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(54) **REGENERATIVE ELECTROCALORIC COOLING DEVICE**

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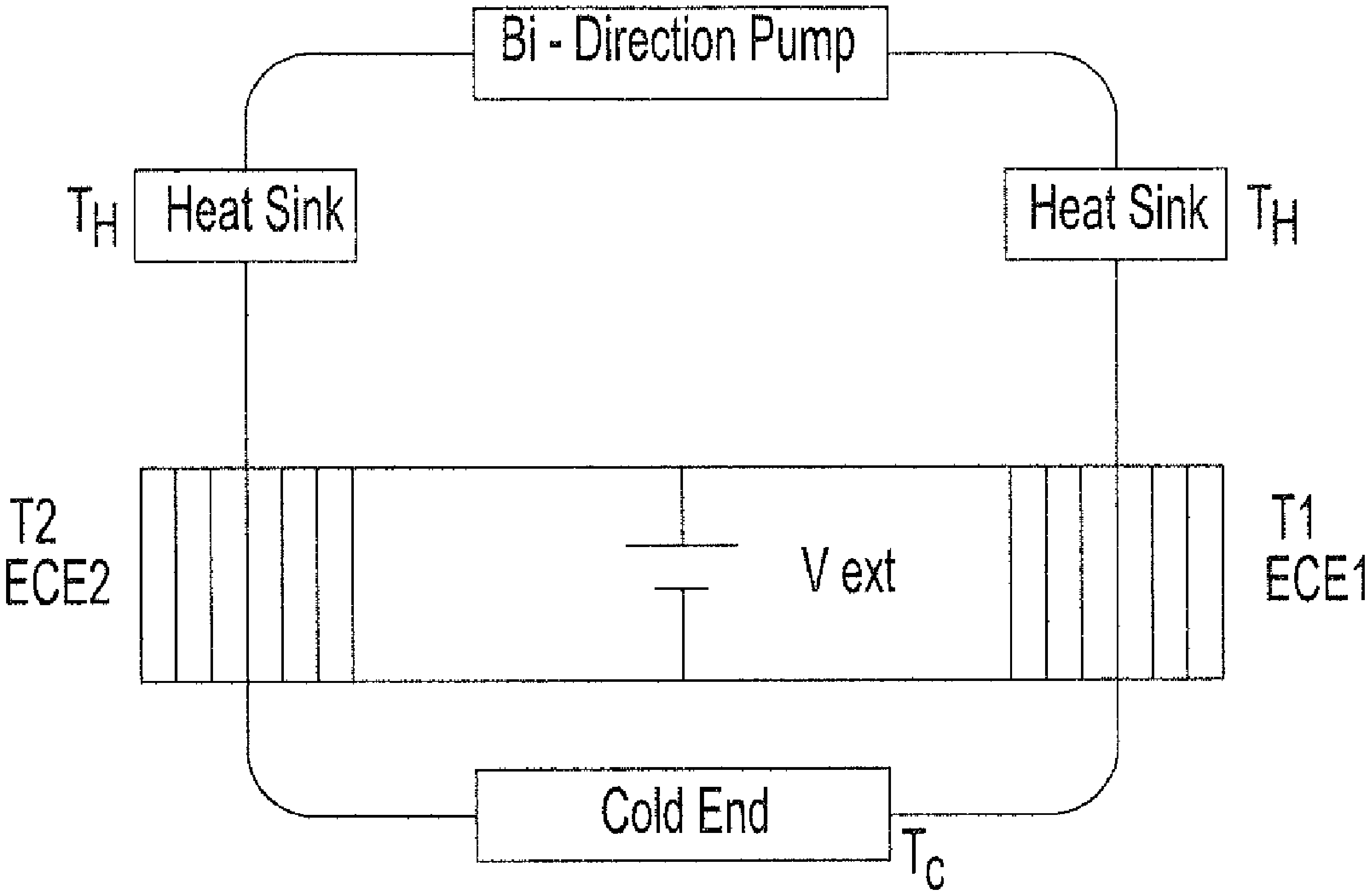
(57) **ABSTRACT**

A regenerative electrocaloric (EC) device is provided. The regenerative EC device uses a special configuration to expand the temperature span T_h-T_c, thereby increasing the cooling power and improving the efficiency thereof. The EC regenerative cooling device includes two electrocaloric effect (ECE) elements/rings in direct thermal contact with each other. The two rings rotate in opposite directions and are divided into multiple sections with an electric field or electric fields applied to every other region/section and an electric field or electric fields removed from remaining sections.



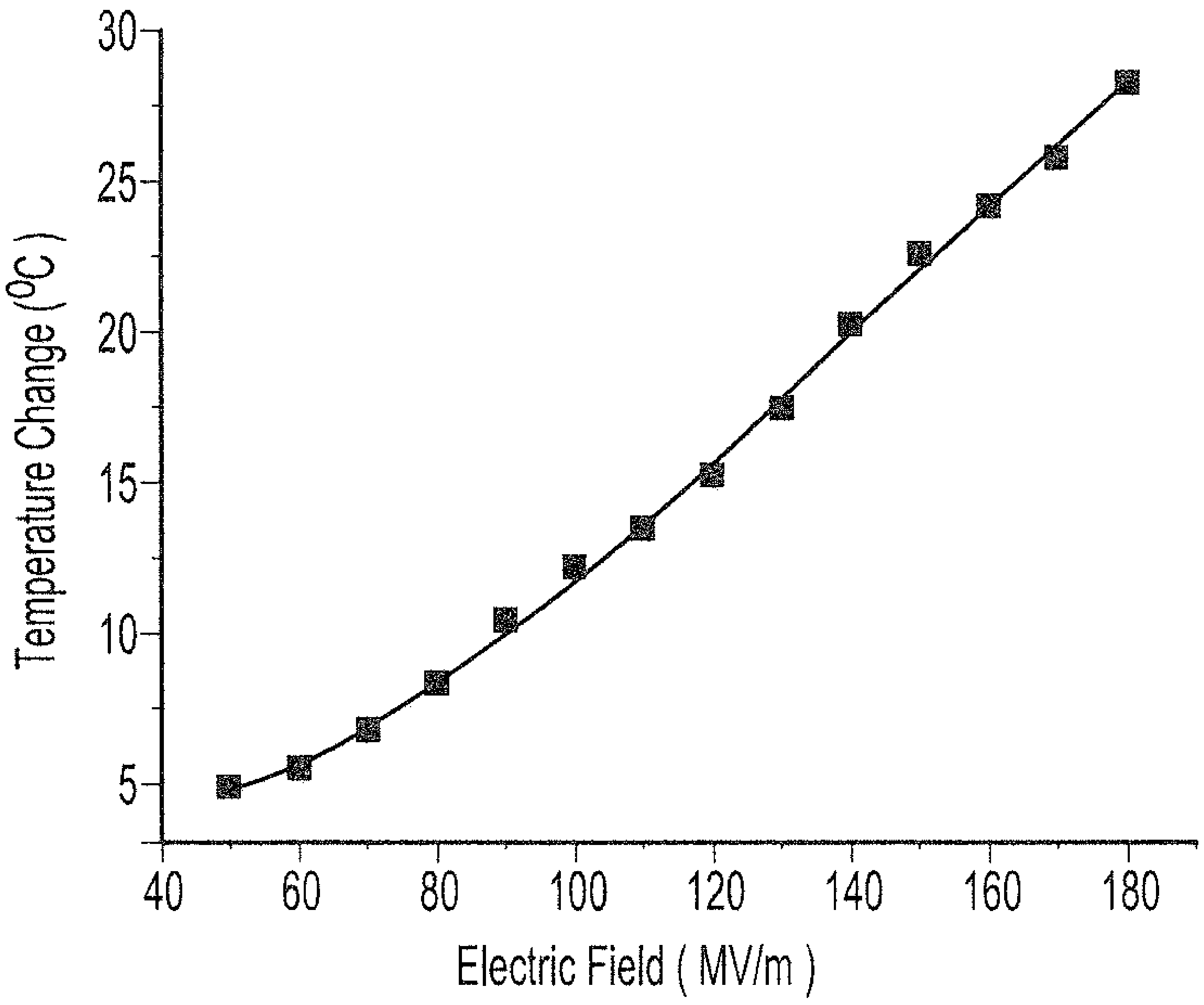

Temperature Change (^{0}C)
Electric Field (MV/m)
5
10
15
20
25
30
40
60
80
100
120
140
160
180

