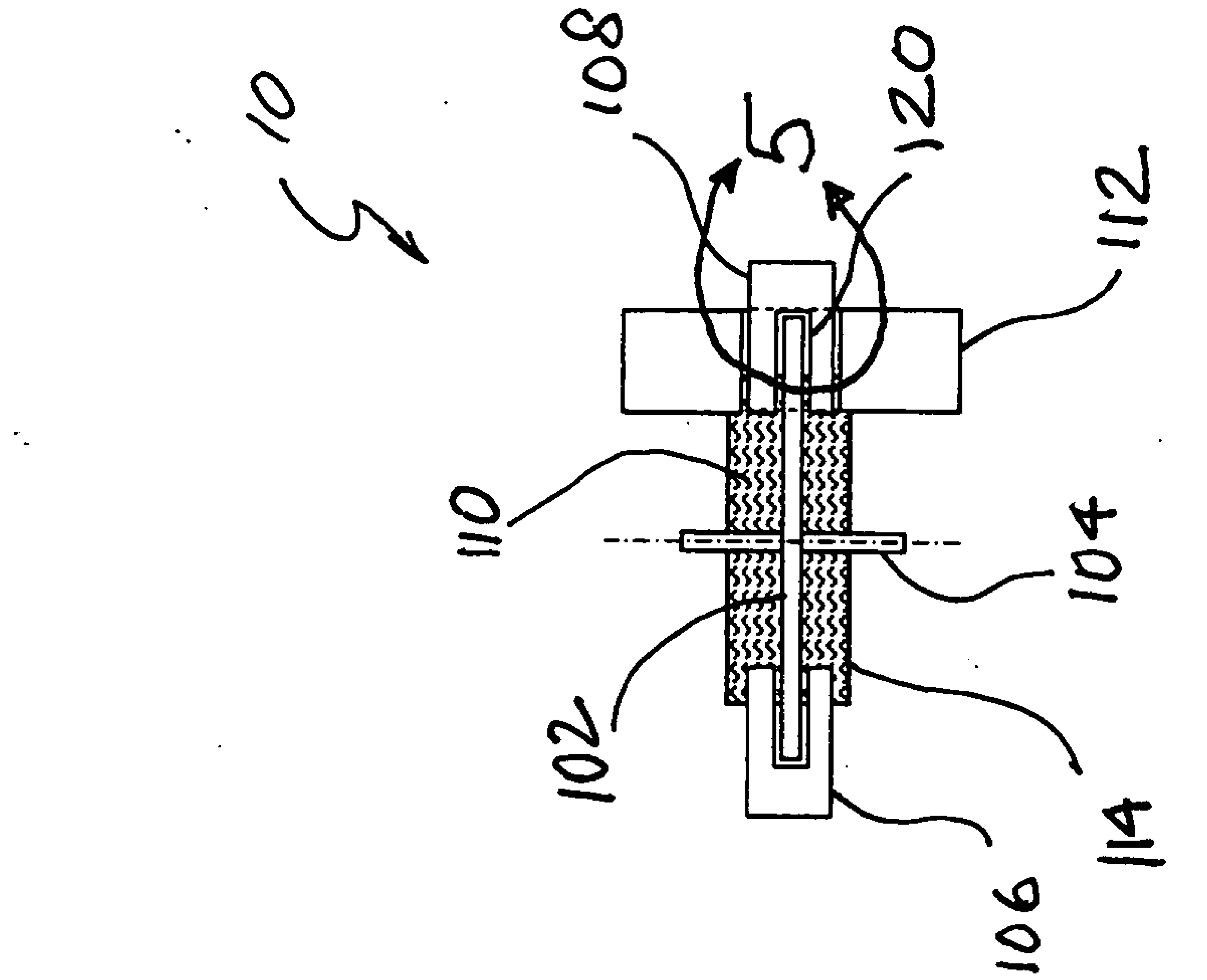

10
108
5
120
112
110
104
102
114
106

FIG. 3

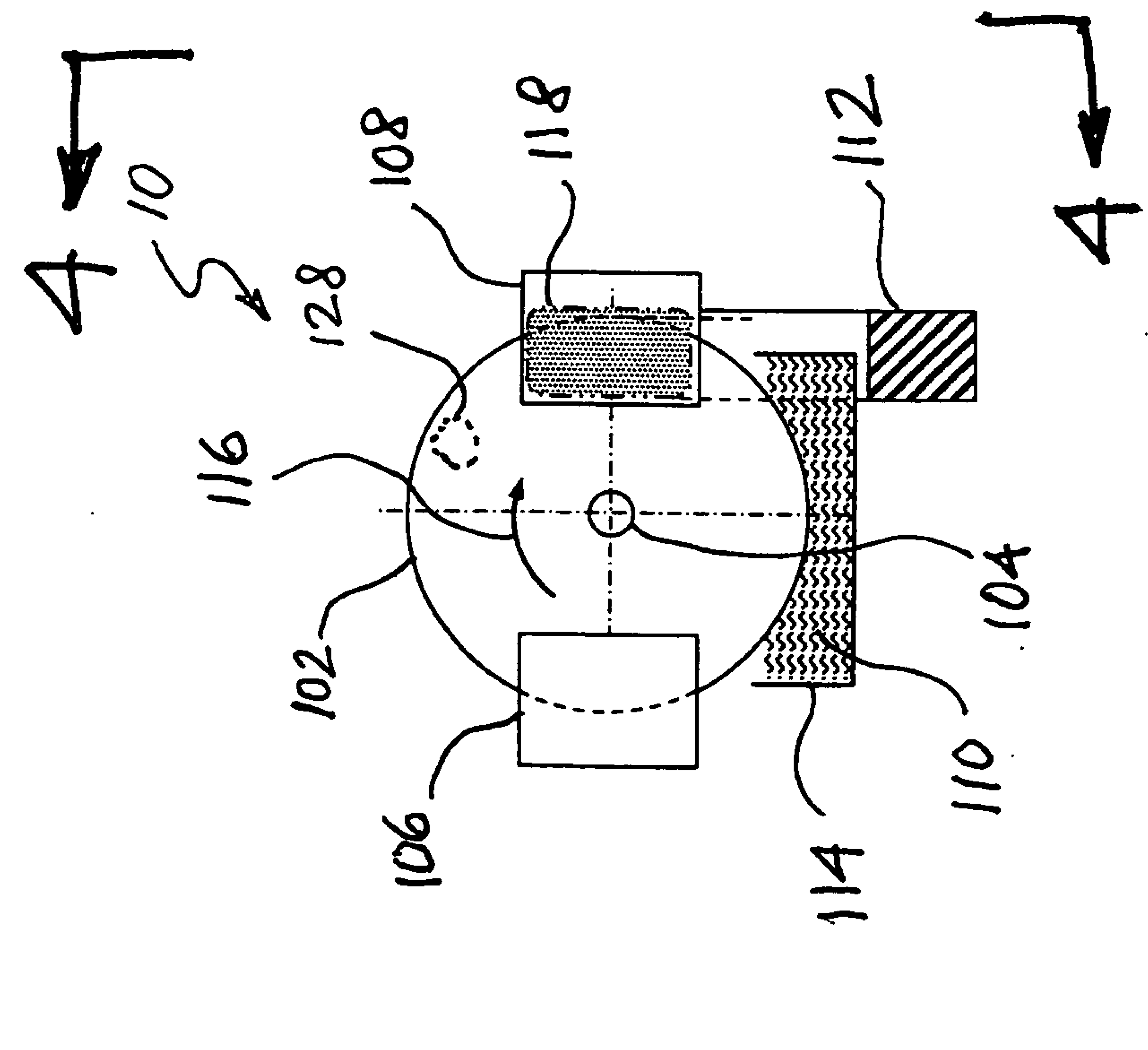

4
10
128
108
118
112
4
116
102
104
106
114
110

FIG. 2

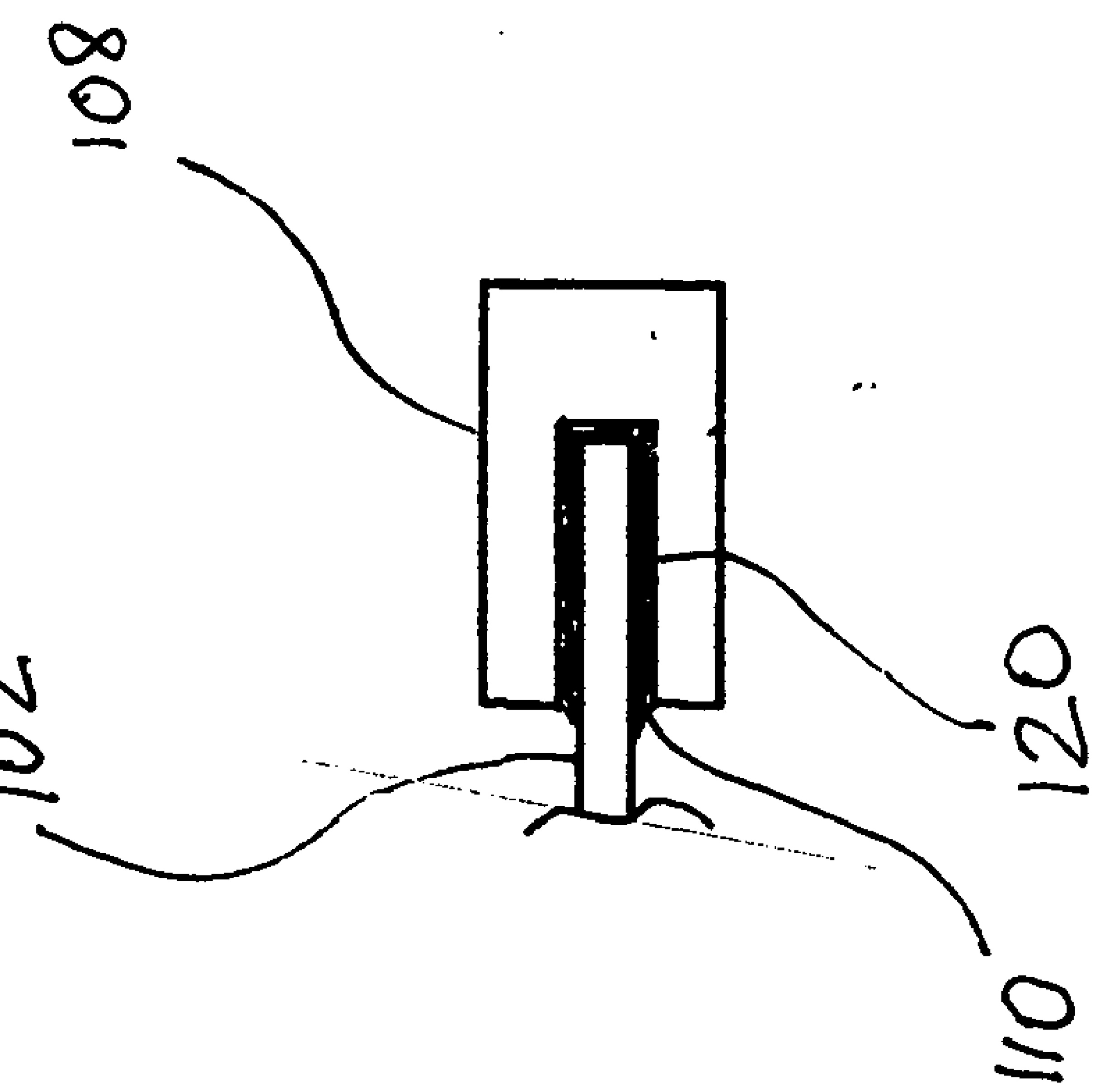


FIG. 5

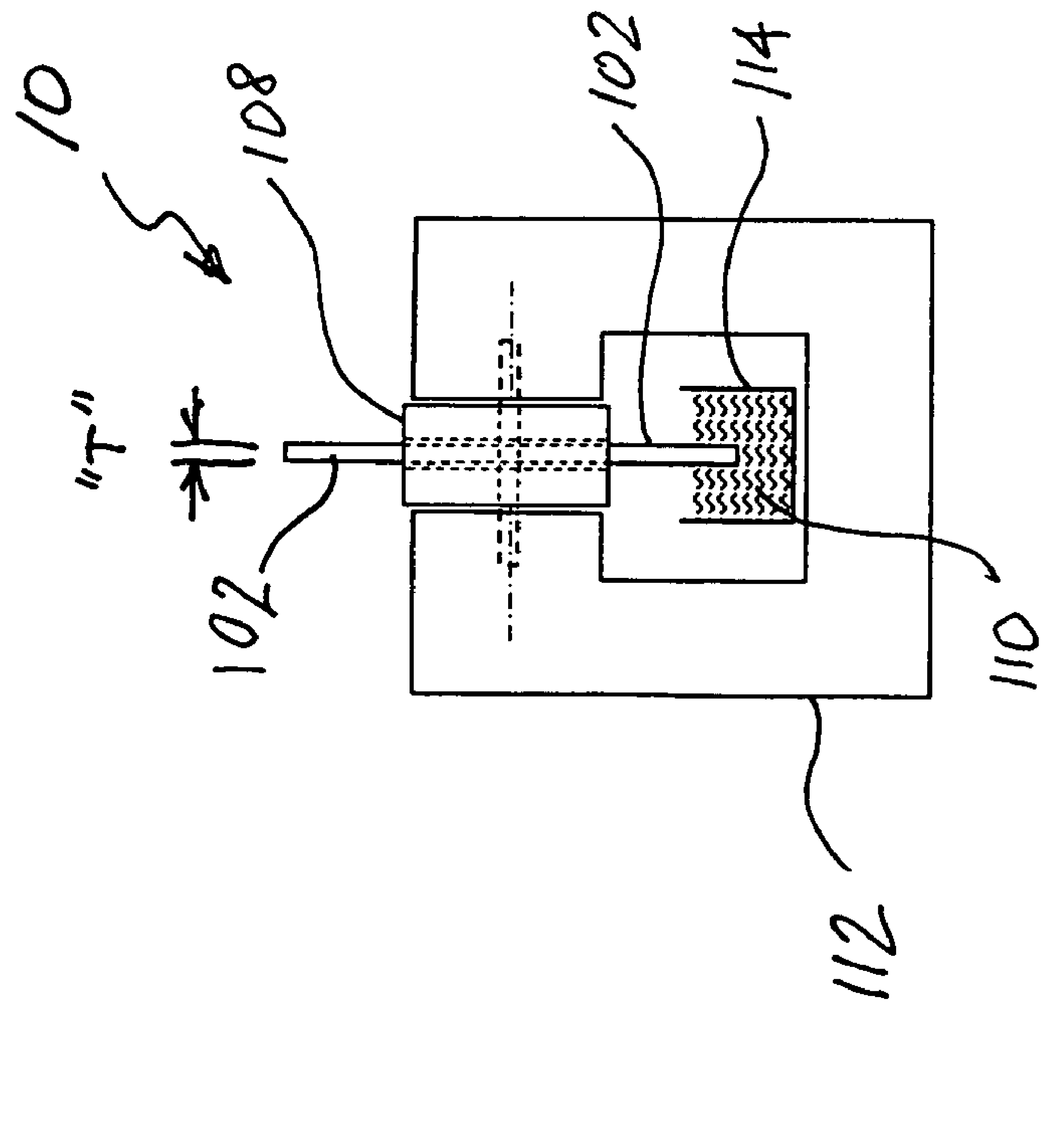