Fig-1

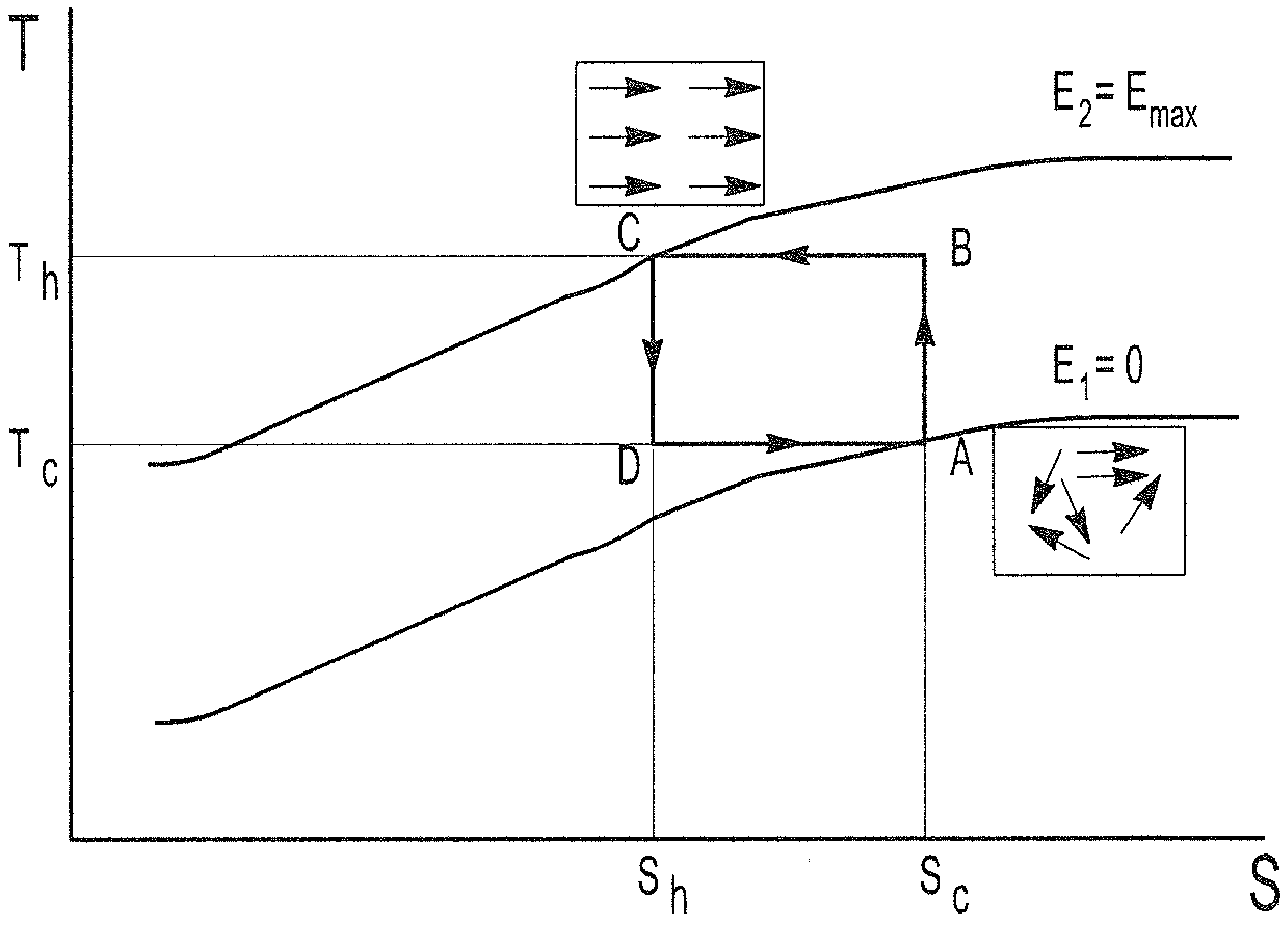

T
S
T_h
T_c
S_h
S_c
$E_2 = E_{max}$
$E_1 = 0$
A
B
C
D

Fig-2

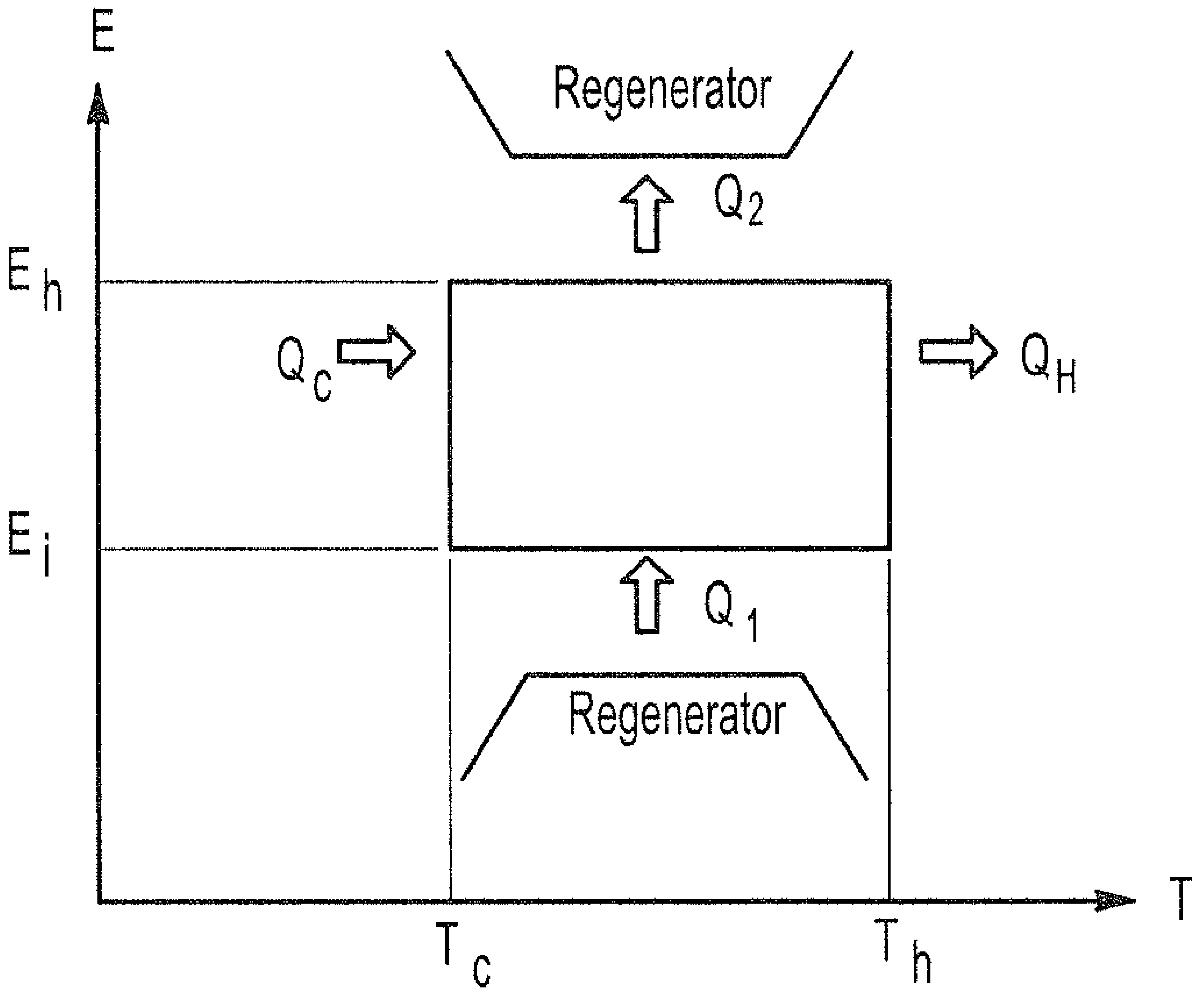

E
Regenerator
Q_2
E_h
Q_c
Q_H
E_i
Q_1
Regenerator
T
T_c
T_h

Fig-3a

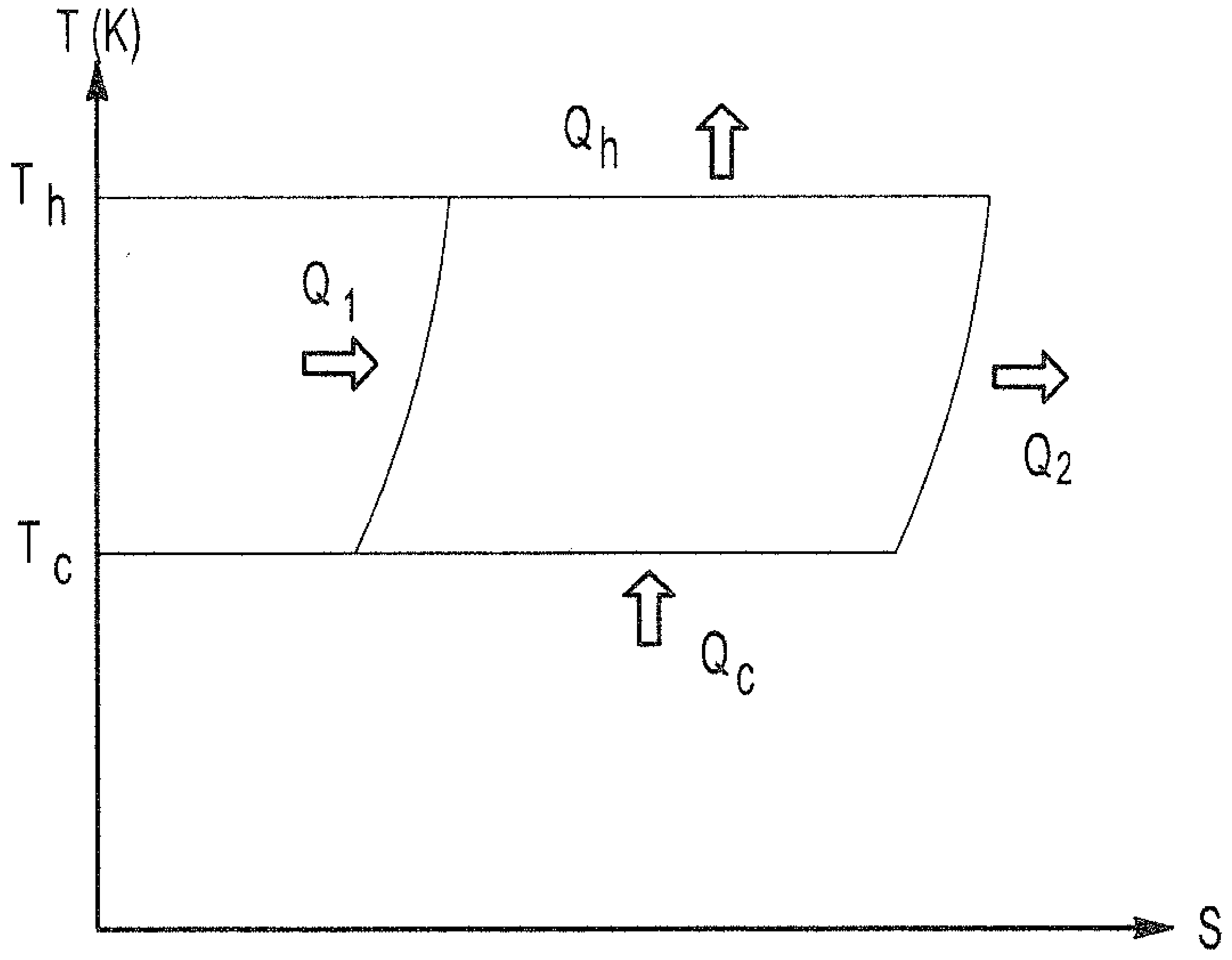

T (K)
Q_h
T_h
Q_1
Q_2
T_c
Q_c
S

Fig-3b

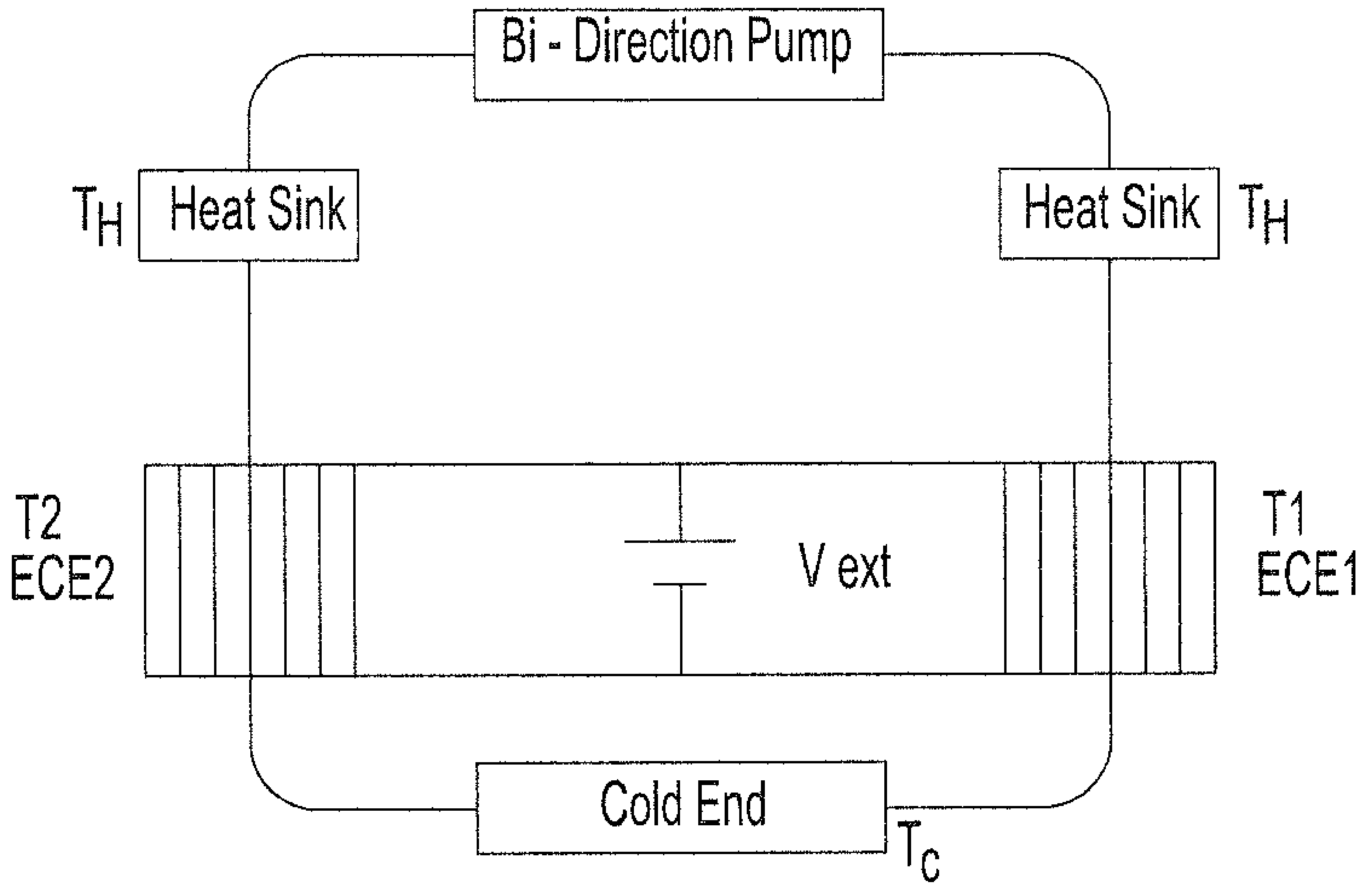

Bi - Direction Pump
T_H
Heat Sink
Heat Sink
T_H
T2
ECE2
V ext
T1
ECE1
Cold End
T_C

Fig-4a

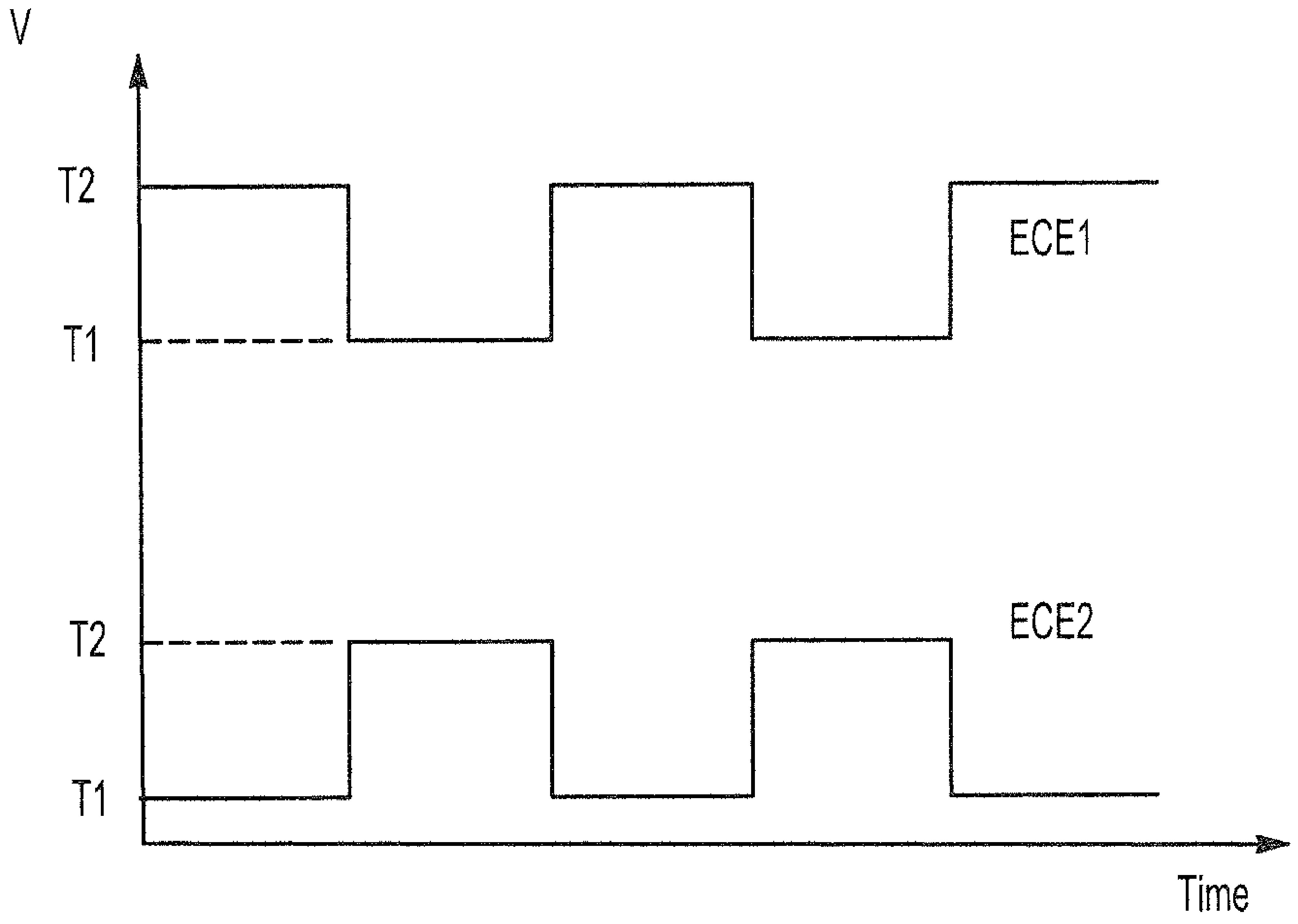

V
T2
T1
ECE1
T2
T1
ECE2
Time

Fig-4b

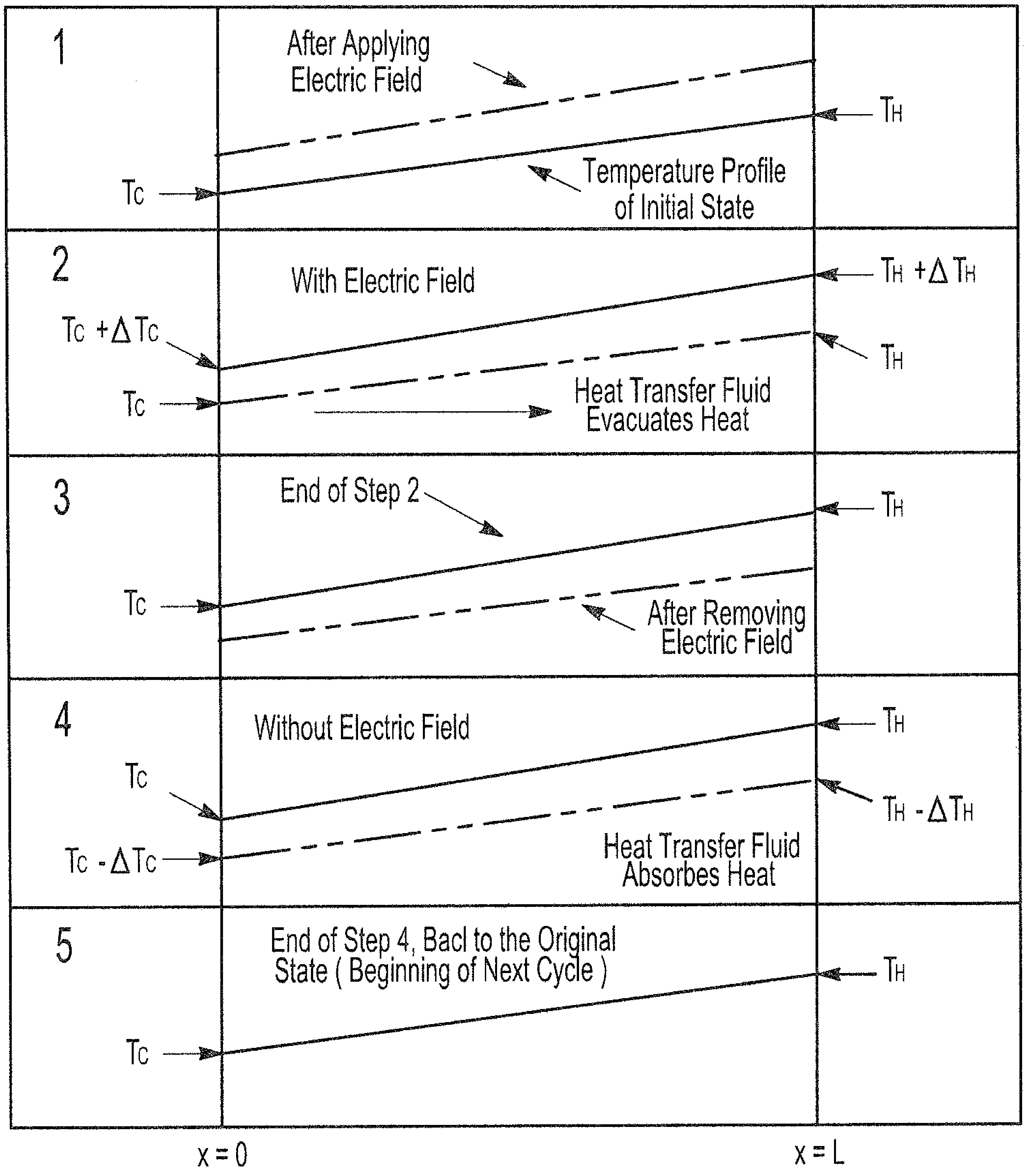

1
After Applying Electric Field
T_H
T_C
Temperature Profile of Initial State
2
With Electric Field
$T_H + \Delta T_H$
$T_C + \Delta T_C$
T_H
T_C
Heat Transfer Fluid Evacuates Heat
3
End of Step 2
T_H
T_C
After Removing Electric Field
4
Without Electric Field
T_H
T_C
$T_H - \Delta T_H$
$T_C - \Delta T_C$
Heat Transfer Fluid Absorbes Heat
5
End of Step 4, Bacl to the Original State (Beginning of Next Cycle)
T_H
T_C
x = 0
x = L