FIG. 4

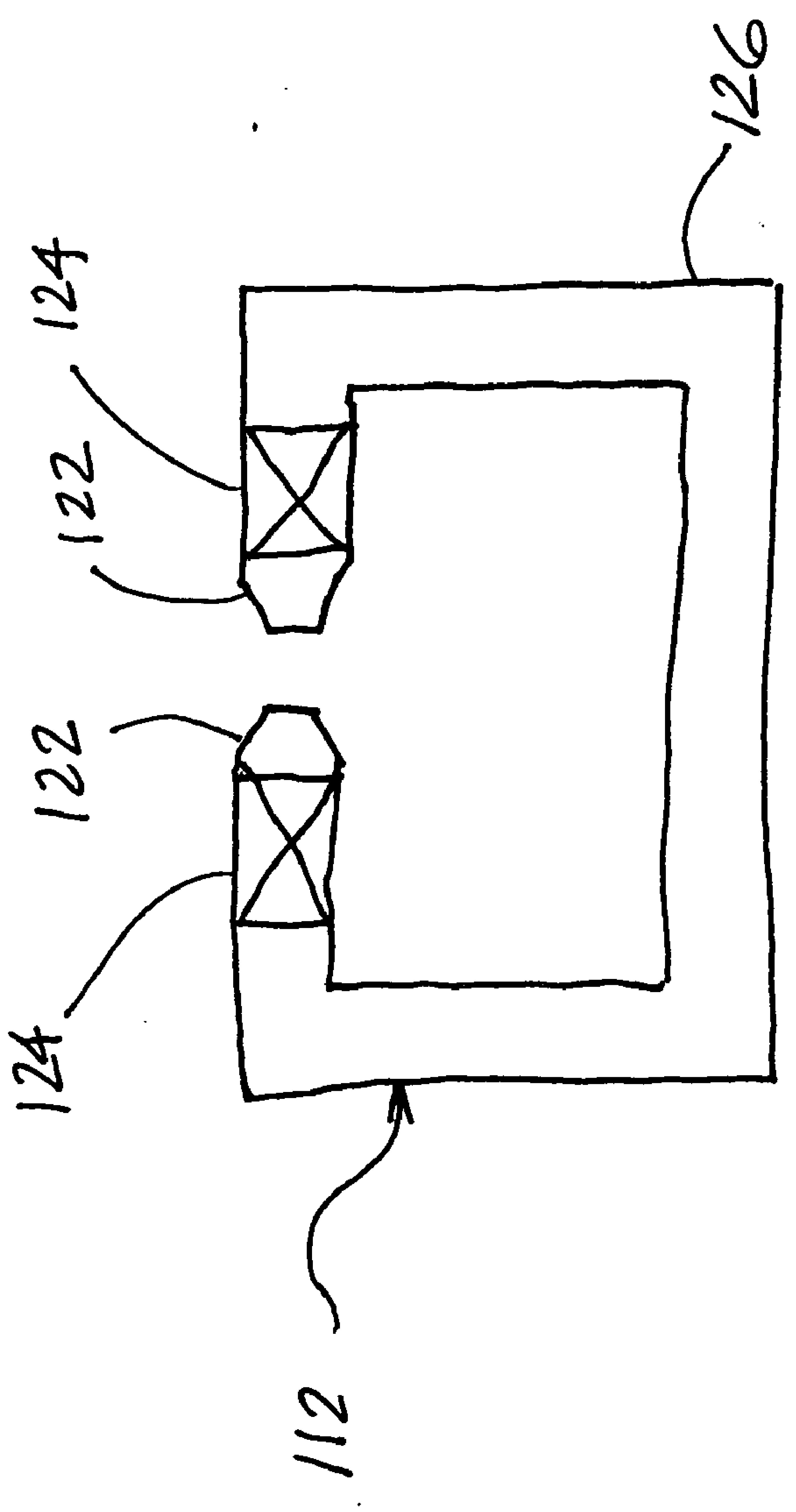


FIG. 6

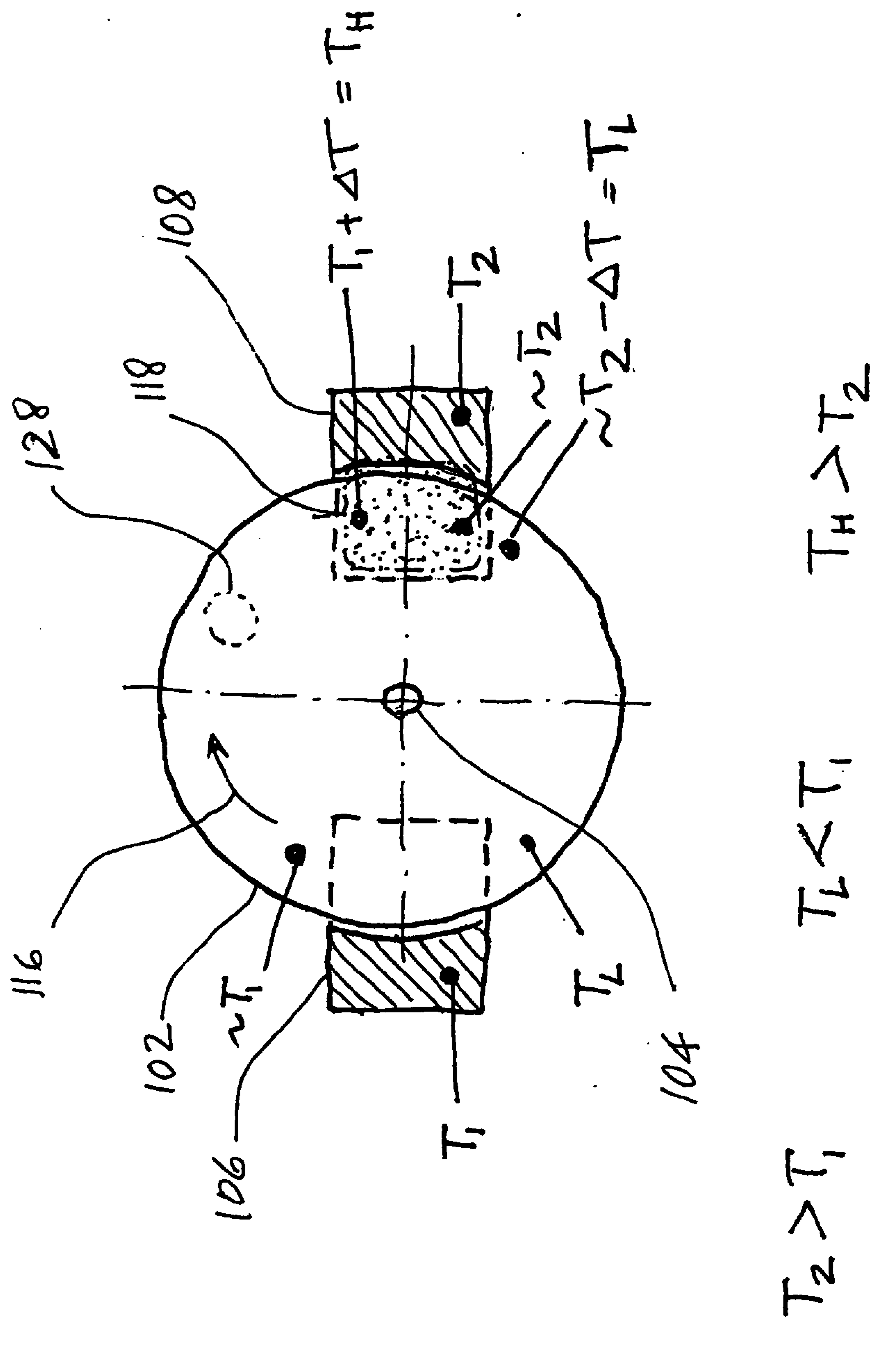

128
118
108
$T_1 + \Delta T = T_H$
T_2
$\sim T_2$
$\sim T_2 - \Delta T = T_L$
$T_H > T_2$
116
102
$\sim T_1$
106
T_1
T_L
104
$T_L < T_1$
$T_2 > T_1$