Fig-5

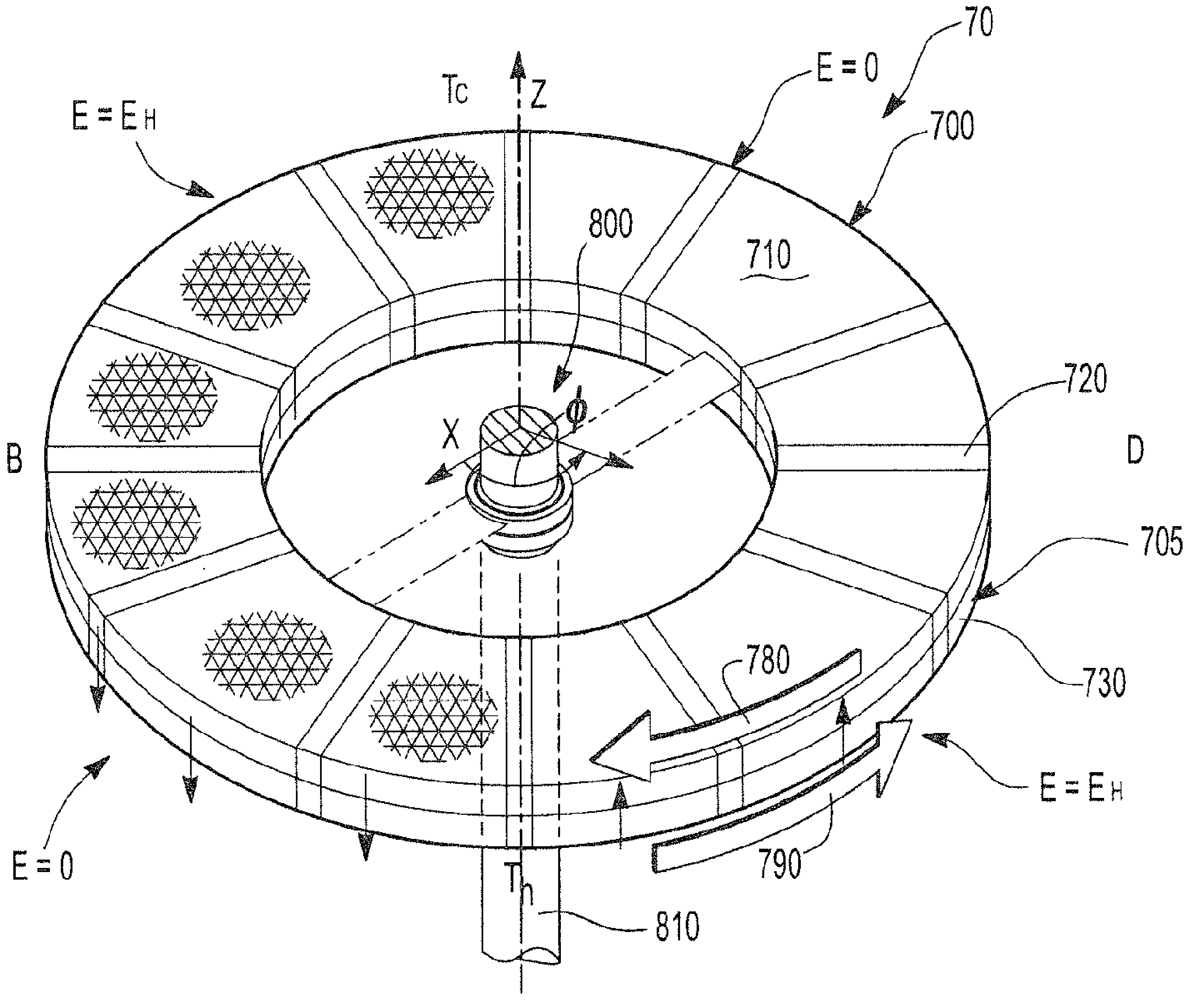

E = EH
Tc
Z
E = 0
70
700
800
710
720
B
ϕ
X
D
705
730
780
E = EH
E = 0
790
Th
810

Fig-6a

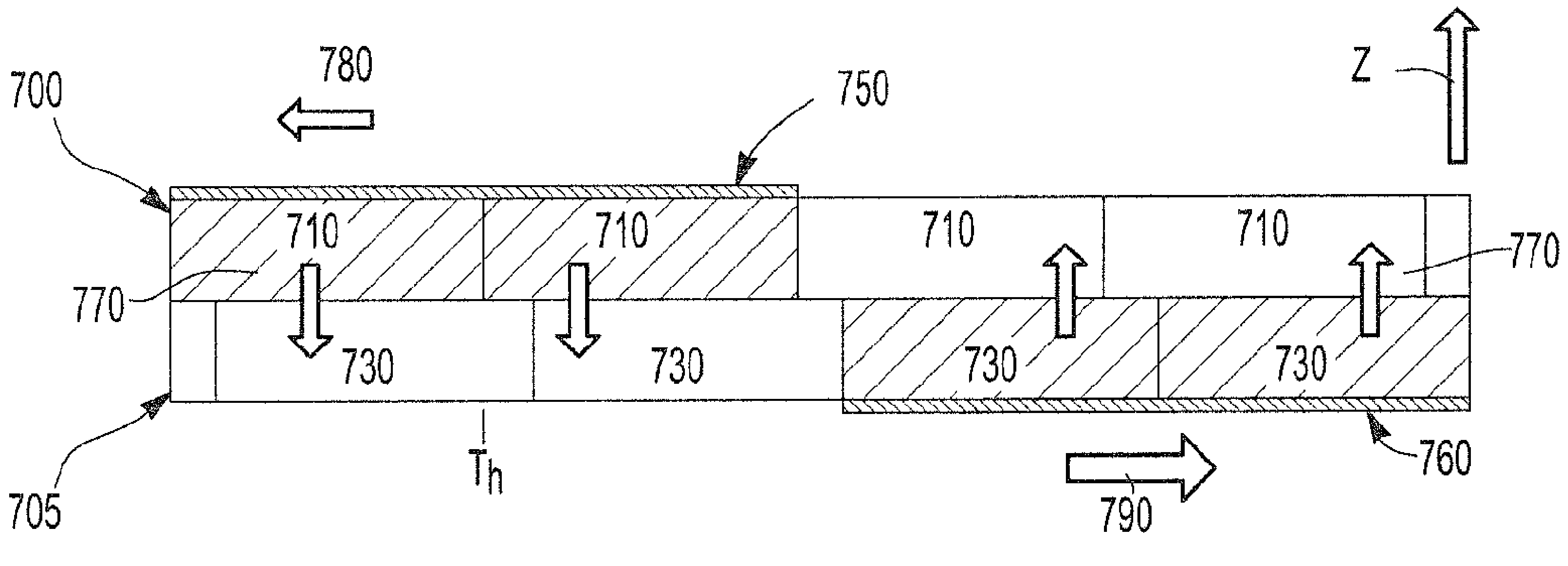

700
780
750
Z
710
710
710
710
770
770
730
730
730
730
705
Th
790
760

Fig-6b

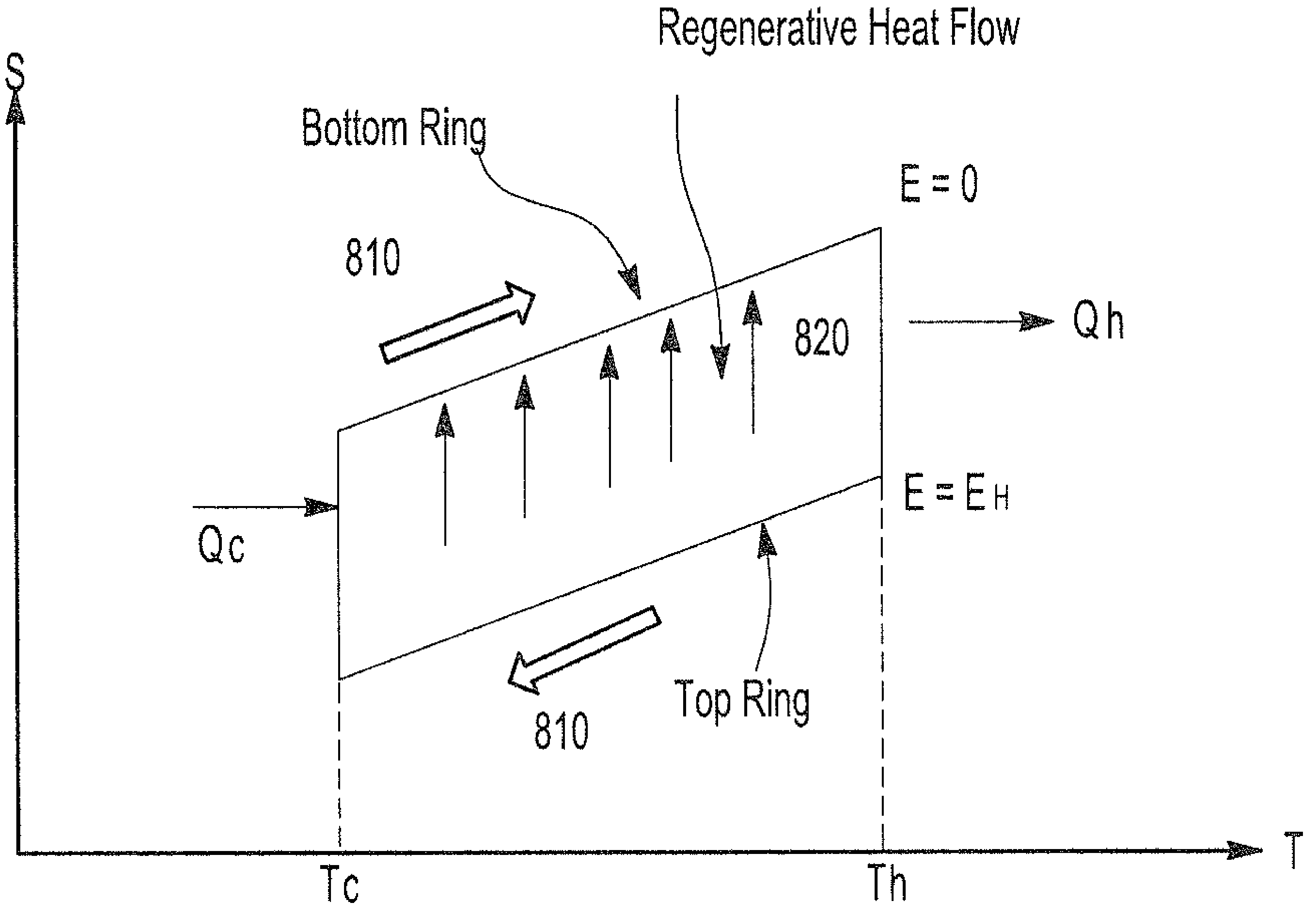

S
Regenerative Heat Flow
Bottom Ring
E = 0
810
820
Qh
Qc
E = EH
Top Ring
810
T
Tc
Th