FIG. 7

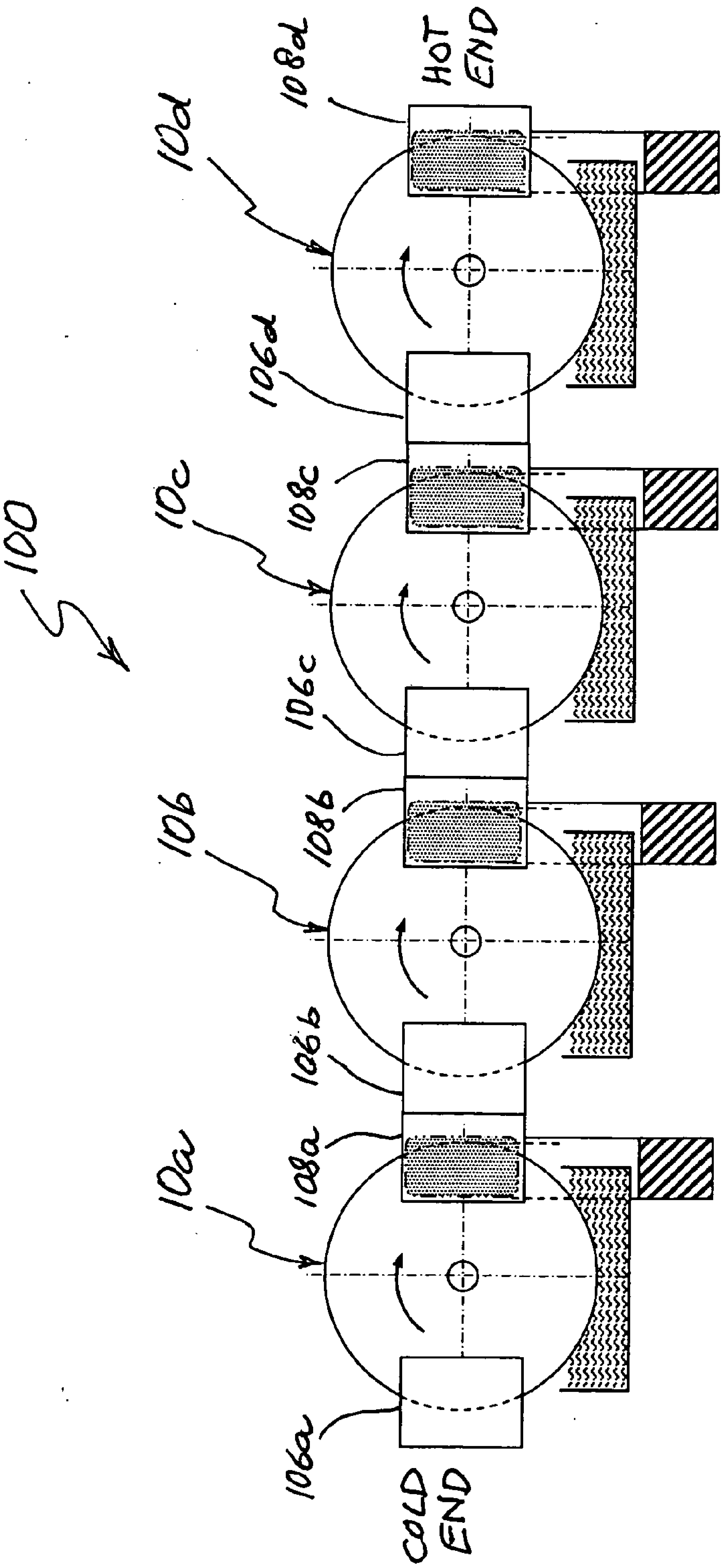

100
10a
10b
10c
10d
106a
106b
106c
106d
108a
108b
108c
108d
COLD END
HOT END

FIG. 8

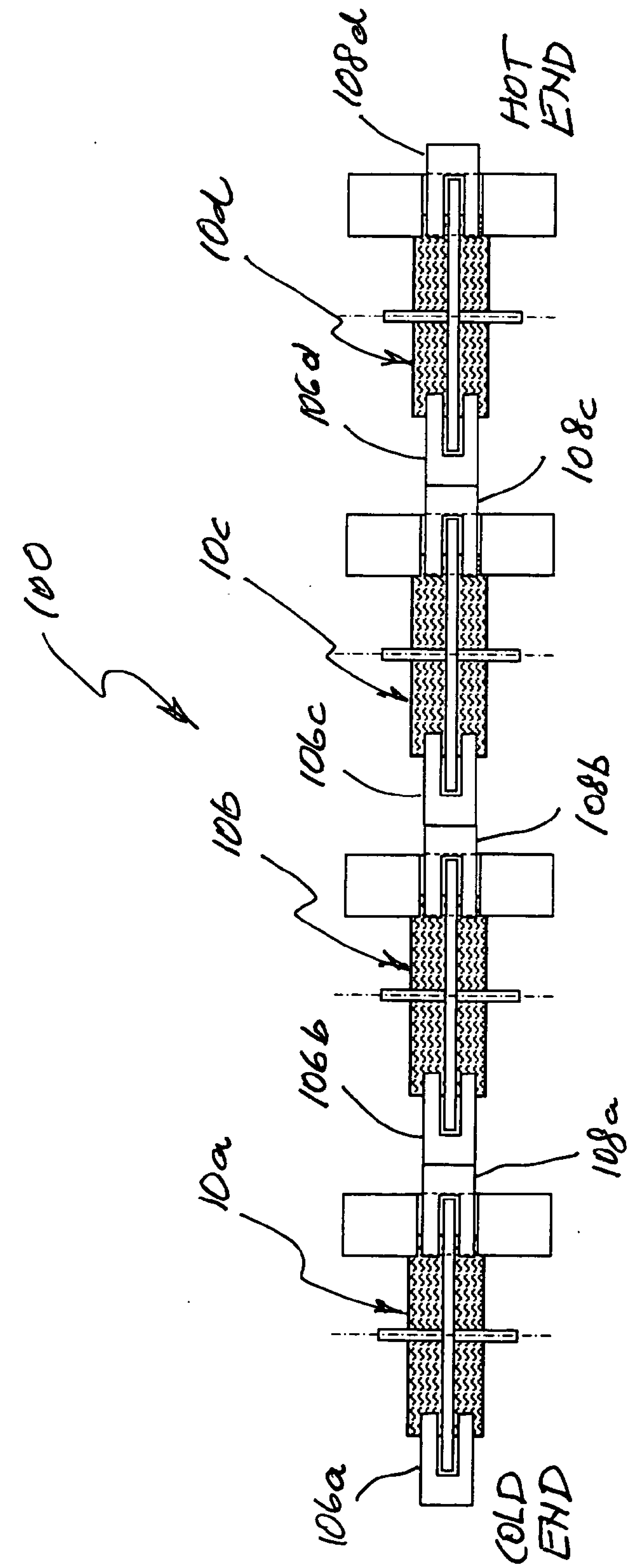

100
10a
10b
10c
10d
106a
106b
106c
106d
108a
108b
108c
108d
HOT END
COLD END

FIG. 9

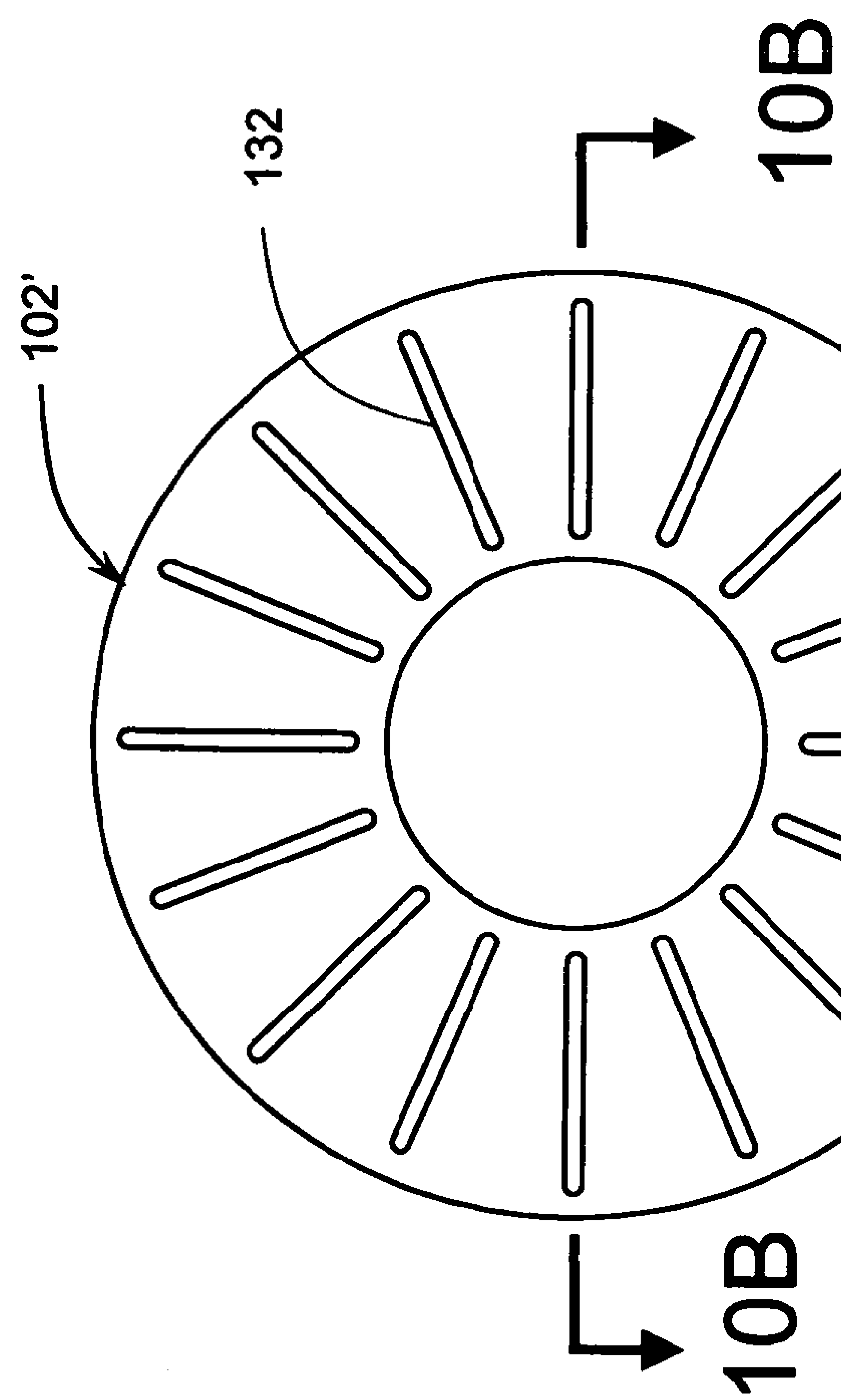


FIG. 10A

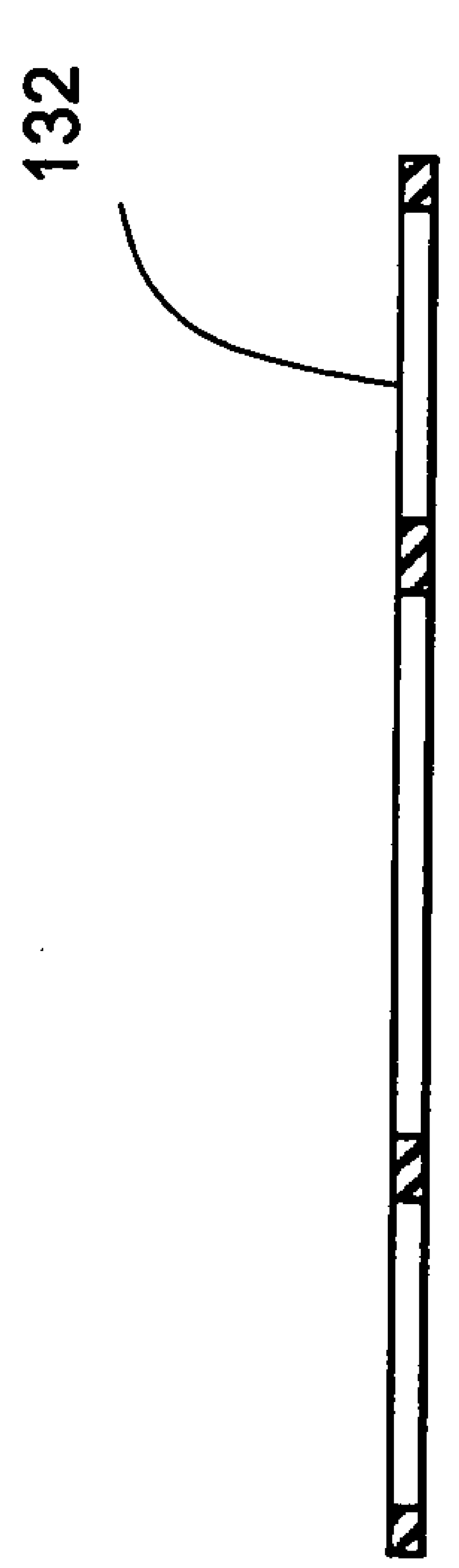


FIG. 10B

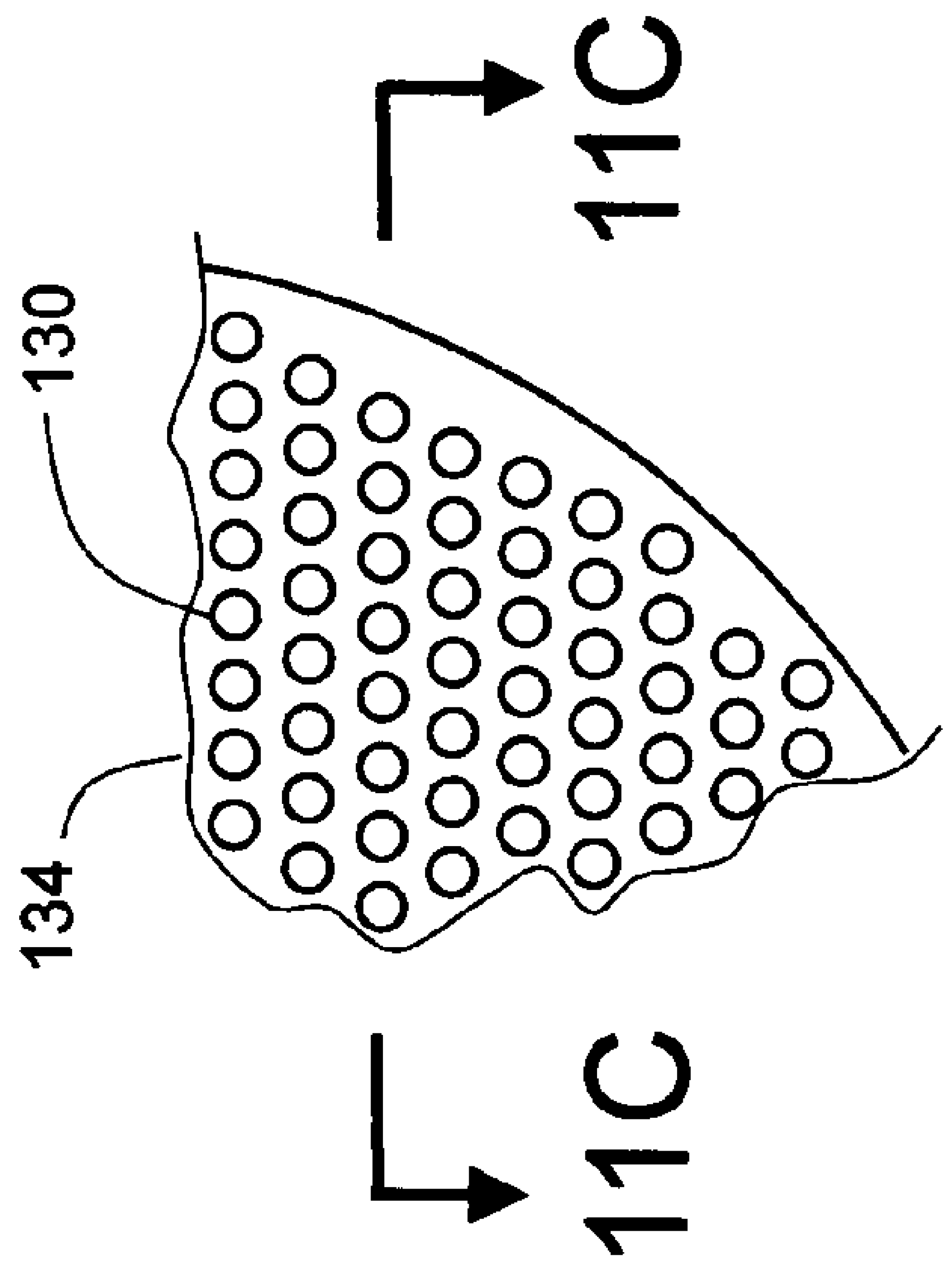


FIG. 11B

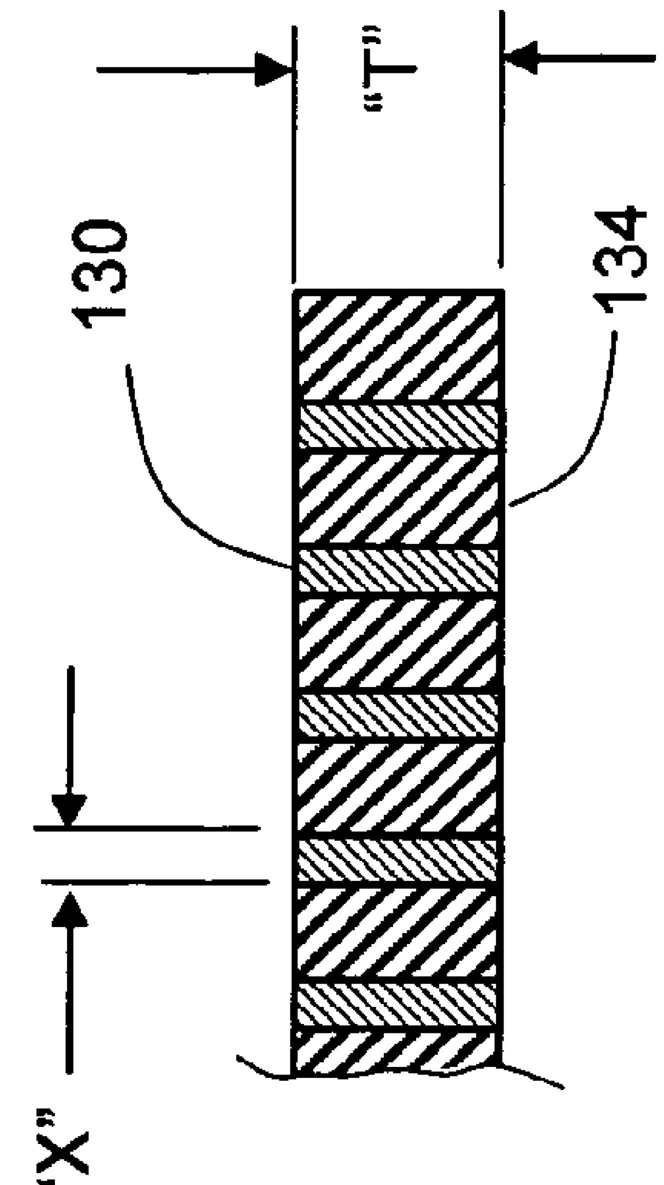


FIG. 11C

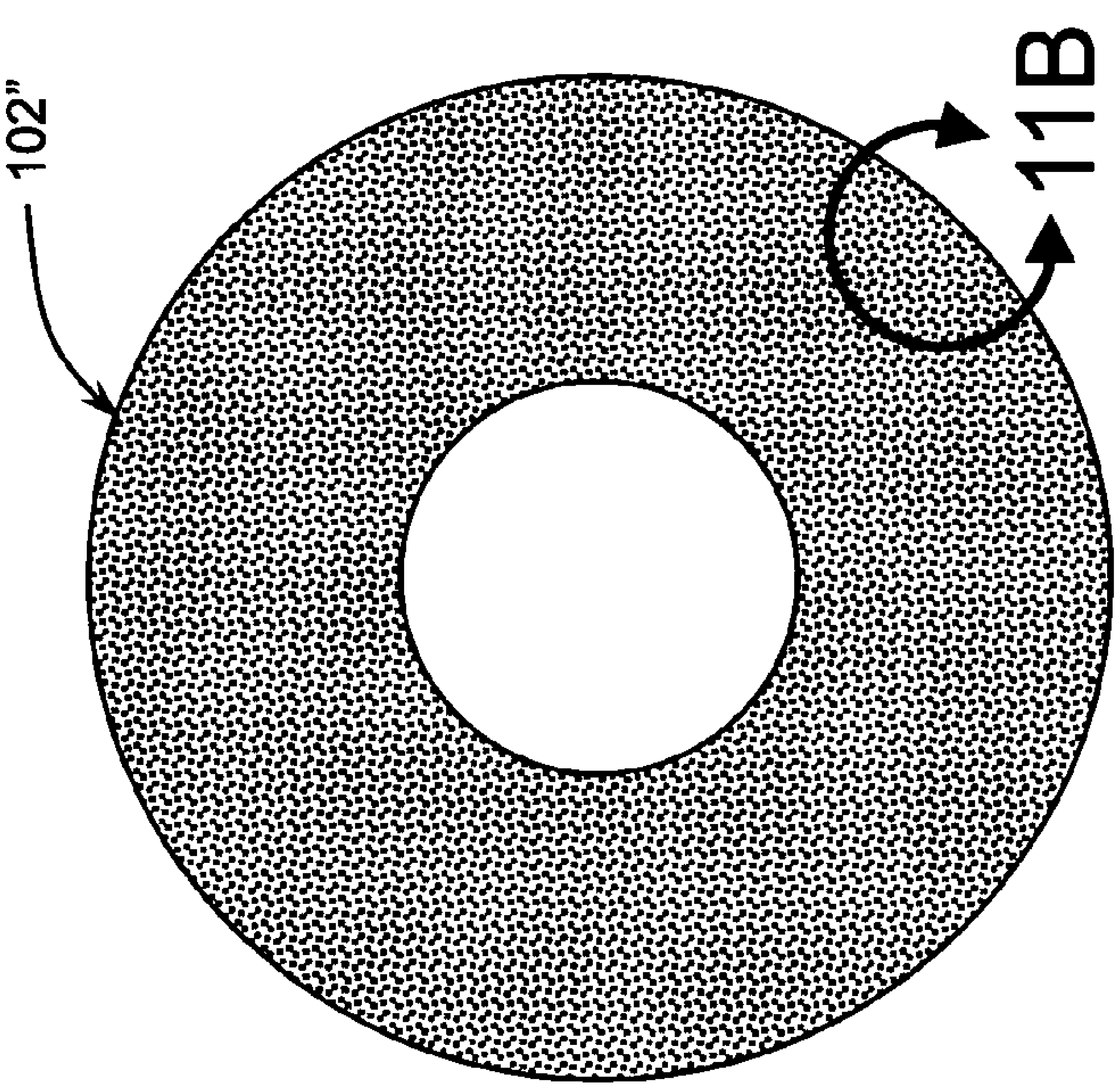


FIG. 11

MAGNETOCALORIC REFRIGERATOR

CROSS-REFERENCE TO RELATED APPLICATIONS:

[0001] This application claims priority from U.S. provisional patent application U.S. Ser. No. 61/397,246, filed on Jun. 7, 2010 and entitled "Magneto-Caloric Refrigerator" and from U.S. provisional patent application U.S. Ser. No. 61/397,175, filed on Jun. 7, 2010 and entitled "Staged Magneto-Caloric Refrigerator," the entire contents of all of which are hereby expressly incorporated by reference.

FIELD OF THE INVENTION

[0002] This invention relates generally to magnetocaloric machines and more specifically to heat pumps based on magnetocaloric effect.

BACKGROUND OF THE INVENTION

[0003] The subject invention is an apparatus and method for magneto-caloric refrigerator (MCR) offering improved energy efficiency, and reduced emissions of pollutants and greenhouse gases.

[0004] According to the U.S. Department of Energy, refrigeration and air conditioning in buildings, industry, and transportation may account for approximately 10^{19} joules of yearly primary energy consumption in the U.S.A. Air conditioning is also a major contributor to electric utility peak loads, which incur high generation costs while generally using inefficient and polluting generation turbines. In addition, peak loads due to air