Fig-7a

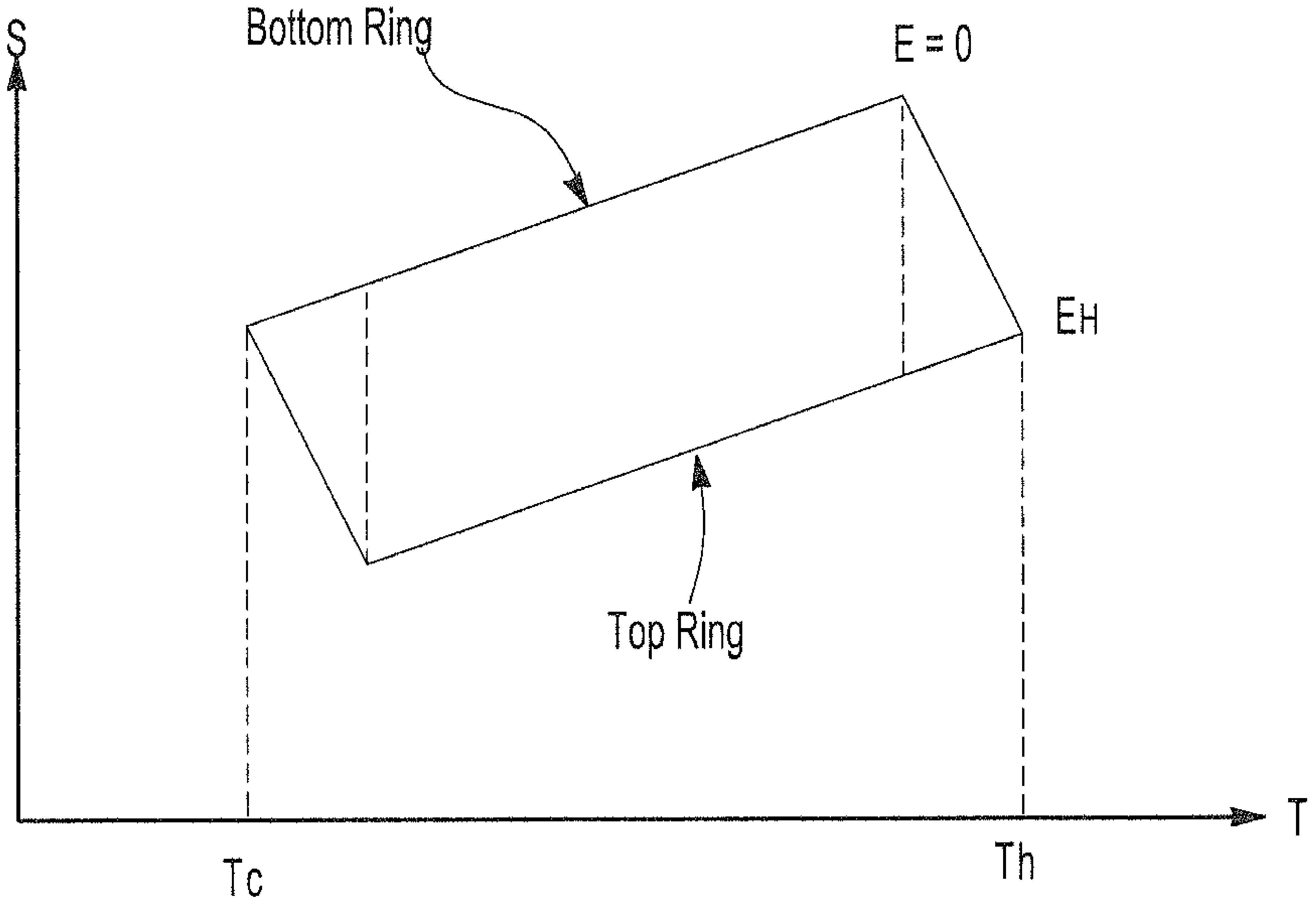

S
Bottom Ring
E = 0
EH
Top Ring
T
Tc
Th

Fig-7b

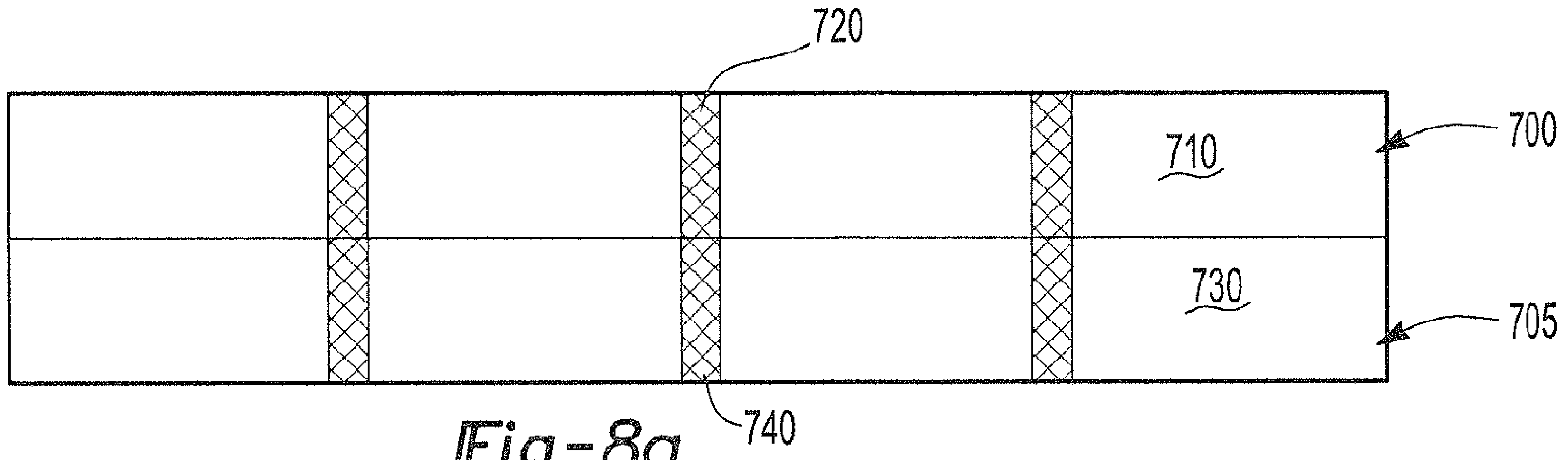


Fig-8a

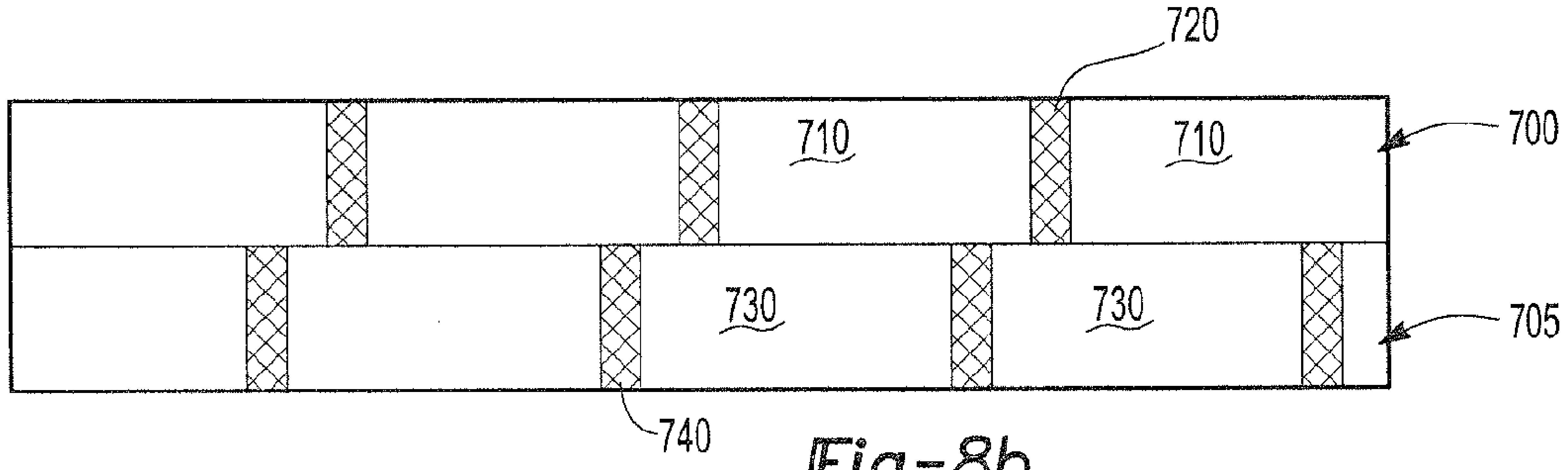


Fig-8b

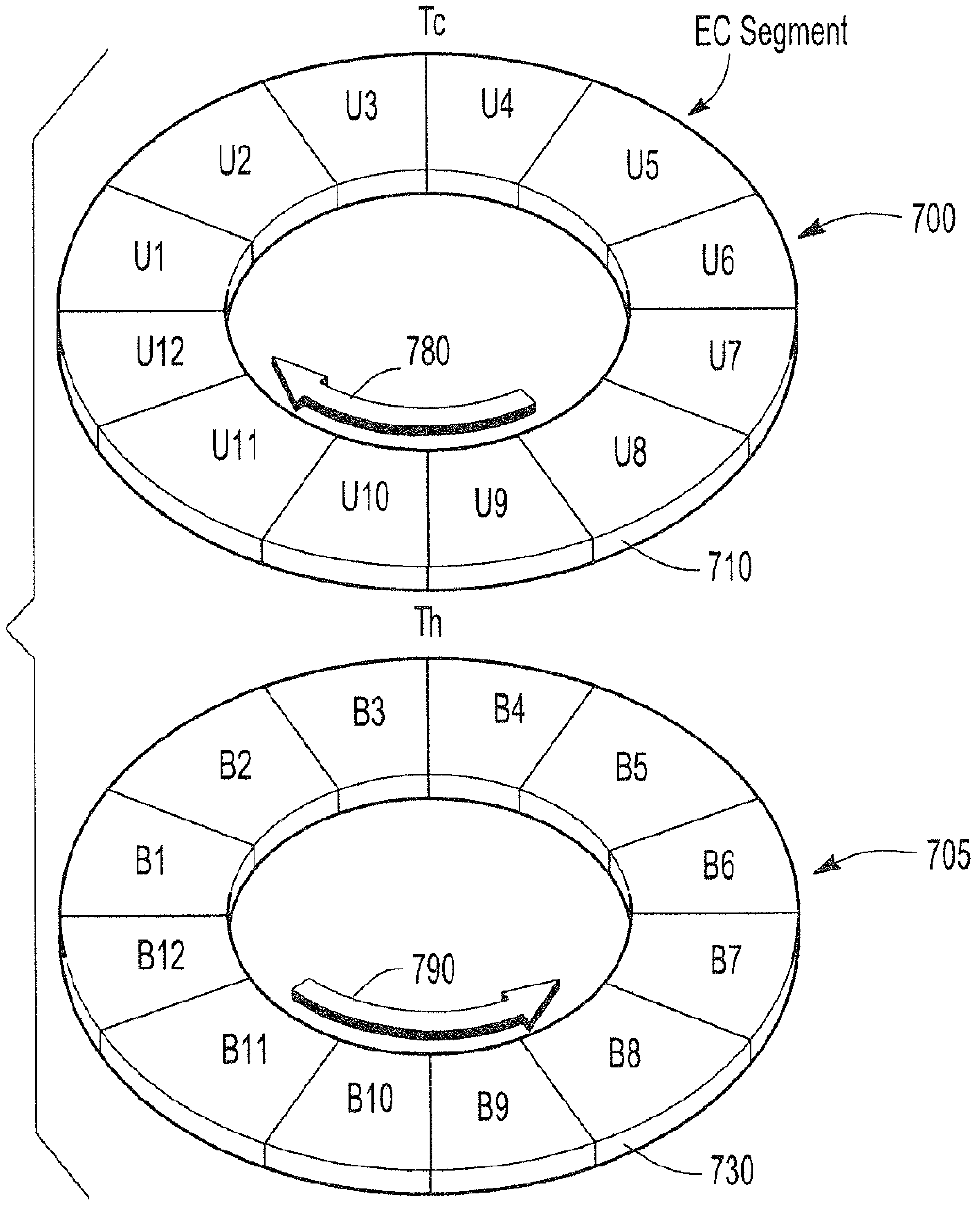


Fig-8c

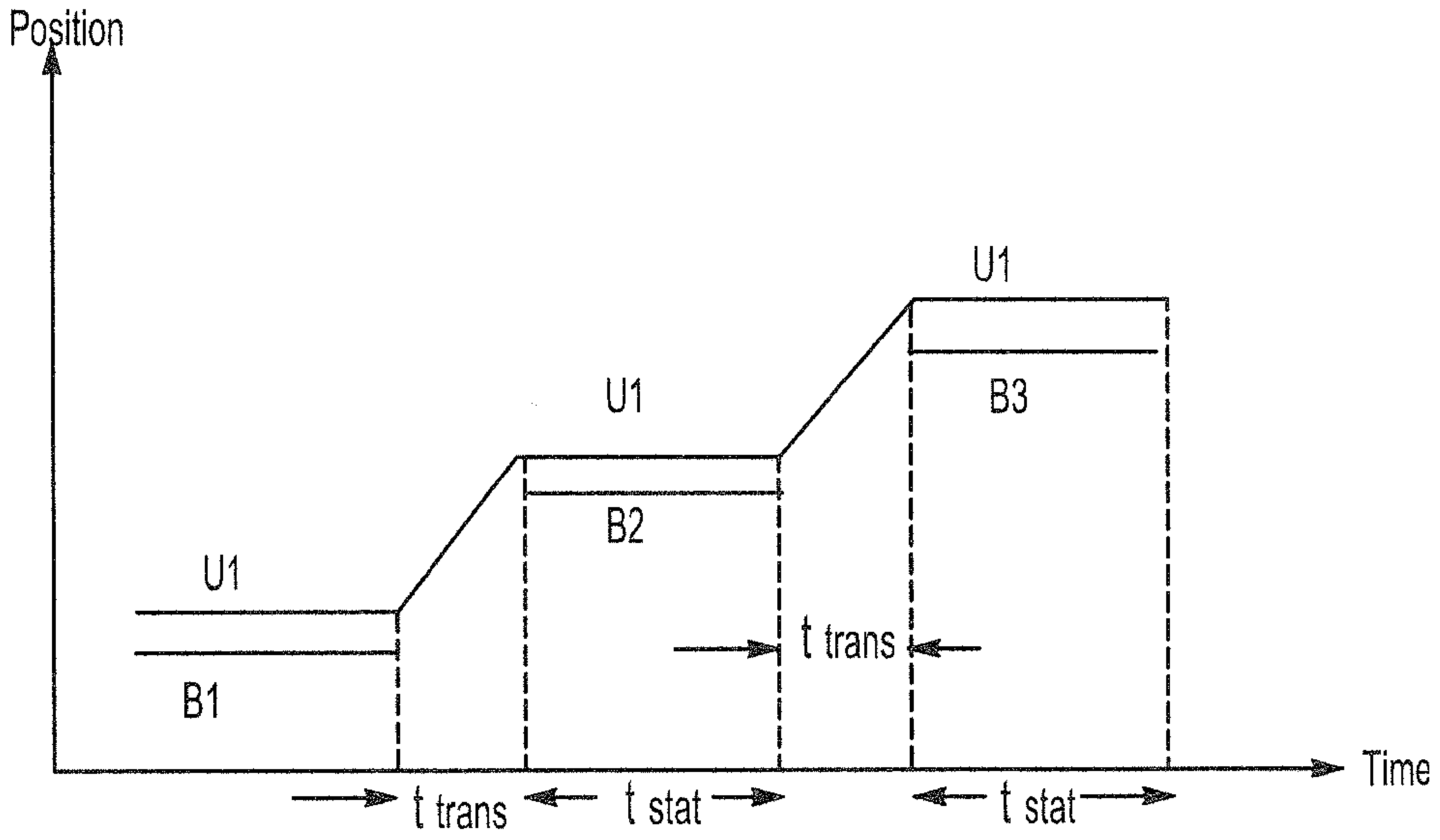


Fig-8d

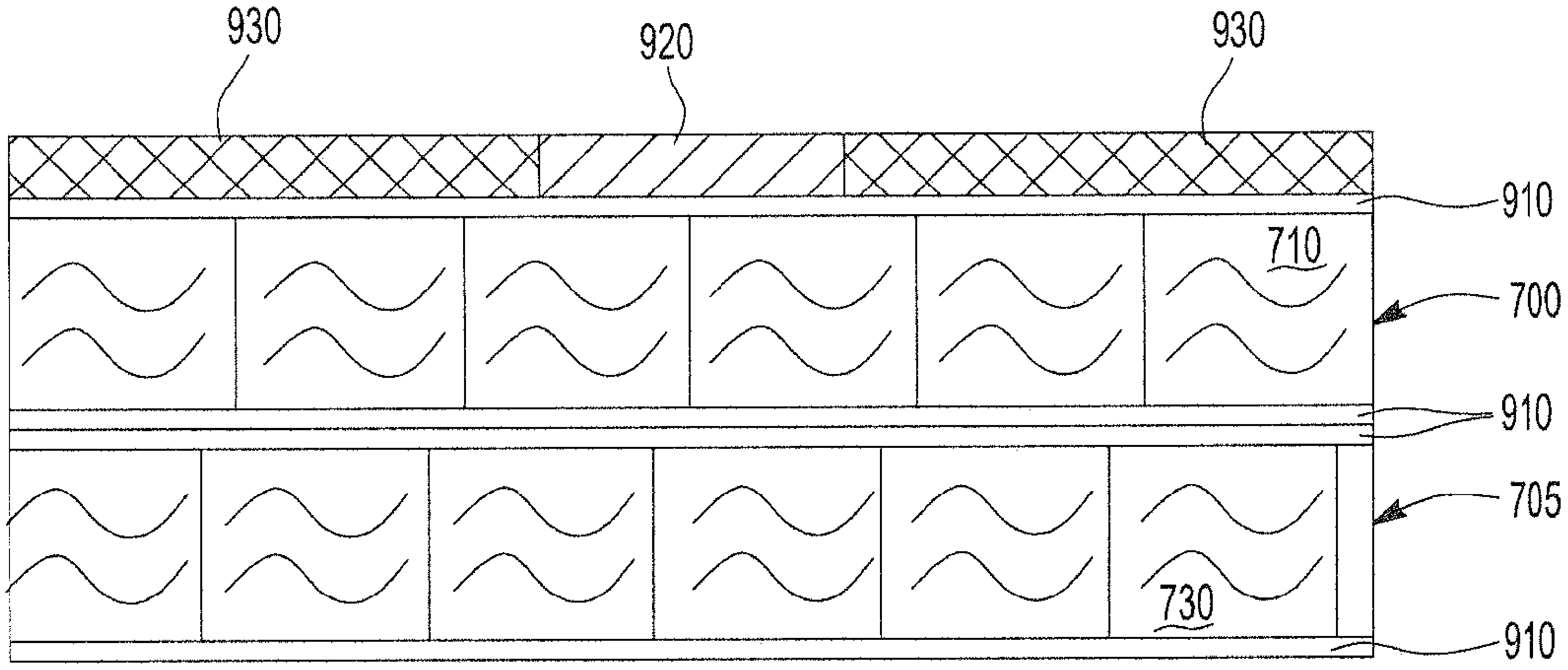


Fig-9a

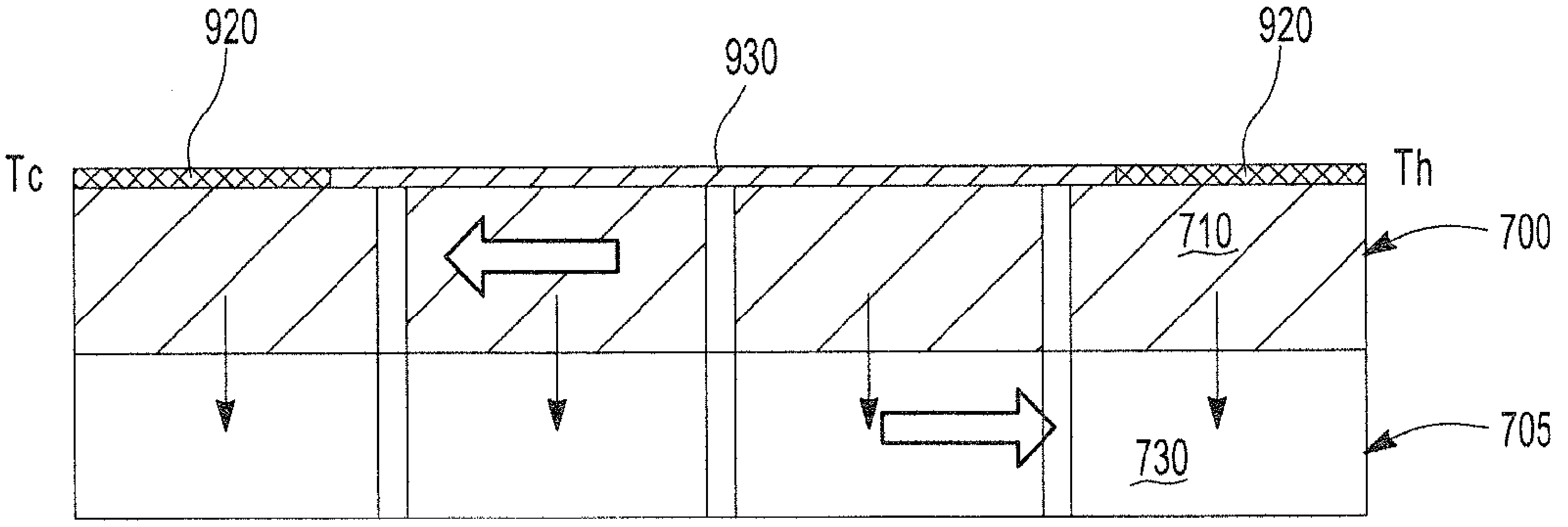


Fig-9b

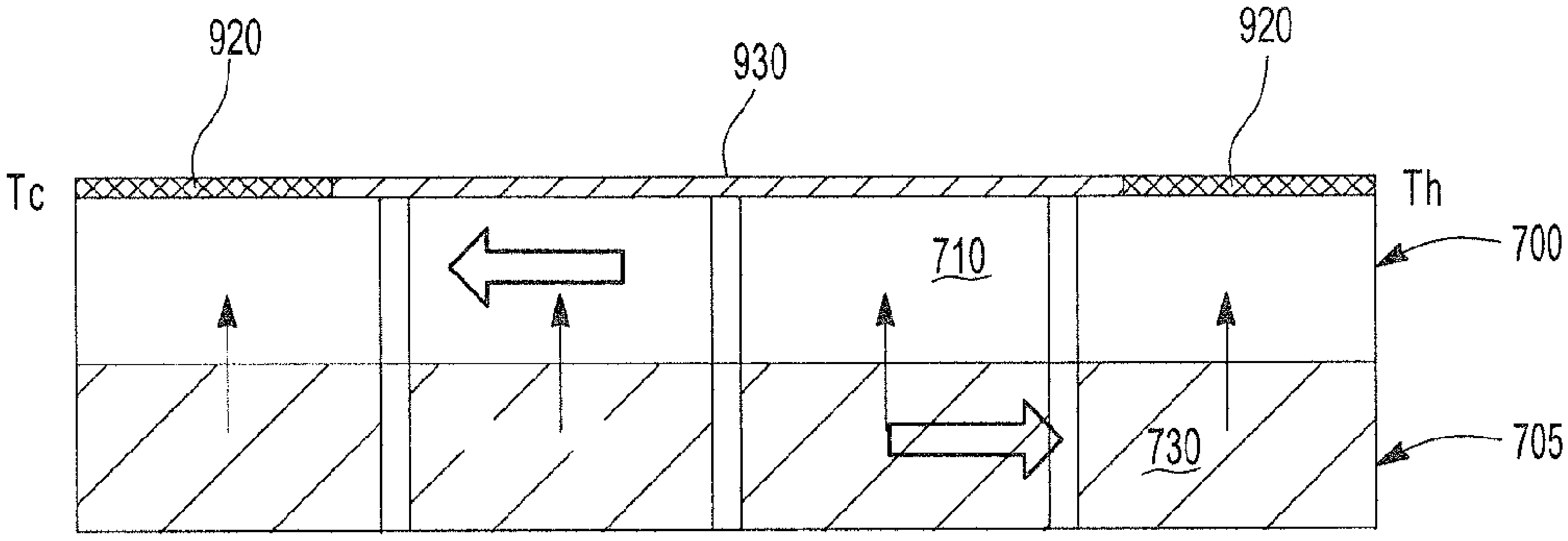

920
930
920
Tc
Th
710
700
730
705

Fig-9c

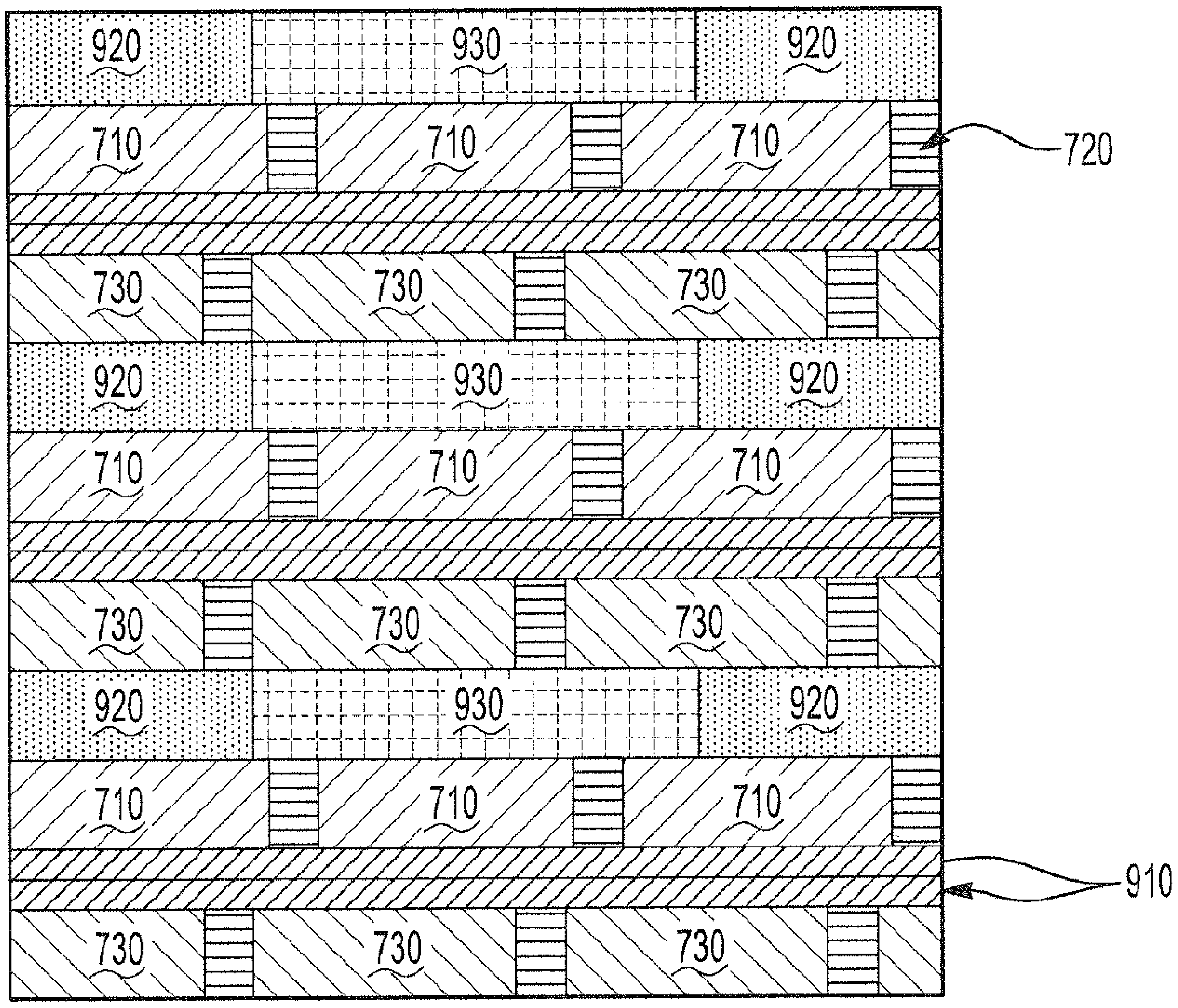

920
930
920
710
710
710
720
730
730
730
920
930
920
710
710
710
730
730
730
920
930
920