conditioning may be a major factor in poor grid reliability. Most of the conventional air conditioning, heat pumps, and refrigerators may achieve cooling through a mechanical vapor compression cycle. The thermodynamic efficiency of the vapor compression cycle is today much less than the theoretical maximum, yet dramatic future improvements in efficiency are unlikely. In addition, the hydrofluorocarbon refrigerants used by vapor compression cycle today are deemed to be strong contributors to the green house effect. Hence, there is a strong need for innovative approaches to cooling with high efficiencies and net-zero direct green house gas emissions.

[0005] The magneto-caloric effect (MCE) describes the conversion of a magnetically induced entropy change in a material to the evolution or absorption of heat, with a corresponding rise or decrease in temperature. In particular, MCE material may heat up when it is immersed in magnetic field and it may cool down when removed from the magnetic field, see FIG. **1**.

[0006] All magnetic materials, to a greater or lesser degree, may exhibit an MCE. However, some materials, by virtue of a unique electronic structure or physical nanostructure, may display a significantly enhanced MCE, which may potentially be harnessed for technological application. In contrast to the MCE found in paramagnetic materials, the large MCE exhibited by ferromagnetic materials near their magnetic phase transition temperature (also known as the Curie temperature or Currie point) may render them suitable as working materials for magnetic cooling at the target temperatures appropriate for commercial, industrial, and home refrigeration application and heat pump devices, namely 200 to 400 degrees Kelvin. For example, gadolinium (Gd) is a ferromagnetic material known to exhibit a significant