710
710
710
910
730
730
730

Fig-10

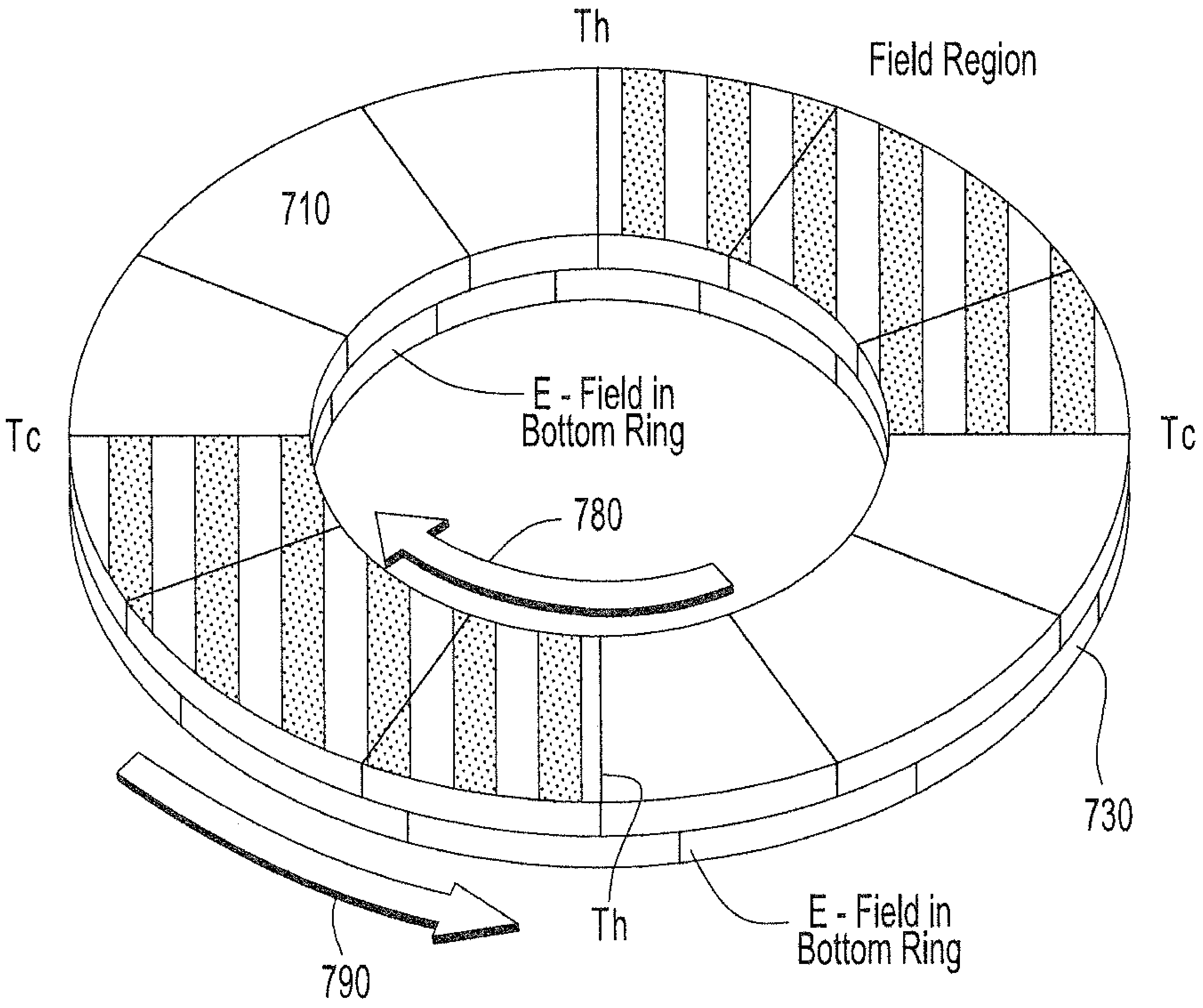

Th
Field Region
710
Tc
E - Field in Bottom Ring
Tc
780
730
Th
E - Field in Bottom Ring
790

Fig-11

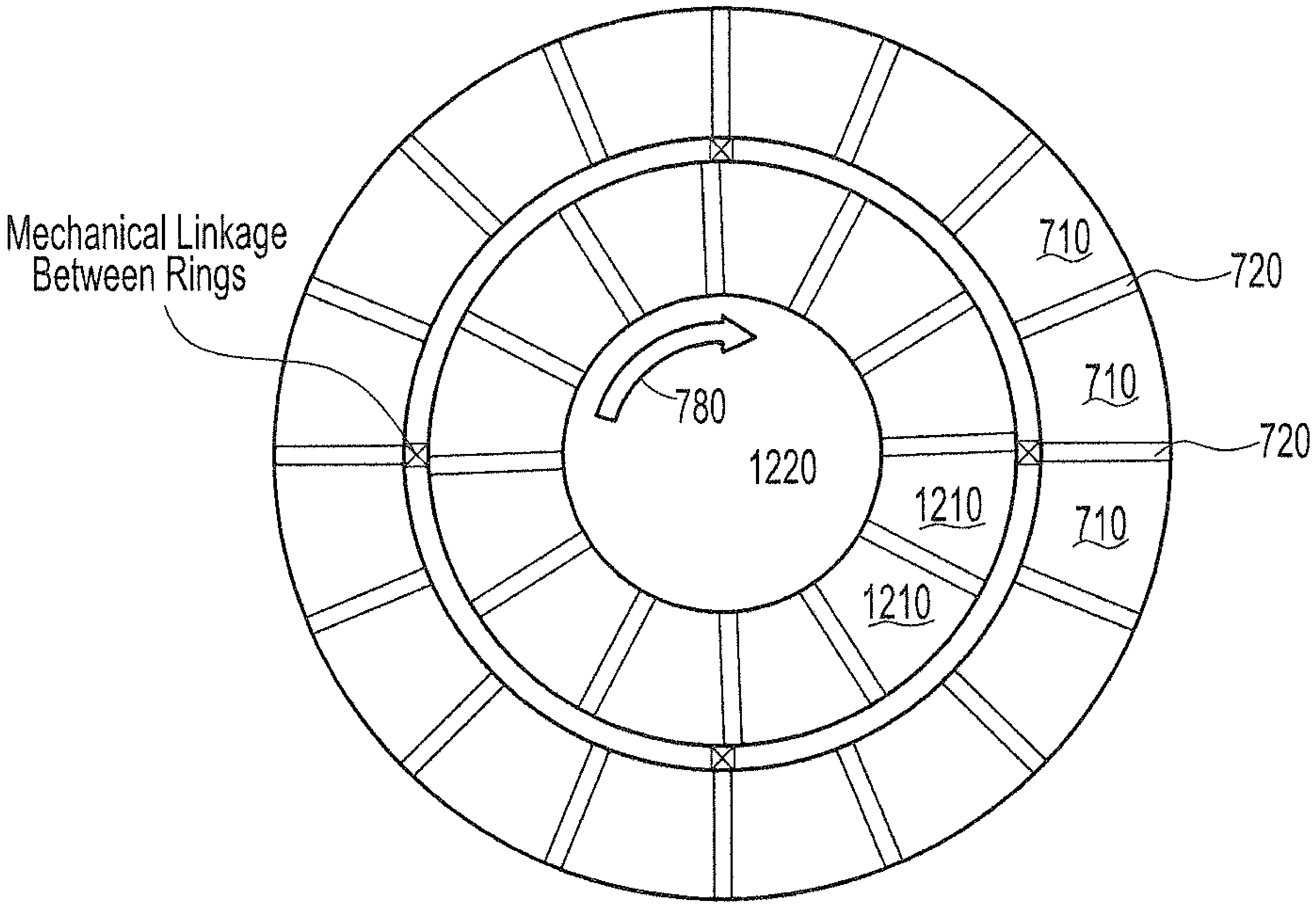

Mechanical Linkage Between Rings
710
720
780
710
720
1220
1210
710
1210

Fig-12

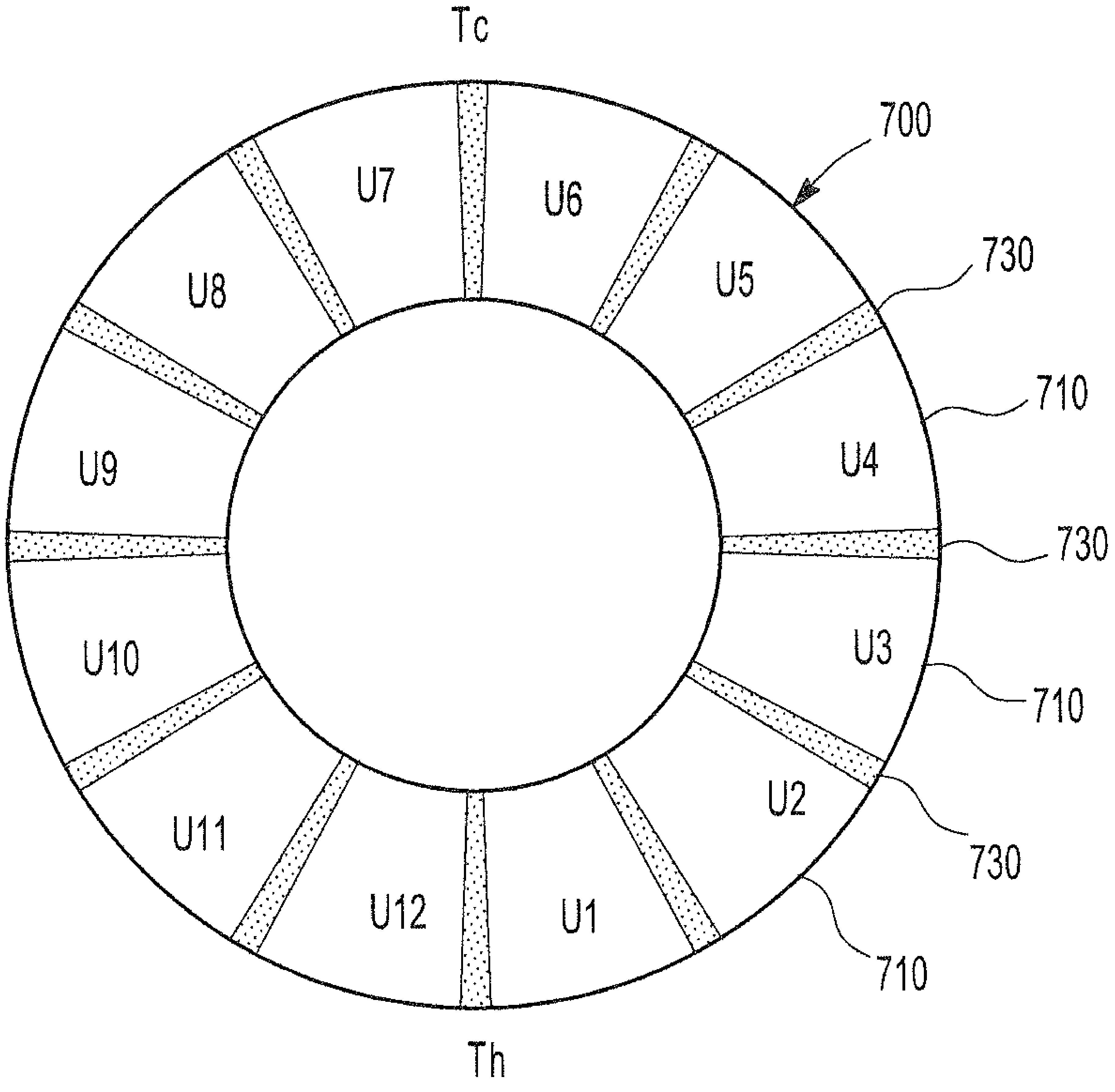


Fig-13a

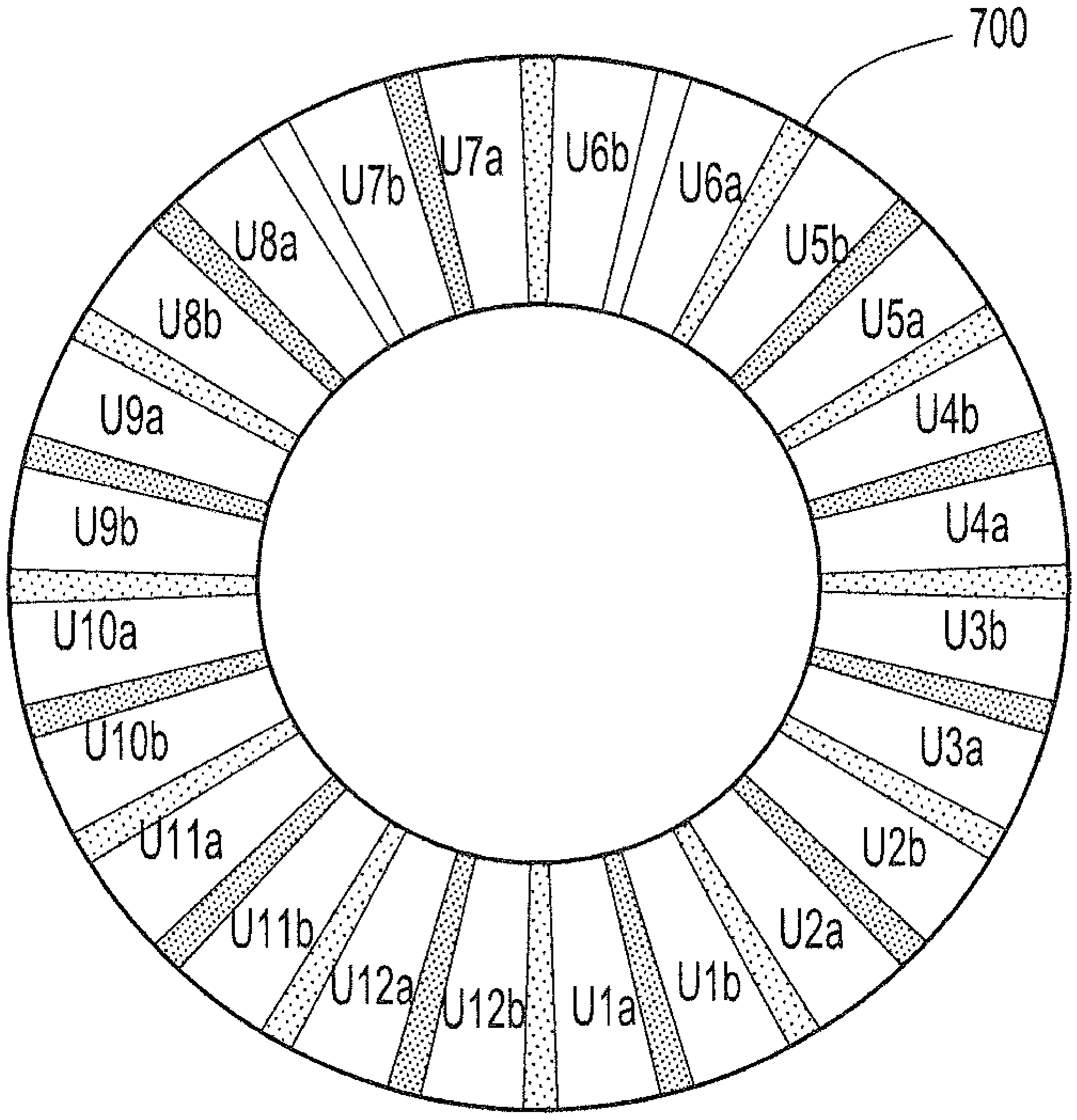


Fig-13b

REGENERATIVE ELECTROCALORIC COOLING DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Provisional Application No. 61/860,452 filed on Jul. 31, 2013, which is incorporated herein in its entirety by reference.