MCE near its Curie point of about 293 degrees Kelvin. In recent years, a variety of other MCE materials potentially suitable for operation at near room temperature have been discovered. See, for example, "Chapter 4: Magnetocaloric Refrigeration at Ambient Temperature," by Ekkes Bruck in "Handbook of Magnetic Materials," edited by K. H. J. Buschow, published by Elsevier B.V., Amsterdam, Netherlands, in 2008.

[0007] One of the very promising novel MCE materials is the intermetallic compound series based on the composition $Gd_5(Si_xGe_{1-x})_4$, where $0.1 \leqq x1 \leqq 0.5$, disclosed by K. A. Gschneider and V. K. Pecharsky in U.S. Pat. No., 5,743,095 issued on Apr. 28, 1998 and entitled "Active Magnetic Refrigerants based on Gd—Si—Ge Materials and Refrigeration Apparatus and Process," which is hereby incorporated by reference in its entirety. See also and article by V. K. Pecharsky and K. A. Gschneider, "Tunable Magnetic Refrigerator Alloys with a Giant Magnetocaloric Effect for Magnetic Refrigeration from ~20 to ~290K," published in Applied Physics Letters, volume 70, Jun. 16, 1997, starting on page 3299. MCE produced by this family of compounds, also referred to as GdSiGe, has been labeled as "giant" because of its relatively large magnitude (reported as 4 to 6 degrees C. per Tesla of magnetic flux density). In particular, the MCE of the GdSiGe alloys may be reversible. Another noteworthy characteristic of the GdSiGe family is that the Curie temperature, may be tuned with compositional variation. This feature allows the working temperature of the magnetic refrigerator to vary from 30 degrees Kelvin to 276 degrees Kelvin, and possibly higher, by adjusting the Si:Ge ratio. For the purpose of this disclosure, an MCE material is defined as a suitable material exhibiting a significant MCE.

[0008] A magneto-caloric refrigerator (MCR) is a refrigerator based on MCE. MCR offers a relatively simple and robust alternative to traditional vapor-compression cycle refrigeration systems. MCR devices may have reduced mechanical vibrations, compact size, and lightweight. In addition, the theoretical thermodynamic efficiency of MCR may be much higher than for a vapor compression cycle and it may approach the Carnot efficiency. An MCR may employ an MCE material (sometimes referred to as a magnetic refrigerant working material) that may act as both as a "coolant" producing refrigeration and a "regenerator" heating a suitable heat transfer fluid. When the MCE material is subjected to strong magnetic field, its magnetic entropy may be reduced, and the energy released in the process may heat the material. With the MCE material in magnetized condition, a first stream of heat transfer fluid directed into a thermal contact with the MCE material may be warmed in the process and the heat may be carried away by the flow. When substantial portion of the heat is removed from the MCE material, the fluid flow may be terminated. As the next step, the magnetic field may be reduced, which may cause an increase in magnetic entropy. As a result, the MCE material may cool. A second stream of heat transfer fluid may be directed into a thermal contact with the MCE material where may deposit some of its heat and it may be cooled in the process. When substantial portion of the heat is deposited into the MCE material, the fluid flow may be terminated. Repeating the above steps may result in a semi-continuous operation. One disadvantage of such an MCR is the need for multiple flow loops typically involving pumps, heat exchangers, and significant plumbing.

[0009] Despite the apparent conceptual simplicity, there are significant challenges to the development of a practical MCR suitable for commercial applications. This is in-part due to the relatively modest temperature changes (typically few degrees Kelvin per Tesla of magnetic flux density) of the MCE material undergoing MCE transition. In addition, at present time the magnetic field produced by permanent magnets is limited to about 1.5 Tesla maximum. As a result, an MCR using permanent magnets and a single step MCE process may produce only a few degrees Kelvin temperature differential. Many important practical applications such as commercial refrigeration and air conditioning may require substantially higher temperature differentials, typically 30 degrees Kelvin and higher.

[0010] One approach to achieving commercially desirable temperature differentials from MCR may use multiple MCR stages (also known as cascades). Heat flow between stages may be managed by heat switches. Each stage contains a suitable MCE material undergoing magnetocaloric transition at a slightly different temperature. While the temperature differential achieved by one stage may be only a few degrees Kelvin, the aggregate operation of multiple stages may produce very large temperature differentials. See, for example, "Thermodynamics of Magnetic Refrigeration" by A. Kitanovski, P. W. Egolf, in International Journal of Refrigeration, volume 29 pages 3-21 published in 2006 by Elsevier Ltd., the entire contents of which are hereby expressly incorporated by reference.

[0011] A variety of heat switching approaches have been proposed but none has won commercial acceptance. For example, Ghoshal, in U.S. Pat. No., 6,588,216 entitled "Apparatus and methods for performing switching in magnetic refrigeration systems," issued on Jul. 8, 2003, and incorporated herein by reference in its entirety, discloses switching of thermal path between MCR stages by mechanical means using micro-electro-mechanical systems (MEMS), and/or electronic means using thermoelectric elements. Ghoshal's thermal path switching by MEMS is inherently limited by the poor thermal conductivity of bare mechanical contacts. Ghoshal's thermoelectric switches have very limited thermodynamic efficiency which substantially increases the heat load to the MCR and reduces the overall MCR efficiency.

[0012] In summary, there is a need for 1) reducing or eliminating moving parts and pumped fluid loops in MCR systems, 2) simpler and more reliable MCR operation, and 3) means for attaining commercially desirable temperature differentials from MCR. A specific need exists for reliable, low-thermal resistance means for switching of the heat flow to and from the MCE material in staged (cascaded) MCR.

SUMMARY OF THE INVENTION

[0013] The present invention provides a magnetocaloric refrigerator (MCR) having one or more stages. An MCR stage in accordance with the subject invention comprises a body made of a suitable magnetocaloric effect (MCE) material positioned in proximity of a first thermal conductor and in proximity of a second thermal conductor with only small gaps therebetween. The gaps between the MCE material and the thermal conductors may be filled with a suitable thermal interface fluid (TIF) having acceptably high thermal conductivity. TIF may significantly enhance thermal communication between the MCE material and the thermal conductors. The MCE material may be arranged to be in relative motion with respect to the thermal conductors, which may cause the TIF layer in the gaps between MCE material and the thermal conductors to flow in a regime known as a shear flow and also known as a Couette flow. TIF flowing in a shear flow regime may further significantly enhance thermal communication between the MCE material and the thermal conductors. The relative motion of the MCE material may cause the MCE material to be alternately exposed to regions of strong magnetic field and weak magnetic field. A portion of MCE material exposed to a weak magnetic field may become cooler. The portion of MCE material in a cooler state may be arranged to be in a good thermal communication through the TIF with the first thermal conductor and it may receive heat from it. A portion of MCE material exposed to a strong magnetic field may become warmer. The portion of MCE material in a warmer state may be arranged to be in a good thermal communication through the TIF with the second thermal conductor and it may transfer heat to it. As a result, the inventive MCR stage may transfer heat from the first thermal conductor to the second thermal conductor against a temperature gradient and, therefore, it may act as a heat pump. The inventive MCR stages may be thermally connected in series to produce higher temperature differential than possible in a single MCR stage.

[0014] For the purposes of this disclosure, the term "strong magnetic field" is defined as a magnetic field having an absolute value of magnetic flux density of at least 0.5 Tesla (5,000 Gauss), and the term "weak magnetic field" is defined as a magnetic field having an absolute value of magnetic flux density of at least 0.1 Tesla (1,000 Gauss) lower than the "strong magnetic field" flux density. In particular, the range of weak magnetic field may include magnetic flux density of essentially zero (0) Tesla (i.e., no field).

[0015] The thermal interface fluid (TIF) is a key material for facilitating efficient heat transfer between MCE material and thermal conductors in the MCR stage of the subject invention. For the purpose of this disclosure, TIF may be a liquid or a paste. Preferably, suitable TIF has a good thermal conductivity, surface wetting capability, lubrication properties, low melting point, acceptably low viscosity, low or no toxicity, and low cost. The inventor has determined that TIF should preferably have a thermal conductivity of at least as 1 W/m-degree K and most preferably at least 3 W/m-degree K. In some embodiments of the invention the TIF may be a liquid metal. Suitable liquid metal may be an alloy of gallium (Ga) such as a non-toxic eutectic ternary alloy known as galinstan and disclosed in the U.S. Pat. No. 5,800,060. Galinstan (68.5% gallium, 21.5% indium, and 10% tin) is reported to have thermal conductivity of about 16 W/m-degree K (about 27 times higher than water), a melting point of minus 19 degrees Centigrade, low viscosity, and excellent wetting properties. Brandeburg et al. in the U.S. Pat. No. 7,726,972 discloses a quaternary gallium alloy having a melting point of minus 36 degrees Centigrade, which may be also suitable for use with the subject invention. Other suitable gallium alloys may include those disclosed in the U.S. Pat. No. 5,792,236.

[0016] Other suitable variants of the TIF may also comprise a fluid containing nanometer-sized particles (nanoparticles) also known as nanofluid. Nanofluids are engineered colloidal suspensions of nanoparticles in a base fluid. The nanoparticles used in nanofluids may be typically made of metals, oxides, carbides, carbon, graphite, graphene, graphite nanotubes, or carbon nanotubes. Common base fluids may include water, alcohol, and ethylene glycol. Nanofluids may exhibit enhanced thermal conductivity and enhanced convective heat transfer coefficient compared to the base fluid alone. In yet other embodiments of the invention the TIF may not be strictly a fluid but rather a paste comprising mainly of microscale and/or nano-scale particles made of high thermal conductivity materials such as silver, copper, or graphite in suitable base liquid or paste.

[0017] In one preferred embodiment of the present invention, the MCR stage comprises an MCE disk, a first thermal conductor, a second thermal conductor, and a magnet assembly. The MCE disk further comprises a suitable MCE material. The MCE disk is arranged to rotate about its axis of rotational symmetry. The magnet assembly is arranged to produce a region of strong magnetic field. A portion of the MCE material of the MCE disk may be exposed to a strong magnetic field while another portion of the MCE material of the MCE disk may be exposed to a weak magnetic field. The first thermal conductor is arranged to be in close proximity of the portion of the MCE material exposed to weak magnetic field with only a small gap therebetween. The second thermal conductor is arranged in close proximity of the portion of the MCE material exposed to strong magnetic field with only a small gap therebetween. A portion of the MCE disk may be submerged in a suitable TIF. The TIF is selected to provide good wetting of the disk surface. When the disk is rotated about its axis, some of the TIF is entrained by the disk surface and carried into the gap between the MCE disk the first thermal conductor, thereby establishing a good thermal communication therebetween. In a similar fashion, some of the TIF entrained by the MCE disk surface is also carried into the gap between the MCE disk the second thermal conductor, thereby establishing a good thermal communication therebetween.

[0018] When a specific portion of the MCE material is rotated into the region of strong magnetic field and exposed to the strong magnetic field, the entropy of the specific portion may be reduced and the temperature of the material of the specific portion may be increased to a temperature higher than the temperature of the second thermal conductor. This may establish a thermal gradient which may transport heat from the specific portion of the MCE material through the TIF into the second thermal conductor. As a result, the specific portion of the MCE material may cool down toward the temperature of the second thermal conductor.

[0019] When the specific portion of the MCE material is subsequently rotated out of the region of strong magnetic field and it is exposed to a weak magnetic field, the entropy of the specific portion of the MCE material may be increased. This may cause reduction in temperature of the specific portion to a temperature that may be lower than the temperature of the first thermal conductor. Further rotation of the MCE disk may deliver the specific portion of the MCE material into proximity of the first thermal conductor. The temperature gradient between the first thermal conductor and the specific portion of the MCE material may transport heat from the first thermal conductor through the TIF into the specific portion of the MCE material portion. This process may cause the temperature of the specific portion to rise toward the temperature of the first thermal conductor. Yet further rotation of the disk may bring the specific portion of the MCE material back into the region of the strong magnetic field, and the whole cycle may be repeated again. As a result, heat is transported (pumped) from the first thermal conductor to the second thermal conductor against a thermal gradient that may exist between the two thermal conductors.

[0020] The MCR stages can be thermally connected in series into an MCR assembly by connecting the second thermal conductor of the first stage to the first thermal conductor of the second stage, the second thermal conductor of the second stage to the first thermal conductor of the third stage, the second thermal conductor of the third stage to the first thermal conductor of the fourth stage, and so on. In this fashion the inventive MCR assembly can produce much higher temperature differential than possible in a single MCR stage.