FIELD OF THE INVENTION

[0002] The present invention is related to regenerative electrocaloric cooling devices and, in particular, regenerative electrocaloric cooling devices using rotating electrocaloric material rings.

BACKGROUND OF THE INVENTION

[0003] Most conventional heat pumps, refrigerators, air conditioning, and climate control devices achieve cooling through a mechanical vapor compression cycle (VCC). Such systems are known to suffer from low efficiency and air conditioning is a major contributor to electric utility peak loads. Another related problem with today's VCC cooling technology is the adverse environmental impact of the refrigerant gases employed, which are strong greenhouse gases. These factors necessitate a search for new cooling technologies for air-conditioning, refrigeration, heat pumps, and climate controlling devices that possess improved energy efficiency, low cost and are environmentally friendly.

[0004] The electrocaloric effect (ECE) is a result of a direct coupling between thermal properties (such as entropy and temperature) and electric properties (such as electric field and polarization) in an insulation dielectric material. In this type of material, a change in the applied electric field induces a corresponding change in polarization, which in turn causes a change in the dipolar entropy S_p as measured by the isothermal entropy change ΔS in the dielectrics. If the field change is carried out in an adiabatic condition, the dielectric material will experience an adiabatic temperature change ΔT. Recently, a large electrocaloric effect has been discovered and developed (Xinyu Li, Xiao-shi Qian, S. G. Lu, Jiping Cheng, Zhao Fang and Q. M. Zhang. Tunable Temperature Dependence of Electrocaloric Effect in Ferroelectric Relaxor P(VDF-TrFE-CFE) Terpolymer. *Appl. Phys. Lett.* 99, 052907 (2011); Xinyu Li, Xiao-shi Qian, Haiming Gu, Xiangzhong Chen, S. G. Lu, Minren Lin, Fred Bateman, and Q. M. Zhang. Giant electrocaloric effect in ferroelectric poly(vinylidene-fluoride-trifluoroethylene) in copolymers near a first-order ferroelectric transition, *Appl. Phys. Lett.* 101 132903(2012)) in modified polar-fluoropolymers such as poly(vinylidene fluoride-trifluoroethylene-chlorofluoroethylene) (P(VDF-TrFE-CFE)) terpolymer and polymer blends. In the EC polymers, a temperature change of ΔT as large as ~28° C. can be induced near room temperature under an applied field change of 180 MV/m (see FIG. **1**).

[0005] A key component of a cooling device is the transportation of entropy from the cold end to the hot end. The objective is to transport entropy from one temperature level to another temperature level in a reversible manner. This requires a substance whose entropy depends on properties other than temperature. In the cooling devices of this invention, this substance is the electrocaloric (EC) material, whose entropy and/or temperature can be changed by external electric fields.

[0006] All steady state converters must be cyclic since the entropy carrying substance is not consumed. FIG. **2** illustrates an ideal cooling cycle (Carnot cycle) which consists of two adiabatic and two isothermal processes. For the Carnot cycle, the heat absorbed from the cold source is $Q_c=T_c(S_c-S_h)$ and the coefficient of performance, $COP=Q_c/W$ (where W is the total external work in the cooling cycle) can be expressed as:

$$\mathrm{COP}=T_c(T_h-T_c) \tag{1}$$

[0007] In the cooling cycles of FIG. **2** (and cooling devices based on the principle of cooling cycles in FIG. **2**), the maximum temperature span T_h-T_c is limited by the adiabatic temperature change ΔT of the EC material. In order to increase the temperature span and also to improve the efficiency, regenerative processes and/or regenerators are often introduced in practical cooling devices such as refrigerators, air conditioning, and heat pumps, and climate controlling devices such as dehumidifiers. For example, illustrated in FIG. **3** is an ideal EC Ericsson cycle in which a regenerator spans temperature between T_h and T_c while there is no change in the electric field to the EC material as a refrigerant. T_h-T_c can be much larger than ΔT in the EC material induced by the field change of E_h-E_l. Several ECE based refrigeration cycles have also been investigated. One example illustrated in FIG. **4** (*a*) is a regenerative EC cooling device in which a heat exchange fluid is employed to transfer heat from the cold end load (absorb heat Q_c) to the hot end (eject heat Q_h). In this cooling device, there are two EC beds and one example of the applied electric fields at the two EC beds is presented in the FIG. **4** (*b*). As the electric field (voltage) in one EC bed (for example, ECE1) is changed from low to high, and hence causes a temperature increase in that EC bed, the electric field (voltage) in the another EC bed (for example, ECE2) is changed from high to low, causing a decrease in EC bed temperature, all due to the ECE in the two EC beds. The heat exchange fluid in this case will flow counter-clock-wise to absorb heat at the cold end and eject heat at the hot end. In the other half cycle, the electric fields in the two EC beds are reversed and the heat exchange fluid flows in the clock-wise direction. In this cooling device, heat exchange fluid has a bi-directional flow in each EC bed.

[0008] FIG. **5** illustrates the temperature profile at one EC bed at different stages of the cooling cycle of such an active electrocaloric regenerative refrigeration (AERR) cooling device as shown in FIG. **4** when the device reaches a steady state operation (maintaining a temperature difference between the hot end T_H and cold end T_C). In step 1, application of a voltage raises the EC bed temperature. In step 2, the heat exchange fluid is pumped from x=0 to x=L, the EC bed length, through the EC bed and heat is ejected at the heat sink (T_H). In step 3, the removal of the electric field causes cooling of the ECE bed (there is no heat exchange fluid flow) and in the step 4, the heat exchange fluid will be pumped in the opposite direction (from x=L to x=0) and heat absorbed from the cold end (at TO. This process is repeated during the cooling device operation. Two EC beds are employed for the AERR device shown in FIG. **4**. Each EC bed consists of EC plates stacked in a parallel configuration with channels (spaces) between EC plates for the bi-directional flow of heat exchange fluid. The channel width is dictated by the thermal diffusion length of the heat exchange fluid, which typically is between 0.1 and 0.5 mm. However, such narrow channels between the EC thin plates can cause high flow resistance which limits the cooling power and reduces efficiency.

[0009] Moreover, a comparison of devices in FIG. **4** (and FIG. **5**) with the Ericsson cycle in FIG. **3** indicates that the regenerative process in the device of FIG. **4** is not ideal since there is a temperature change in the regenerator (also in the heat exchange fluid) as the electric field is changed. More recently, a solid state EC refrigerator was introduced and demonstrated, however, the regenerator temperature of that cooling device still changes with the applied field [Haiming Gu, Brent Craven, Xiaoshi Qian, Xinyu Li, Ailan Cheng, S. C. Yao, Q. M. Zhang. Simulation of electrocaloric refrigerator with high cooling-power density. *Appl. Phys. Lett.* 102, 112901 (2013)]. In these regenerative refrigerators, the electric field along the length of the regenerator changes with time, which causes change of the regenerator temperature. The bi-directional flow of the heat exchange fluid in the cooling device of FIG. **4** is also not convenient.

[0010] Even though the EC materials have great potential for cooling devices with high cooling power and high cooling efficiency, the current ECE cooling device designs are not convenient for practical operation and cannot fully utilize the superior performance of the EC materials. Therefore, new cooling system design and now cooling control method are highly desirable to achieve high cooling power and high efficiency.

SUMMARY OF THE INVENTION

[0011] A regenerative electrocaloric (EC) device is provided. The regenerative EC device uses a special configuration to expand the temperature span T_h-T_c, thereby increasing the cooling power and improving the efficiency thereof. One embodiment of the EC regenerative cooling device of the instant invention includes two electrocaloric effect (ECE) elements/rings in direct thermal contact with each other. The two rings rotate in opposite directions and are divided into multiple sections with an electric field or electric fields applied to every other region/section and an electric field or electric fields removed from remaining sections.

[0012] The regenerative EC device can include a first EC ring and a second EC ring, the first EC ring rotating in an opposite direction to the second EC ring and in sliding contact therewith. The EC device has a hot end and a cold end, and an electrical power supply (or supplies) in communication with the two EC rings. The electrical power supply produces an electric field across a portion of the first EC ring, the electric field reducing an entropy of the subjected portion of the first EC ring. The reduced entropy results in an increase in temperature of the selected portion of the first EC ring such that the portion with the electric field thereacross has a higher temperature than another portion of the EC ring which does not have the electric field thereacross. The cold end of the regenerative EC device absorbs heat from an outside source of heat and the hot end of the EC device transfers or expels heat to a heat sink. In addition, rotation of the first EC ring relative to the second EC ring pumps heat from the cold end to the hot end via the rotation and applied electrical field and thereby provides a regenerative EC cooling device.

[0013] The first EC ring has a first ring high electric field region (HEFR) and a first ring low electric field region (LEFR), and the second EC ring has a second ring HEFR and a second ring LEFR. The regenerative EC device is arranged and operates such that the first ring HEFR is oppositely disposed from and in direct sliding thermal contact with the second ring LEFR. Also, the first ring LEFR is oppositely disposed from and in sliding contact with the second ring HEFR. During operation of the regenerative EC device, heat passes from the first ring HEFR to the second ring LEFR and from the second ring HEFR to the first ring LEFR.

[0014] In some instances, the regenerative EC device includes a frame and the first EC ring and the second EC ring rotate relative to the frame. In such instances, the first ring HEFR, first ring LEFR, second ring HEFR, and second ring LEFR are stationary relative to the frame and the first EC ring and second EC ring have portions that rotate into and out of their respective HEFR and LEFR.

[0015] The first EC ring can have a plurality of first ring segments, a first subset of the first ring segments located within the first ring HEFR and a second subset of the first ring segments located within the first ring LEFR. In addition, the second EC ring can have a plurality of second ring segments, a first subset of the second ring segments located within the second ring HEFR and a second subset of the second ring segments located within the second ring LEFR. Similarly as stated above, rotation of the first EC ring and/or the second EC ring affords for a ring segment of the first subset of the first ring segments to travel from the first ring HEFR into the first ring LEFR as a ring segment of the second subset of the first ring segment travels or passes from the first ring LEFR into the first ring HEFR. The same can be true for the second ring, that is as one ring segment of the second EC ring passes or travels into the second ring HEFR, another ring segment passes or enters into the second ring LEFR.

[0016] The segments of the first EC ring and/or second EC ring are naturally made from an EC material and are divided from each other with a low thermal conductivity divider. In this manner, heat conduction within a given ring from T_h to T_c can be reduced since the heat conduction is proportional to the thermal conductivity of the material between T_h and T_c. Stated differently, the low thermal conductivity dividers cause a low thermal conductivity of the ring. Also, the overall thermal conductivity of the ring between T_h and T_c should be less than 0.3 W/mK and most plastics have thermal conductivity <0.3 W/mK and thus can be selected for the dividers.

[0017] A process for removing heat from a heat source is also included, the process including providing a regenerative EC device as disclosed herein and contacting the cold end of the EC device with an object having heat and contacting the hot end of the regenerative EC device with a heat sink. The cold end of the regenerative EC device absorbs heat from the object, the EC device pumps the heat to the hot end of the regenerative EC device, and the hot end expels the heat to the heat sink as the first EC ring rotates in an opposite direction to the second EC ring. In this manner, a cooling device is provided to remove heat from heat sources or objects such as electronic devices, engine components, a room, cold chamber of a refrigerator and the like.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] Reference is made to the attached drawings, wherein elements having the same reference numeral designations represent similar elements throughout.

[0019] FIG. **1** is a graphical representation of an adiabatic temperature change as a function of applied electric field for an EC material such as a polymer;

[0020] FIG. **2** is a graphical representation of a thermodynamic refrigeration cycle (Carnot cycle) based on the electrocaloric effect, where S is entropy, T is temperature, E is applied electric field, subscripts h and c refer to high and low end temperatures, and the arrows in boxes near the labels 'A' and 'C' represent disordered dipolar and ordered dipolar states of an EC material;

[0021] FIG. **3** is a graphical representation of an ECE Ericsson cooling cycle with: (a) electric field (E) versus temperature (T); and (b) entropy (S) versus temperature (T);

[0022] FIG. **4** is: (a) schematic diagram of a regenerative EC cooling device employing two EC beds with a heat exchange fluid; and (b) an example of an electrical field pattern applied to the two EC beds (ECE1 and ECE2) for the cooling device shown in **4**(*a*) and with heat exchange fluid in the device flowing in two opposite directions and provided by the bidirectional fluid pump shown in the figure;

[0023] FIG. **5** is a graphical representation of a cooling cycle and temperature profile for one EC bed shown in FIG. **4**(*a*) and with steady state having been obtained by the EC bed;

[0024] FIG. **6** is: (a) a perspective view of an embodiment of the present invention; and (b) a cross-sectional view of section B-B shown in FIG. **6**(*a*);

[0025] FIG. **7** is: (a) a temperature-entropy diagram for an ideal cooling cycle for the cooling device shown in FIG. **6**(*a*); and (b) a temperature-entropy diagram for a non-ideal cooling cycle for the cooling device shown in FIG. **6**(*a*), where in the illustration, $E_L=0$ but for the general case, $E_L<E_H$ and may not be=0;

[0026] FIG. **8** is: (a) a schematic illustration of two EC rings aligned with each other such that EC material segments and gaps of low conductivity material between the EC material segments are aligned with each other; (b) a schematic illustration of the segments shown in FIG. **8**(*a*) in misalignment; (c) an expanded view of the two rings shown in FIG. **6**; and (d) a schematic illustration of position versus time for segments of the rings shown in FIGS. **8**(*a*), (*b*), and (*c*);

[0027] FIG. **9** is: (a) a side cross-sectional view of the section **9**A-**9**A shown in FIG. **6**; (b) a side cross-sectional view of section **9**B-**9**B shown in FIG. **6**; and (c) a side cross-sectional view of section **9**C-**9**C shown in FIG. **6**;

[0028] FIG. **10** is a schematic illustration of a regenerative EC unit having a plurality of EC ring units (FIG. **9**) stacked on top of each other.

[0029] FIG. **11** is a schematic illustration of a regenerative EC cooling device with more than two regions for applying an electric field to a top ring and more than two regions for applying an electric field to a bottom ring;

[0030] FIG. **12** is a schematic illustration of a regenerative EC cooling device with coaxial rings;

[0031] FIG. **13** is: (a) a schematic illustration of an EC ring having a plurality of EC material segments and each segment being covered by a single electrode; and (b) a schematic illustration of the EC ring shown in FIG. **12**(*a*) with each EC material segment covered by multiple smaller electrodes; and

DETAILED DESCRIPTION OF THE INVENTION

Definitions

[0032] The following terminology and definitions are used throughout the specification and are provided here for clarity.

[0033] T_h (T_H): Temperature of the heat sink (hot end) of the EC cooling device.

[0034] T_c (T_L): Temperature of the cold load (cold end) of the EC cooling device.

[0035] E_H (E_h): The maximum electric field applied to a cooling device of an embodiment of the present invention.

[0036] E_L (or $E_L=0$): The low electric field applied to an EC cooling device of an embodiment of the present invention ($E_H>E_L$, and in some cases, $E_L=0$).

[0037] $\Delta E=E_H-E_L$ is the change of electric field.

[0038] EC ring: A ring shaped EC module of outer-diameter (OD), inner diameter (ID) and thickness d, with multiple EC segments separated by gaps consisting of low thermal conductivity (k<0.2 W/mK).

[0039] Regions with or without electric fields: Regions fixed in the space. As the EC rings rotate, the EC segments will leave a region without electric field and enter a region with electric field and vice versa.

[0040] Thermal diffusion length: $\delta=\sqrt{2\alpha/\omega}$, where co is the angular frequency and $\alpha=k/(\rho c)$ is the thermal diffusivity.

[0041] The heat exchange layer: consisting of high thermal conductivity segments (such as Al, with thermal conductivity >100 W/mK) and low thermal conductivity segments filling the spaces between the high thermal conductivity segments. The high thermal conductivity segments are in thermal contact with the EC rings at T_h and T_c areas to exchange heat between the EC rings and external heat sink and cold load,

[0042] Aligned position of the two EC rings: the EC segments and gaps in one ring overlapped (aligned) with the EC segments and gaps in the other ring, respectively.

[0043] The present invention provides a regenerative electrocaloric (EC) cooling device. As such, the invention has use for refrigeration or cooling of devices, objects, rooms (e.g. air conditioning), etc.

[0044] The regenerative EC device includes two EC material rings that rotate in opposite directions of each other. The two EC rings are also in direct thermal contact with each other. In this manner, heat flows between the two EC rings and affords for regeneration thereof. In addition to the two EC rings, an electrical power supply affords for applying an electrical field across at least a portion of one of the EC rings. As such, the portion of the EC ring that has the electrical field applied thereacross exhibits a rearrangement of dipolar states, i.e. from a disordered dipolar state to an ordered dipolar state. In addition, and with an adiabatic system, the ordering of the dipolar states reduces the entropy and increases the temperature of the material. Likewise, the removal of the electric field from the portion of the EC material results in a disordered dipolar state and an associated increase in entropy and decrease in temperature.

[0045] With the electrical field applied across a portion of at least one of the EC rings, in combination with rotation of the two EC rings, the regenerative EC device has a cold end and a hot end. In addition, the cold end absorbs heat from an object having heat, and which is desired to be cooled, and the EC device pumps the heat to the hot end where it is expelled to a heat sink.

[0046] It is appreciated that when a given EC ring portion has an electric field applied thereacross, the corresponding and oppositely disposed portion of the other ring does not have an electric field applied thereacross. As stated above, the temperature of the EC ring portion with the electric field applied thereacross increases due to the ordering of the dipolar states and reduction in entropy, and this portion has a higher temperature than the corresponding and oppositely disposed EC ring portion without the electric field. As such, heat is transferred from the EC ring having the electric field applied thereacross to the oppositely disposed EC ring that does not have the EC ring applied thereto. In this manner, the cooling device is regenerated.

[0047] In some instances, a pair of oppositely disposed and oppositely rotating EC rings are in thermal contact with each other and each ring has a plurality of EC material segments separated by gaps of low thermal conductivity material. Also, each of the rings has a high electric field region and a low electric field region. The high electric field region of one ring is oppositely disposed and in thermal contact with a low electric field region of the other ring. It is appreciated that a given ring can have more than one high electric field region and more than one low electric field region. In such cases, the corresponding and oppositely disposed ring would likewise have more than one high electric field region and low electric field region.

[0048] In order to apply the electric field across a portion of an EC ring, electrodes are in contact therewith. In addition, each EC material segment can have one electrode thereacross or, in the alternative, have more than one electrode thereacross. Finally, a regenerative EC device can have a plurality of EC rings stacked on top of each other in order to increase the cooling efficiency and/or cooling power of the device.

[0049] Turning now to the figures, one embodiment of an EC device **70** is schematically illustrated in FIG. **6** in which a top EC ring **700** and a bottom EC ring **705** are stacked together. In addition, the top and bottom EC rings **700**, **705** are thermally coupled to each other along the z-direction (the direction perpendicular to the plane of the ring). The two rings rotate about the z-axis but in opposite directions along a central axis and/or shaft **810**. Although shown to rotate about the z-axis via an arm or brace, it is appreciated that the invention includes rotation of the EC rings **700**, **705** about the z-axis via any method, attachment device, etc., known to those skilled in the art. Also, it is appreciated that the orientation of the z-axis shown in FIG. **6***a* is for illustrative purposes only, i.e. the z-axis and the EC rings **700**, **705** can be oriented in any direction so long as the rings rotate opposite to each other relative to a fixed space.

[0050] As illustratively shown in the FIG. **6***a*, the top EC ring **700** rotates clockwise **780** and the bottom ring **705** rotates counter-clockwise **790**. It is appreciated the terms "top", "bottom", "clockwise" and "counter-clockwise" are used for descriptive purposes only and that the orientation of the EC rings can be sideways, inverted, etc. Also, the two EC rings can rotate in opposite directions respective to what is shown in the figure.

[0051] The top EC ring **700** and bottom EC ring **705** are made from a plurality of EC material segments **710** and **730**, respectively. Also, and in a first example of the invention, an electric field ($E=E_H$) is applied to half of the ECE segments **710** in top EC ring **700** as indicated by the cross-hatching on six of the segments **710** on the top EC ring **700**. Also, the other half of the EC ring segments **710** have no field electric field applied thereto (E=0).

[0052] The region under the electric field region for the top ring **700** is 180 degrees apart from the region under electric field for the bottom ring **705**. Stated differently, there is no electric field (or lower electric field) in the EC segments **730** of the bottom ring **705** when the corresponding (right above) EC segments **710** of the top ring **700** are under electric field (E_H). Furthermore, as the top ring **700** rotates clockwise **780**, EC segments **710** near T_h (high temperature end) move from the region of no-electric-field (E=0) or low field ($E=E_L$) to the region of high-electric-field E_H. Such rotation causes an entropy reduction and heat ejection from the EC segments that have "crossed-over" from the no-electric-field or low-electric-field region to the high-electric-field region. Likewise, as the bottom EC ring **705** rotates counter-clockwise **790**, EC segments **730** near T_h move from the no-electric-field (E=0) or low-electric-field E_L to high field E_H and eject heat.

[0053] At T_c, the EC segments **710**, **730** of the top ring **700** and bottom ring **705**, respectively, move from high-electric-field regions to no-electric-field or low-electric-field regions, thereby affording an entropy increase in the EC segments, a reduction in temperature and heat absorption from the cold end. Therefore, as the top ring rotates clockwise from T_h to T_c (along the path T_h-B-T_c) in the E_H region, the temperature of the EC segments will decrease from T_h to T_c. At the same time, the bottom ring rotates counter-clockwise from T_c to T_h in the no-field (or low field) region (along the path T_c-B-T_h), the temperature of EC segments will increase from T_c to T_h. Through the heat exchange between the two rings, a regenerative process occurs via heat flow from the EC segments **710** in the top ring **700** to EC segments **730** in the bottom ring **705** as indicated by the arrows pointing "up" and "down" along the z-direction.

[0054] In the other half-rings, i.e. the half rings shown on the right hand side of the figure, heat flows from the EC segments **730** in the bottom ring **705** to the EC segments **710** in the top ring **700**. FIG. **6***b* is an illustration of the EC rings **700**, **705** rotating from E=0 to E_H regions and affording regenerative heat flow in the EC cooling device.

[0055] In a steady state operation, as the EC segments **710** in the top ring **700** enter the E_H region, the ECE causes a temperature increase, resulting in heat ejection to a heat sink (not shown) at T_h. Also, as the EC segments **710** in the top ring **700** rotate clockwise **780** from T_h towards T_c, the EC elements **730** in the bottom ring **705** rotate counterclockwise **790** from T_c towards T_h. The heat transfer between the EC elements **710** from the top ring **700** under high-electric-field to the EC elements **730** of the bottom ring **705** under no- or low-electric-field as indicated by the vertically oriented arrows in FIG. **6** provides a heat regenerative process similar to that illustrated FIG. **3** and FIG. **7** to be discussed below.

[0056] A similar process occurs in the other half of the rings with the functions of top and bottom rings are reversed. In particular, and referring to the ring halves shown on the right-hand-side of FIG. **6***a* and the vertically oriented arrows in FIG. **6***b*, the temperature of the EC segments **730** of bottom ring **705** will be slightly higher than the EC segments **710** of the top ring **700**. Thus, the heat will flow from the bottom ring **705** to the top ring **700**.

[0057] When an EC segment moves near T_c, the electric field for the EC segment is reduced from E_H to E_L, the entropy of the segment increases, the temperature of the EC segment decreases, and the EC segment absorbs heat at the cold end and thereby affords cooling of heat source (not shown). In order for the cooling device in FIG. **6** to function effectively, i.e. with high cooling power and high efficiency, the thermal conductivity of the EC segments **710**, **730** along the z-direction should be as high as possible so that the regenerative process between the two rings can occur with a very small temperature gradient (much less than 1° C.) along the z-direction, and within a very short time. Such a high thermal conduction rate affords the two rings to rotate at high speed and increase the cooling power of the EC device.

[0058] Looking now at FIG. **7**, a pair of temperature-entropy diagrams for the half of the top ring **700** under high-electric-field (E_H) and the half of the bottom ring **705** under no- or low-electric-field (E_L). It is appreciated that the other two halves of the rings have the same temperature-entropy diagram, except that the electric field is applied to opposite halves of the respective rings. Also, direct thermal coupling between the two rings affords for heat ejected from EC segments under the high-electric-field to be absorbed by oppositely disposed EC segments under the low-electric-field (a regenerative process).

[0059] Regarding the specific diagrams in FIG. **7**, FIG. **7***a* is for an ideal thermodynamic cycle, i.e. quasi-static with perfect heat exchange. However, in a practical situation the EC cooling devices are not operated at very low speed and a temperature difference exists between the EC segments near the T_h region and T_c region. Also, the temperature of the EC segments near the T_h region will be higher than the external heat sink and the temperature of EC segments near the T_c region will be lower than the external cold load temperature. Both of these effects are shown in the temperature-entropy diagram of FIG. **7***b*.

[0060] Although the two EC rings rotate in opposite directions, a temperature distribution will not change with time once a steady state condition is reached. The temperature gradient from T_h to T_c along the plane of the rings, hereafter referred to as the ϕ-direction, causes heat conduction from the T_h end to the T_c end. Such heat conduction along the ϕ-direction is a heat loss and lowers the cooling power and cooling device efficiency. Therefore, it is important to reduce or eliminate the thermal conduction along the ϕ-direction.

[0061] In order to reduce the thermal conductivity of the EC rings along the ϕ-direction, the EC rings are divided into segments as illustrated in FIG. **6** with neighboring EC segments **710**, **730** separated by the gaps **720**, **740**, respectively. The narrow gaps **720**, **740** between the neighboring EC segments **710**, **730** are filled with electrically insulating low thermal conductivity materials (or epoxy) ($k<0.2$ W/mK). The electrically insulating low thermal conductivity materials in gaps **720** and **740** can also be porous materials. The cavity in the porous materials can be either air, special gas such as SF6, or vacuum. It is appreciated that porous materials typically have lower thermal conductivity than non-porous materials.

[0062] From the above discussion, it is appreciated that the EC rings of the cooling device should have a high thermal conductivity along the z-direction and a low thermal conductivity along the ϕ-direction. For the cooling device of FIG. **6**, the EC segments can be EC polymers or EC ceramics. In general, the thermal conductivity k of an EC polymer is low and typically less than 0.3 W/mK. In contrast, EC ceramics usually have a higher thermal conductivity (e.g., $k>5$ W/mK). Also, by embedding electrically insulating high thermal conductivity fillers within EC polymers, EC composites can be fabricated and the thermal conductivity of an EC segment can be improved to greater than 1 W/mK.

[0063] The width of the gaps **720**, **740** is generally small compared to the overall width and/or length of the EC segments. For example, the gaps **720**, **740** can be less 5%, less than 10% or less than 15% of the corresponding length of an EC segment. In addition, the width of the gaps **720**, **740** can determined by or be a function of a device performance or cost parameter such as cooling power, temperature span T_h-T_c, COP, manufacturing cost, etc. Finally an EC ring structure is easily fabricated.

[0064] Typical dimensions of an EC ring be on the order of a 5 cm diameter and a 0.2 mm thick. In addition, such a ring can be fabricated into at least two segments using conventional fabrication techniques. For example, the top EC ring **700** and bottom EC ring **705** shown in FIG. **6** each have 12 EC segments with six of the segments having a high-electric-field applied thereto and six of the segments having no- or low-electric-field applied thereto.

[0065] Not being bound by theory, the EC properties of EC rings can be used to derive the performance of an EC device such as the one illustrated in FIG. **6**. Taking an EC polymer as the EC material, an electric field change $\Delta E=100$ MV/m affords and entropy change of $\Delta S=0.081$ J/cm^{3}K and a heat absorbed from the cold end of $Q_c=24.3$ J/cm^3. In the cooling cycle, the heat exchange between the EC ring and external cold load occurs at the interface within the thermal diffusion length, $\delta=\sqrt{2\alpha/\omega}$, where ω is the angular frequency and $\alpha=k/(\rho c)$ is the thermal diffusivity. For EC polymer composites, adding small amounts of high thermal conductivity fillers can provide a thermal conductivity increase to greater than 0.5 W/mK, or even greater than 1 W/mK, without affecting the ECE.

[0066] In addition, although the cooling device with two rings rotating at a constant angular speed can work, a variable angular velocity, such as a stepwise rotation, can be used to reduce conduction heat loss between the hot and cold ends and thereby improve the heat exchange and regenerative process between the two rings along the z-direction. Naturally, improving heat exchange between the two rings improves the cooling power and efficiency of an EC device.

[0067] Referring to FIG. **8**, as the two EC rings **700**, **705** rotate in opposite directions, the two rings can be in an aligned position as illustrated in FIG. **8***a* or in an unaligned position as illustrated in FIG. **8***b*. In the aligned position, the gaps **720** of the top ring **700** align with the gaps **740** of the bottom ring **705** and the EC segments **710**, **730** of the top and bottom rings **700**, **705** completely overlap each other. In contrast, the unaligned position results in the gaps **720** in the top ring **700** to be in direct contact with EC segments **730** of the bottom ring **705**. It is appreciated that the unaligned position results in higher thermal conductivity along the 0-direction since the EC segments **710**, **730** thermally short circuit the thermal conduction gaps **720**, **740**. Stated differently, the thermal conduction path through the gaps **720**, **740** is by-passed when the EC rings are in the unaligned position.

[0068] Given the above, it is desirable that the time period which the two EC rings **700**, **705** are in an unaligned position be reduced to as low or little as practically possible. As such, another embodiment of the present invention rotates the two EC rings **700**, **705** opposite to each other, but not at constant angular velocity. Instead, drivers rotate the two EC rings **700**, **705** such a transient time (t_{trans}) during which the two rings are unaligned with each other is less than (FIG. **8***b*), and preferably mush less than, a static time (t_{stat}) during which the two rings are aligned with each other (FIG. **8***a*). Preferably, $t_{trans}<0.3\ t_{stat}$, and in some instances $t_{trans}<0.2\ t_{stat}$, and in other instances $t_{trans}<0.15\ t_{stat}$, and in still other instances $t_{trans}<0.05\ t_{stat}$. It is appreciated that during the static time, the two rings do not necessarily have relative motion to each and are in thermal contact and exchanging heat along the z-direction.

[0069] As mentioned above, step motors drive or move the two EC rings such that the transient time (t_{trans}) during which the two rings are in unaligned position is much shorter than the stationary time t_{stat}, during which the two rings are in the aligned position. In particular, FIG. **8***d* graphically illustrates how an EC segment U1 of the top ring **700** shown in FIG. **8***c* moves and overlaps with EC segments B1, B2, and B3 of the bottom ring **705** as a function of time.

[0070] Although two EC rings of an EC device rotate in opposite directions, a temperature profile of the device does not change with time once a steady state condition is established. Such a feature or aspect of the inventive EC device disclosed herein makes easily affords for an external thermal load to exchange heat with the EC segments at both the hot and cold ends. For example, direct contact of an aluminum (Al) plate (k_{Al}=205 W/mK at room temperature) with EC rings affords heat exchange between the rings and external thermal loads as schematically shown in FIG. **9***a* at reference numeral **920**. Because of the very high thermal conductivity of Al, the thickness of Al plate here can be in 0.1 mm or any thickness which is determined by the requirement of the device. Also, the lateral area of the Al heat exchange plate in contact with the rings can be the same as the area of one segment of the EC ring.

[0071] It is another embodiment, heat exchange plate(s) are stationary do not rotate with the EC rings. The heat exchange plate(s) are in direct thermal contact with the EC rings at the hot end and cold end in order to provide effective heat exchange between the EC segments and cold load T_c at the cold end and between EC segments and heat sink at the hot end T_h. The remaining areas between the two high thermal conductivity heat exchange plates can have a low thermal conductivity layer **930** thereon in order to prevent the heat conduction loss.