[0021] Accordingly, it is an object of the present invention to provide an MCR that is relatively simple and robust alternative to traditional vapor-compression cycle refrigeration systems, while attaining comparable or even higher thermodynamic efficiency.

[0022] It is another object of the invention to provide an MCR for general refrigeration and air conditioning while improving energy efficiency and reducing emissions of pollutants and greenhouse gases.

[0023] It is yet another object of the invention to provide an MCR having one or more stages to achieve commercially useful temperature differentials.

[0024] It is still another object of the subject invention to provide an MCR having low mechanical vibrations, compact size, and lightweight coupled with a thermodynamic efficiency exceeding that of thermo-electric coolers.

[0025] It is a further object of the subject invention to provide efficient switching of heat to and from an MCE material.

[0026] These and other objects of the present invention will become apparent upon a reading of the following specification and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] FIG. **1** is an illustration of the magneto-caloric effect.

[0028] FIG. **2** is a partial side cross-sectional side view of an MCR stage in accordance with one embodiment of the subject invention.

[0029] FIG. **3** is a plan view of an MCR stage in accordance with one embodiment of the subject invention.

[0030] FIG. **4** is a view **4-4** of an MCR stage of FIG. **2**.

[0031] FIG. **5** is an enlarged view of portion **5** of the MCR stage of FIG. **3** showing the relative arrangement of the disk and the thermal conductor.

[0032] FIG. **6** is an exemplary arrangement of the magnet assembly.

[0033] FIG. **7** is an illustration of the MCR operation showing exemplary temperatures.

[0034] FIG. **8** is a side cross-sectional side view of an MCR assembly with four MCR stages.

[0035] FIG. **9** is a plan view of the MCR assembly with four MCR stages of FIG. **8**.

[0036] FIG. **10**A is a view of an alternative MCE ring for reduced parasitic heat flow in azimuthal direction.

[0037] FIG. **10**B is a cross-sectional view **10**B-**10**B of the alternative MCE ring of FIG. **10**A.

[0038] FIG. **11**A is a view of another alternative MCE disk having portions made of material having high thermal conductivity.

[0039] FIG. **11**B is an enlarged view of portion **11**B of the another alternative MCE ring of FIG. **11**A.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0040] Selected embodiments of the present invention will now be explained with reference to drawings. In the drawings, identical components are provided with identical reference symbols in one or more of the figures. It will be apparent to those skilled in the art from this disclosure that the following descriptions of the embodiments of the present invention are merely exemplary in nature and are in no way intended to limit the invention, its application, or uses.

[0041] Referring now to FIGS. **2**, **3**, **4** and **5**, there is shown an MCR stage **10** in accordance with one preferred embodiment of the present invention. The MCR stage **10** comprises an MCE disk **102**, a first thermal conductor **106**, a second thermal conductor **108**, a reservoir **114**, thermal interface fluid (TIF) **110**, and a magnet assembly **112**. The MCE disk **102** further comprises a suitable MCE material. For example, the MCE disk **102** may be made in its entirety from a suitable MCE material. Alternatively, only selected portions of the MCE disk (for example, the perimetral portion) may be made from MCE material. Suitable MCE materials include but are not limited to gadolinium (Gd) and a family of gadolinium-silicon-germanium (GdSiGe) alloys disclosed in the above noted U.S. Pat. No. 5,743,095.

[0042] The MCE disk **102** is rotatably mounted on a shaft **104** having an axis of rotation **103**. The magnet assembly **112** is configured to produce strong magnetic field in a region **118** overlapping a portion of the MCE disk **102**. The MCE disk **102** is constructed and arranged so that at any given time, a portion of the disk MCE material is immersed in the strong magnetic field of the region **118** while other portion of the MCE disk **102** is immersed in a weak magnetic field outside the region **118**. The magnet assembly **112** may further comprise permanent magnets **122**, a yoke **126** made of soft magnetic material, and flux focusing pole pieces **124** as shown in FIG. **6**. The permanent magnets **122** are preferably of the rare earth type such as neodymium-iron-boron (NdFeB), most preferably having a remanent field in excess of 1.4 Tesla. However, the invention may be practiced with alternative magnets. The yoke **126** and flux focusing pole pieces **124** are preferably made of soft magnetic material having a high magnetic saturation such as, but not limited to, mild steel, low carbon steel, silicon steel, iron, iron-cobalt-vanadium alloys, Consumet® electrical iron, and Hyperco® 50. Consumet® electrical iron and Hyperco® 50 are available from Carpenter Technology Corporation in Wyomissing, Pa.

[0043] The reservoir **114** contains suitable TIF **110**. The reservoir **114** is arranged so that a portion of the MCE disk **102** is immersed in and wetted by the TIF **110** within the reservoir. TIF **110** is selected to provide good wetting of the disk surface material. If TIF **110** comprises gallium, the MCE disk and the thermal conductors may require protective coating to prevent corrosion. Suitable protective coatings may include but they are not limited to titanium nitride (TiN) and the diamond-like coating (DLC) Titankote C11 available from Richter Precision, Inc. in East Petersburg, Pa.

[0044] The first thermal conductor **106** is arranged to be in close proximity of the portion of MCE disk **102** exposed to a weak magnetic field outside the region **118**. The second thermal conductor **108** is arranged to be in close proximity of the disk portion exposed to strong magnetic field in the region **118**. Preferably, only a small gap **120** exists between the MCE disk **102** and the thermal conductors **106** and **108**. FIG. **5** shows an enlarged view of the gap **120** between the MCE disk **102** and the second thermal conductor **108**. Preferably, the gap **120** should be between about 50 and about 500 micrometers wide. The gap **120** is filled with TIF **110**. The TIF **110** is selected to have a good thermal conductivity (compared to the MCE material) to facilitate a good thermal communication path between the disk **102** and the thermal conductors **106** and **108**. The thermal conductors **106** and **108** are preferably made of material having high thermal conductivity. Suitable materials for the thermal conductors **106** and **108** may include but are not limited to copper, aluminum, tungsten, silicon, silicon carbide, aluminum nitride, and beryllium oxide.

[0045] In operation, the MCE disk **102** is arranged to rotate on the shaft **104** about its axis **103** in the direction of the arrow **116** (FIG. **2**) so that at any given time a portion of the MCE material of the MCE disk **102** is exposed to a strong magnetic field in the region **118** while another portion of the MCE material of the MCE disk **102** is exposed to a weak magnetic field. In particular, a specific portion **128** of the MCE material of the MCE disk **102** may rotate into and out of the region **118** of strong magnetic field. Therefore, the specific portion **128** of the MCE material of the disk **102** is alternately exposed to the strong magnetic field in the region **118** and weak magnetic field outside the region **118**.

[0046] As the MCE disk **102** is rotated in the direction of arrow **116** (FIG. **2**), some of the TIF **110** in the reservoir **114** is entrained by the disk surface. Entrained TIF **110** is carried into the gap **120** between the MCE disk **102** the first thermal conductor **106**, thereby establishing a good thermal communication therebetween. In a similar fashion, some of the TIF **110** entrained by the disk surface is also carried into the gap **120** between the disk **102** the second thermal conductor **108**, thereby establishing a good thermal communication therebetween.

[0047] When the specific portion **128** of the MCE material of the MCE disk **102** is rotated in the direction of the arrow **116** into the region **118** of strong magnetic field and exposed to the strong magnetic field, the entropy of the MCE material portion may be reduced. As a consequence, the temperature of the material may be increased to a temperature higher than the temperature of the second thermal conductor **108**. The resulting thermal gradient may transport heat from the specific portion **128** of the MCE material through the TIF **110** in the gap **120** into the second thermal conductor **108**. Consequently, the specific portion **128** of the MCE material may cool down toward the temperature of the second thermal conductor **108**. As the specific portion **128** of the MCE material is subsequently rotated in the direction of arrow **116** out of the region **118** of strong magnetic field, it is becoming exposed to a weak magnetic field. Thus, the entropy of the specific portion **128** of the MCE material may be increased. As a consequence, the temperature of the specific portion **128** of the MCE material may be decreased to a temperature lower than the temperature of the first thermal conductor **106**. Further rotation of the disk **102** in the direction of arrow **116** delivers the specific portion **128** of the MCE material into proximity of the first thermal conductor **106**. The temperature gradient between the first thermal conductor **106** and the specific portion **128** of the MCE material may transport heat from the first thermal conductor **106** through the TIF **110** in the gap **120** into the specific portion **128** of the MCE material. As a result, the temperature of the specific portion **128** may rise toward the temperature of the first thermal conductor **106**. Yet further rotation of the disk **102** in the direction of arrow **116** brings the specific portion **128** of the MCE material back into the region **118** of the strong magnetic field, and the whole process may be repeated again. As a result, heat may be transported (pumped) from the first thermal conductor **106** to the second thermal conductor **108** against a thermal gradient that may exist between the two thermal conductors.

[0048] FIG. **7** shows exemplary relative temperatures that may exists in various portions of the disk **102** and the thermal conductors **106** and **108** during the operation of the MCR stage **10**. The thermal conductors **106** and **108** may be thermally coupled to heat reservoirs having temperatures T_1 and T_2, respectively. With the MCE disk **102** rotating in the direction of the arrow **116**, a specific portion **128** of the MCE material may terminate its thermal communication with the first thermal conductor **106** and it may have a temperature approximately equal to the temperature T_1. When the specific portion **128** enters the region **118**, its temperature may increase to the temperature about $T_H=T_1+\Delta T$, where the temperature increase ΔT is due to MCE. The temperature T_H is arranged to be higher than the temperature T_2 (namely, $T_H>T_2$). For example, T_H may be increased by increasing the strength of the magnetic field in the region **118** and/or by choosing an MCE material having a strong MCE. In addition, the temperatures T_1 and T_2 may be selected so that $\Delta T>T_2-T_1$. Therefore, heat may flow from the portion **128** into the thermal conductor **108** (through TIF **110** in the gap **120**) and the temperature of the portion **128** may be reduced toward the temperature T_2. For example, the temperature of the portion **128** may arranged to be approximately equal to the temperature T_2. When the portion **128** further rotates in the direction of the arrow **116** out of the region **118**, its temperature may decrease due to MCE to about $T_L=T_2-\Delta T$. The portion **128** is subsequently rotated in the direction of the arrow **116** into a thermal communication with the thermal conductor **106**. Because T_L is arranged to be smaller than T_1, (namely, $T_L<T_1$), heat may flow from the first thermal conductor **106** into the specific portion **128** and the temperature of specific portion **128** may rise toward the temperature T_1. For example, the temperature of the portion **128** may arranged to be approximately equal to the temperature $T1_2$. The specific portion **128** is now rotated further in the direction of arrow **116**, and the cycle may be repeated.