[0072] Friction due to rotation of the two rings **700**, **705** in the EC device **70** shown in FIG. **6** can cause damage to the EC segments and can be reduced or alleviated by an optional thin protective layer **910**. Examples of a thin protective layer includes, but is not limited to, a 50 micron thick layer of stainless steel, nickel alloy, copper alloy, cobalt, cobalt alloy, SiC, AlC, etc. The contact surfaces of the protective layers should be smooth to reduce friction and a thin lubricant layer (such as liquid or grease) may or may not be present between the protective layers **910**, thereby improving thermal contact and reducing friction between two protective layers. The thin coupling layers **910** are firmly attached to the EC rings **700**, **705** and do not have significant effect in causing heat loss between T_h and T_c.

[0073] As stated above, the EC segments can be made from EC polymer composites. Such ECE composites have an EC response of ΔT=9 K and Q_c=24.3 J/cm^3 under an electric field change of 100 MV/m at 300 K.

[0074] The EC segments in two EC rings can also be an EC ceramic, e.g. $Ba(Ti_{0.8}Zr_{0.2})TiO_3$ and other EC ceramics with high EC responses induced by a change of electric field. Such ceramics can have an EC response of $|\Delta T|>5$ K and Q_c=15.4 J/cm^3 under an electric field change of less than 20 MV/m at room temperature.

[0075] Such relatively high thermal conductivity EC ceramics (k=6 W/mK) make it possible to operate an EC device illustratively shown in FIG. **6** at higher frequencies than EC devices that use EC polymers. Also, for a ring of thickness=0.2 mm, the time for heat to conduct completely through two EC rings along a z-direction is about 0.11 seconds. Such a cooling device can achieve a cooling power greater than 90 W/cm^3 with a temperature span T_h-T_c=20 K and a COP>8.5.

[0076] Taking into consideration the brittleness of a ceramic EC segment, the thickness of a ceramic EC ring needs to be greater than the thickness of a polymer EC ring, e.g. 0.4 mm for a ceramic ring compared to 0.2 mm for a polymer ring. Such an increase in thickness will reduce the lower limit of the cooling power to 23 W/cm^3. However, it should be appreciated that this is still a high cooling power. By reducing the lateral dimensions and assembling the EC segment using polymer and epoxy to bond the small ceramic sections of EC elements into large area EC cooling elements, one can improve the fracture resistance of the ceramic EC segments.

[0077] A plurality of two EC ring units or pairs can be stacked together to form a bulk cooling device (or heat pump) as illustrated in FIG. **10** where **3** EC units or pairs are stacked together. It is appreciated that the number of EC units in the cooling device can vary, e.g. from 1 to 5 units, 5 to 10 units, 10 to 15 units, 15 to 20 units, 20 to 30 units, 30 to 40 units, 40 to 60 units, 60 to 80 units, 80 to 100 units or more than 100. In this manner, a plurality of first EC rings **700** and a plurality of second EC rings **705** are stacked alternately on top of each other. Also, each of the first EC rings **700** rotate in an opposite direction to and are in sliding contact with a paired second EC ring **705**.

[0078] A method, apparatus and/or embodiment for increasing the cooling power of the cooling device of FIG. **6** is also provided. Specifically, the way the electric field is applied is modified by applying electric field to several smaller regions on a particular EC segment instead of the enter EC region as illustrated in FIG. **6**. For example and for illustrative purposes only, an electric field can be applied to two regions as illustrated in FIG. **11**. The two regions with an electric field and the two regions without an electric field are arranged alternatively. Also, such a design can increase, e.g. double, the cooling power of an EC device compared with that in FIG. **6**. Hence, the cooling power of the cooling device is increased by increasing the number of regions with and without an applied electric field.

[0079] The heat exchange of the device shown in FIG. **11** is accommodated by increasing the number of the heat exchange plates accordingly. For example, the cooling device of FIG. **6** has one region with an applied electric field and one region without an electric field. Thus, two high thermal conductivity plates are used—one at T_h end and one T_c end—as shown in FIGS. **9***b* and **9***c*. However, the cooling device shown in FIG. **11** has two regions of high electric field and two regions without electric field. Therefore, four high thermal conductivity plates are used—one for each T_h end and one for each T_c end.

[0080] In general, the number of applied electric field regions depends on the size of the device. The cooling device in FIG. **6** has one pair of applied electric field regions while the example in FIG. **11** illustrates two pairs of applied electric field regions. A large size device can be divided into a large number of regions. It also depends on the thermal conduction loss between the hot and cold ends. As the number of regions for applying and removing electric field increases, the distance between the hot and cold ends will be reduced, which, in turn, will increase the heat conduction loss due to the increased temperature gradient between T_h and T_c in the device. Moreover, a large number of regions for applying and removing electric field in the cooling device may increase the design and manufacturing complication. Hence, design of the cooling devices takes into account some or all of the above mentioned factors into consideration.

[0081] In another embodiment, a method of increasing the cooling power of an EC device is provided. In particular, if the rings of the cooling devices of FIGS. **6**, **8**, and **11** have a large OD and ID, a relatively large empty space inside the ID of rings will be present. As such, the cooling power of the device is increased by adding co-axial smaller rings (small OD EC rings) that utilize the relatively large empty space as illustrated in FIG. **12**. It is appreciated that the device configuration illustrated in FIG. **12** can be used when a cooling device such as shown in FIG. **6** has a large outer diameter (e.g., 50 cm) and a large inner diameter (e.g., 30 cm).

[0082] By using the inner space, i.e. the space within the inner diameter, with rings of smaller outer diameter, the total cooling power per unit volume is increased. In such a cooling device design, the large and small diameter rings can rotate at the same angular velocity and the number of segments at each ring and number of regions of applying and removing electric field are optimized to achieve high performance in terms of the cooling power density, coefficient of performance, and temperature span between T_h and T_c. In the alternative, the small diameter rings do not rotate at the same angular velocity and/or do not have the same number of ring segments as the larger diameter outer rings.

[0083] In general, reducing the cooling power will increase the temperature span T_h-T_c. In the adiabatic condition, i.e., there is no heat exchange between the EC devices with external load and heat sinks at T_h and T_c, T_h-T_c then will be totally determined by the thermal conduction heat loss through the devices (from T_h and T_c) and by the operation temperature range of EC material. For the current designs of the cooling devices using the EC materials in consideration, a $T_h-T_c>40$ K can be obtained.

[0084] In the cooling devices illustrated in the figures, an electric field is applied to the EC segments and as EC rings rotate into and out of the region of high electric field temperature changes of the EC segments occur. In order to apply an electric field to EC segments, the EC segments are coated with thin films of an electrical conductor material in order to form or serve as an electrode. Such electrodes can be made from a thin layer of Al or gold (Au) have a typical thickness of less than 10 nm, less than 20 nm, less than 30 nm, less than 40 nm, less than 50 nm . . . less than 1 micron.

[0085] Turning now to FIGS. **13***a* and **13***b*, two different electrode patterns on a top EC ring **700** are shown. The bottom EC ring **705** has a similar electrode pattern and is not shown. In FIG. **13***a*, each EC segment **710** is covered by a single thin electrode U1 . . . U12 with no electrodes one the gaps **730**. It is appreciated that such an electrode pattern an electric field change will occur at one EC segment at a time since neighboring EC segments are separated by the electrically insulating low thermal conducting gaps **730**. For example, as the top ring **700** rotates clockwise, the EC segment U1 will enter the region of high electrical field, then U2 will enter the high electric field region, then U3, and so on. Analogously, the EC segment U7 will leave the region of high electric field, then U8, then U9, and so on.

[0086] However, each EC segment can be further divided into two or more electric sections as illustrated in FIG. **13***b*. Correspondingly, as each EC segment enters the high electric field, the electric field of each EC segment is increased at a smaller increment when compared to the design illustrated in FIG. **13***a*. For the case of FIG. **13***b*, in which there are two electrode sections, the increment of the electric field applied or removed is divided by 2, i.e. from E_H to ½ (E_H-E_L) or ½ E_H when E_L=0.

[0087] As the top ring rotates, the EC section U1a will enter the field region ½ E_H, and then E_H, at this time, U1b will enter ½ E_H, etc. A smaller field increment, in this case, ½ E_H, will improve the EC cooling device reliability and also the efficiency. In general, it is preferred that the electrode at each EC segment is divided into N sections, with N>1, and correspondingly, the electric field increment should also become E_H/N when $E_L=0$ or $(E_H-E_L)/N$ when $E_L \neq 0$. It is appreciated that the reduced electric field increment as the EC segment enters the high electric field region can improve the EC device performance since a large and sudden escalation of electric field will increase the probability of electric breakdown of the EC material.

[0088] In order to better embody the present invention but not limit its scope in any way, examples are provided below.

Examples

[0089] Using a device performance model, an EC ring having an anisotropic thermal conductivity is assumed. The thermal conductivity along and perpendicular to the z-direction are k_Z and k_Φ, respectively. Also, by preparing EC polymers differently, the k_Z and k_Φ can be varied. A base EC polymers having a thermal conductivity k=0.2 W/mK was assumed and the following two device parameters were used: Case (1): k_z=0.5 W/mK and k_Φ=0.2 W/mK, and Case (2): k_z=1 W/mK and k_Φ=0.2 W/mK.

[0090] For simulation purposes, an EC cooling device as illustrated in FIG. **6** was used, and the EC ring thickness was set at 0.2 mm, the outer diameter was 5.5 cm and the inner diameter was 3 cm. Given the EC ring thickness, a desirable thermal diffusion length of 0.2 mm was calculated. Each EC ring had 12 segments that were spaced apart from each other and joined together with a low thermal conductivity polymer of k=0.2 W/mK.

[0091] The cooling device illustratively shown in FIG. **6** was simulated to be subjected to a high electric field of 100 MV/m with the EC segments having a specific heat c=1.5 J/gK and a density ρ=1.8 J/cm^3. The results showed the EC device to exhibit a temperature change of ΔT=9 K, an entropy change of ΔS=0.081 J/cm^{3}K, and heat absorption from the cold end of Q_c=24.3 J/cm^3. Also, and during operation of the cooling device of FIG. **6**, when each segment undergoes an electric field change of E=100 MV/m, a total heat Q_c=8.11 J is absorbed, assuming the heat in each segment has enough time to be transported to the cold load via heat exchange. In Case (1), the thermal diffusion time was 1.3 seconds and this the time (1(2f) needed one EC segment to go through the change of electric field. When the electric field changes from high electric field E_H to low electric field, one EC segment will absorb 8.11 J heat from the cold load. In Case (2), the thermal diffusion time was 0.65 seconds.

[0092] In Case (1), and considering the fact that there are two rings in the EC device, the cooling power at the cold end is W_c=2×8.11/0.5=12.5 W. In Case (2), the total cooling power is 25 W. Also, and considering the EC device has EC rings with dimensions of 0.4 mm ring thickness and 5.5 cm OD, the cooling device in FIG. **6** exhibits a rather high cooling power density of greater than 26 W/cm^3.

[0093] These modeling results have indeed been confirmed by a finite element simulation of a real device in which a temperature span T_h-T_c=20 K, a cooling power >20 W/cm^3, and a coefficient of performance (COP) larger than 9 (Carnot COP is 15) for k=1 W/mK for EC segments were obtained. The temperature gradient between T_h and T_c will cause a heat conduction loss, which reduces the cooling power and efficiency. Hence the EC rings in the cooling device(s) illustrated in the figures are divided into segments with a low thermal conductivity gap between two neighboring segments.

[0094] It is appreciated that the disclosed examples and embodiments are presented for illustrative purposes only and are not meant to limit the scope of the invention. As such, it is the claims, and all equivalents thereof, that define the scope of the invention.

We claim:

1. A regenerative electrocaloric (EC) cooling device comprising:

a first EC ring having N spaced apart first ring high electric field regions (HEFRs) and N spaced apart first ring low electric field regions (LEFRs);

a second EC ring having N spaced apart second ring HEFRs and N spaced apart second ring LEFRs, N being equal to or greater than 1;

said first EC ring rotating in an opposite direction to said second EC ring and in sliding contact therewith, said N first ring HEFRs, N first ring LEFRs, N second ring HEFRs and N second ring LEFRs fixed in space during rotation of said first EC ring and said second EC ring;

at least one hot end located between a first ring HEFR and a first ring LEFR;

at least one cold end located between a second ring HEFR and a second ring LEFR;

an electrical power supply in communication with said first and second EC rings and producing an electric field thereacross, said electric field across said first and second EC rings reducing an entropy and increasing a temperature thereof such that said first EC ring is at a higher temperature than said second EC ring and vice versa; and

a fixed ring in thermal contact with at least one of said first EC ring and said second EC ring, said fixed ring having N hot ends at a temperature of T_h and N cold ends at a temperature of T_c, said fixed ring also having 2N spaced apart regions of heat exchange at said N hot ends and said N cold ends;

each of said heat exchange regions made from a high thermal conductivity material with a thermal conductivity >50 W/mK and separated from adjacent heat exchange regions by regions of a low thermal conductivity material with a thermal conductivity <0.3 W/mK;

said heat exchange regions at said N cold ends absorbing heat from an outside source of heat and said heat exchange regions at said N hot ends transferring heat to a heat sink such that heat is pumped from the outside heat source at T_c to the heat sink at T_h.

2. The regenerative device of claim **1**, wherein each of said N first ring HEFRs is oppositely disposed from and in sliding contact with each of said N second ring LEFRs and each of said N first ring LEFRs is oppositely disposed from and in sliding contact with each of said N second ring HEFRs during said rotating of said first EC ring relative to said second EC ring.

3. The regenerative device of claim **2**, wherein heat passes from said N first ring HEFRs to said N second ring LEFRs and from said N second HEFRs to said N first ring HEFRs.

4. The regenerative device of claim **3**, wherein said first EC ring and said second EC ring rotate relative to a fixed ring, said fixed ring having N hot ends at a temperature of T_h and N cold ends at a temperature of T_c, said fixed ring also having 2N spaced apart regions of heat exchange (at T_h and T_c), each of said heat exchange regions made from a high thermal conductivity material (thermal conductivity >50 W/mK) and separated from adjacent regions of heat exchange by regions of low thermal conductivity material (thermal conductivity <0.3 W/mK). The heat exchange regions at T_c absorb heat from an outside source of heat and the heat exchange regions at T_h transfer heat to a heat sink such that heat is pumped from an outside heat source at T_c to a heat sink at T_h.

5. The regenerative EC device of claim **4**, wherein said first EC ring has a plurality of first ring EC segments and subsets of said plurality of first ring EC segments are located within each of said N first ring HEFRs and other subsets of said plurality of first ring EC segments are located within each of said N first ring LEFRs as said first EC ring rotates; and

said second EC ring has a plurality of second ring segments and subsets of said plurality of second ring EC segments are located within each of said N second ring HEFRs and other subsets of said plurality of second ring EC segments are located within each of said N second ring LEFRs as said second EC ring rotates.

6. The regenerative device of claim **5**, wherein a ring segment of each of said subsets of said plurality of first ring EC segments travels from a first ring HEFR into the adjacent first ring LEFR, causing a lowering of temperature to T_c as a ring segment of each of said other subsets of said plurality of first ring segments travels from a first ring LEFR into the adjacent first ring HEFR, causing a rising in temperature to T_h.

7. The regenerative device of claim **6**, further comprising a low thermal conductivity (thermal conductivity <0.3 W/mK) divider between adjacent first ring EC segments and between each adjacent second ring EC segments.

8. The regenerative device of claim **7**, further comprising a ring rotation source operable to rotate said first EC ring and said second EC ring opposite to each other, said ring rotation source also operable to rotate said first EC ring relative to said second EC ring at a constant angular speed or rotate said first EC ring relative to said second EC ring at a non-constant angular speed.

9. The regenerative device of claim **7**, wherein said ring rotation source has a first angular speed when said plurality of first ring segments are not aligned with said plurality of second ring segments and a second angular speed when said plurality of first ring segments are aligned with said plurality of second ring segments, said first angular speed greater than said second angular speed.

10. The regenerative devices of **7**, wherein each of said plurality of first ring segments and each of said plurality of second ring segments is covered by a single electrode, said electrical power supply applying an electric field of magnitude $|E_H-E_L|$ across each ring segment via said single electrode.

11. The regenerative device of **7**, wherein each of said plurality of first ring segments and each of said plurality of second ring segments is covered by a M electrodes, said electrical power supply applying an electric field of magnitude $|E_H-E_L|$ at increments of $|E_H-E_L|/M$ across each ring segment via said M electrodes.

12. The regenerative device of claims of **7**, further comprising a plurality of first EC ring-second EC ring-fixed ring units stacked together to form a large cooling device.

13. The regenerative device of claim **7**, further comprising a first small OD EC ring and a second small OD EC ring, said first and second small EC rings located and occupying an inner space within an inner diameter of said first and second EC rings.

14. The regenerative device of claim **7**, further comprising a plurality of first EC ring-second EC ring units stacked together to form a large cooling device and a plurality of first small OD EC ring and a second small OD EC ring units, said plurality of first and second small EC rings units located and occupying inner spaces within inner diameters of said plurality of first EC ring-second EC ring units.

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