[0049] Multiple MCR stages **10** may be thermally connected in series. FIGS. **8** and **9** show an MCR assembly **100** having four (4) MCR stages. In particular, the MCR assembly **100** is constructed by thermally connecting MCR stages **10*a***, **10*b***, **10*c***, and **10*d***. More specifically, the second thermal conductor **108*a*** of the first stage **10*a*** is thermally coupled to the first thermal conductor **106*b*** of the second stage **10*b***, the second thermal conductor **108*b*** of the second stage **10*b*** to the first thermal conductor **106*c*** of the third stage **10*c***, the second thermal conductor **108*c*** of the third stage **10*c*** to the first thermal conductor **106*d*** of the fourth stage **10*d***. Additional stages may be added in a similar fashion to obtain desired temperature differential between the cold and hot ends. In this fashion the inventive MCR assembly can produce higher temperature differential than possible in a single MCR stage.

[0050] Heat conduction in the azimuthal direction within the MCE disk may be undesirable because it may reduce the efficiency of the MCR stage **10**. FIG. **10**A shows an alternative MCE disk **102'** having radial slots **132** for restricting parasitic flow of heat in azimuthal direction. The slots **132** may be empty or filled with a suitable thermally insulating material. FIG. **10**B is a cross-sectional view of the MCE disk **102'** showing that the slots **132** may penetrate through the full thickness of the MCE ring material. An alternative slots (not shown) may not be necessarily radial and/or may not necessarily penetrate through the full thickness of the MCE ring material.

[0051] MCE materials may have only a limited thermal conductivity generally in the range of about 10 Watts/meter-degree Kelvin and often lower. This makes it challenging to conduct heat to and from the interior of the MCE disk **102**. FIG. **11**A shows another alternative MCE disk **102"** having portions **134** made of suitable MCE material and portions **130** (FIGS. **11**B and **11**C) made of material having high thermal conductivity. For example, portions **130** may be made of copper, silver, aluminum, graphite, graphite fiber, graphene, or other suitable material. The transverse dimension "X" of portions **130** is preferably made comparable to or smaller than the thickness "T" of the MCE disk **102"**. Portions **130** may be formed as a cylinder, prism, parallel-piped, cones, or pyramids, or other suitable shapes. Portions **130** may enhance the conductive heat transfer between the interior of the MCE material of the MCE disk **102"** and the flat surfaces of the MCE disk **102"**, thus mitigating the limited thermal conductivity of typical MCE materials. This may beneficially allow for a substantial increase of the thickness "T" of the MCE disk **102"**, and/or substantial increase of the speed of rotation of the MCE disk **102"**. In either case, an increased refrigeration power may be obtained.

[0052] The above description of the embodiments of the present invention are merely exemplary in nature and are in no way intended to limit the invention, its application, or uses. For example, other embodiments of the invention may use linearly moving strips or plates of MCE material rather than rotating rings. Suitable linear motion may be continuous or reciprocating. As another example, yet other embodiments of the invention may use electromagnets or superconducting magnets instead (or in a combination with) permanent magnets.

[0053] The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," and "includes" and/or "including" when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

[0054] The terms of degree such as "substantially", "about" and "approximately" as used herein mean a reasonable amount of deviation of the modified term such that the end result is not significantly changed. For example, these terms can be construed as including a deviation of at least ±5% of the modified term if this deviation would not negate the meaning of the word it modifies.

[0055] The term "suitable," as used herein, means having characteristics that are sufficient to produce a desired result. Suitability for the intended purpose can be determined by one of ordinary skill in the art using only routine experimentation.

[0056] Moreover, terms that are expressed as "means-plus function" in the claims should include any structure that can be utilized to carry out the function of that part of the present invention. In addition, the term "configured" as used herein to describe a component, section or part of a device includes hardware and/or software that is constructed and/or programmed to carry out the desired function.

[0057] Different aspects of the invention may be combined in any suitable way.

[0058] While only selected embodiments have been chosen to illustrate the present invention, it will be apparent to those skilled in the art from this disclosure that various changes and modifications can be made herein without departing from the scope of the present invention as defined in the appended claims. Furthermore, the foregoing description of the embodiments according to the present invention are provided for illustration only, and not for the purpose of limiting the present invention as defined by the appended claims and their equivalents. Thus, the scope of the present invention is not limited to the disclosed embodiments.

What is claimed is:

1. An apparatus for transferring heat from a cooler reservoir to a warmer reservoir while expending mechanical energy in the process; said apparatus comprising a member made of magnetocaloric effect (MCE) material, a first thermal conductor, a second thermal conductor, a means for producing a region of strong magnetic field and a region of weak magnetic field, and a thermal interface fluid (TIF); said first thermal conductor being arranged to be in a good thermal communication by means of said TIF with a portion of said MCE material when said portion of said MCE material is immersed in said weak magnetic field; and said second thermal conductor being arranged to be in a good thermal communication by means of said TIF with a portion of said MCE material when said portion of said MCE material is immersed in said strong magnetic field.

2. The apparatus of claim **1**, wherein said first thermal conductor and said member are arranged to form a first gap therebetween and said first gap is substantially filled with said TIF; and said second thermal conductor and said member are arranged to form a second gap therebetween and said second gap is substantially filled with said TIF.

3. The apparatus of claim **2**, wherein the width of said first gap and said second gap are each chosen to be between about 50 micrometers and 500 micrometers.

4. The apparatus of claim **2**, wherein said TIF is selected from the family consisting of liquid metal, gallium-based liquid metal alloy, gallium-indium-tin liquid metal alloy, gallium-indium-tin-zinc liquid metal alloy, nanofluid, and nanofluid substantially comprising carbon nanotubes.

5. The apparatus of claim **1**, wherein said member is arranged to be in motion relative to each said first thermal conductor and said second thermal conductor.

6. The apparatus of claim **5**, wherein said motion is causing said TIF to flow in a shear flow regime.

7. The apparatus of claim **5**, wherein said motion is causing a portion of said member to be cyclically exposed to said weak magnetic field and said strong magnetic field.

8. The apparatus of claim **1**, wherein said means for producing said region of strong magnetic field is selected from the family consisting of a permanent magnet, electromagnet, and superconducting coil.

9. A staged magnetocaloric refrigerator (MCR) comprising a plurality of MCR stages;

a) each said MCR stage comprising a member made of magnetocaloric effect (MCE) material, a first thermal conductor, a second thermal conductor, a means for producing a region of strong magnetic field and a region of weak magnetic field, and a thermal interface fluid (TIF);

b) within each said MCR stage, said first thermal conductor of that MCR stage being arranged to be in a good thermal communication by means of said TIF with a portion of said MCE material of that stage when said portion of said MCE material of that stage is immersed in a weak magnetic field;

c) within each said MCR stage, said second thermal conductor of that MCR stage being arranged to be in a good thermal communication by means of said TIF with a portion of said MCE material of that MCR stage when said portion of said MCE material of that MCR stage is immersed in a strong magnetic field;

d) the thermal conductor of the first MCR stage being thermally coupled to a lower heat reservoir;

e) for each subsequent said MCR stage, the first thermal conductor of that MCR stage being coupled to the second thermal conductor of the preceding MCR stage; and

f) said second thermal conductor of the last MCR stage being thermally coupled to an upper heat reservoir.

10. The staged MCR of claim **9**, wherein the temperature of said lower heat reservoir is substantially lower than the temperature of said upper heat reservoir.

11. The staged MCR of claim **9**, wherein within each said MCR stage said member of that MCR stage is arranged to be in motion relative to each said first thermal conductor of that MCR stage; and within each said MCR stage said member of that MCR stage is arranged to be in motion relative to each said second thermal conductor of that MCR stage.

12. The staged MCR of claim **11**, wherein said motion is causing said TIF to flow in a shear flow regime.

13. The staged MCR of claim **9**, wherein within each said MCR stage, said first thermal conductor of that MCR stage and said member of that MCR stage are arranged to form a first gap therebetween and said first gap is substantially filled with said TIF; and said second thermal conductor of that MCR stage and said member of that MCR stage are arranged to form a second gap therebetween and said second gap is substantially filled with said TIF.

14. The staged MCR of claim **13**, wherein the width of said first gap and said second gap are each chosen to be between about 50 micrometers and 500 micrometers.

15. The staged MCR of claim **9**, wherein said TIF is selected from the family consisting of liquid metal, gallium-based liquid metal alloy, gallium-indium-tin liquid metal alloy, gallium-indium-tin-zinc liquid metal alloy, nanofluid, and nanofluid substantially comprising carbon nanotubes.

16. A method for pumping heat comprising the steps of:

a) providing a magnetocaloric effect (MCE) material;

b) providing a first thermal conductor at a first temperature;

c) providing a second thermal conductor at a second temperature;

d) arranging said MCE material to be in close proximity of said first conductor with a first gap therebetween;

e) arranging said MCE material to be in close proximity of said second conductor with a second gap therebetween;

f) substantially filling said first gap and said second gap with a thermal interface fluid (TIF);

g) moving said MCE material with respect to said first thermal conductor;

h) moving said MCE material with respect to said second thermal conductor;

i) flowing said TIF in said first and said second gap in a shear flow regime;

j) exposing said MCE material to a weak magnetic field;

k) forming a good thermal communication between said MCE material and said first thermal conductor through said TIF;

l) exposing said MCE material to a strong magnetic field;

m) forming a good thermal communication between said MCE material and said second thermal conductor through said TIF.

17. The method of claim **16**, wherein said second temperature is higher than said first temperature.

18. The method of claim **16**, wherein said steps of (j) exposing said MCE material to a weak magnetic field and (k) forming a good thermal communication between said MCE material and said first thermal conductor through said TIF, are performed concurrently.

19. The method of claim **16**, wherein said steps of (l) exposing said MCE material to a strong magnetic field and (m) forming a good thermal communication between said MCE material and said second thermal conductor through said TIF, are performed concurrently.

20. The method of claim **16**, wherein said step of forming a good thermal communication between said MCE material and said first thermal conductor through said TIF further comprises flowing of heat from said first thermal conductor through said TIF to said MCE material.

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