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(54) Title: MAGNETOCALORIC REFRIGERATION REGENERATOR USING THE DEMAGNETIZING

(57) Abstract: The present invention relates to a refrigeration apparatus and method based on magnetocaloric effect. The object of the present invention is a magnetocaloric refrigeration apparatus comprising: at least one external magnetic field source configured to produce a magnetic field; at least one regenerator bed disposed within the magnetic field and containing a magnetocaloric material; means of rotation configured to change the relative orientation of the magnetic field; a tubing circuit arranged to encompass the at least one regenerator bed and connecting the at least one regenerator bed to a low-temperature side and a high-temperature side of a heat exchange unit; heat exchange fluid inside the tubing circuit; a flow control device; wherein the magnetocaloric material comprises an anisotropic shape. The apparatus allows the occurrence of a magnetocaloric effect in any kind of magnetocaloric material subjected to a rotating magnetic field.



MAGNETOCALORIC REFRIGERATION REGENERATOR USING THE DEMAGNETIZING FIELD-BASED ROTATING MAGNETOCALORIC EFFECT

DESCRIPTION

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FIELD OF THE INVENTION

The present invention relates to a refrigeration apparatus and method based on the magnetocaloric effect.

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PRIOR ART

Most of the conventional refrigeration, air conditioning, and heat pumping devices are based in vapor-compression technology, in which a refrigerant is cycled through
15 pressurization (temperature increases) and expansion (temperature decreases), with each of these steps separated by heat exchange at the condenser and evaporator, respectively. This causes an asymmetric heat exchange, removing heat from the volume surrounding the condenser (in the case of domestic refrigerators, the air inside the refrigerator) and dissipating it to the air surrounding the evaporator. The climate crisis
20 is leading to international laws for strict limitations on the use of the typical gaseous refrigerants, as they rely on the use greenhouse gases as the active material and are responsible for 8% of all greenhouse gas emissions.

Magnetic refrigeration devices have an analogous working principle, where the pressurization and expansion of a refrigerant are replaced by the application and
25 removal of a magnetic field on a solid state magnetocaloric material, respectively. By eliminating the use for these greenhouse gases and potentially improving energetic efficiency, this technology promises to greatly reduce the environmental footprint of the refrigeration industry.

The conventional magnetocaloric effect is a well-documented effect based on changing
30 the external magnetic field amplitude to which a magnetocaloric material is exposed. In

most materials, increasing the magnetic field amplitude increases the magnetization of the material, which induces ordering of the material's magnetic structure. If the magnetic field intensity change is made "quickly" (not slowly enough to maintain thermal equilibrium with the environment at all times, *i.e.* isothermally), the reduction
5 of entropy of the magnetic structure is compensated through a corresponding increase of the entropy of the atomic lattice, manifested as an increase of temperature.

However, the magnetocaloric effect often relies in the use of large amounts of permanent magnets, such as NdFeB magnets, which are expensive.

The present invention provides a solution that aims to achieve refrigeration by means
10 of the magnetocaloric effect using less intense and, thereby, less expensive magnets, enabling the exploration of new device architectures which can result in cheaper and more efficient magnetic refrigeration devices.

SUMMARY OF THE INVENTION

15 An object of the present invention is a magnetocaloric refrigeration apparatus comprising:

- at least one external magnetic field source configured to produce a magnetic field;
- 20 - at least one regenerator bed containing a magnetocaloric material, being said at least one regenerator bed disposed within the magnetic field;
- means of rotation configured to change the relative orientation of the magnetic field by either rotating the magnetocaloric material or rotating the magnetic field source or rotating both the magnetocaloric material and the magnetic field
25 source by an angle within the range of 0° to 180°;
- a tubing circuit arranged to encompass the at least one regenerator bed and connecting the at least one regenerator bed to a low-temperature side and to a high-temperature side of a heat exchange unit;
- heat exchange fluid, being said heat exchange fluid inside the tubing circuit;

- a flow control device configured to control and direct the flow of heat exchange fluid through the tubing circuit;

wherein the magnetocaloric material of the at least one regenerator bed comprises an anisotropic shape.

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The demagnetizing field is the tendency for a material to generate an internal magnetic field which opposes the externally applied one. It is shape-dependent, being most significant along the shortest dimension. If an anisotropically shaped material (i.e. non-spherical) is rotated while an applied magnetic field is kept constant, the change of demagnetizing field results in a change of the internal magnetic field and subsequent change on the magnetization of the material, illustrated in Figure 1. This is analogous to a change in the applied magnetic field amplitude for the case where the orientation of the material is kept constant. Thus, this is an alternative way of inducing the magnetocaloric effect.

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In an advantageous aspect of the present invention, the magnetocaloric refrigeration apparatus can function without the typical modulation of magnetic field amplitude by application and removal of the magnetic field applied to the magnetocaloric material, instead changing, by rotation, the direction of the magnetic field applied to the magnetocaloric material. The rotation of the magnetic field to induce a magnetocaloric effect may also be applied to isotropic, polycrystalline magnetocaloric materials.

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Moreover, the anisotropic shape of the magnetocaloric material allows the occurrence of a magnetocaloric effect in any kind of magnetocaloric material subjected to a rotating magnetic field, such as polycrystalline magnetocaloric materials, which are less expensive than using large amounts of anisotropic, single crystal magnetocaloric materials.

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In a preferred embodiment of the present invention, the means of rotation are configured to change the relative orientation of the magnetic field by either rotating the magnetocaloric material or rotating the magnetic field source or rotating both the magnetocaloric material and the magnetic field source by an angle of 90°. A 90° rotation

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of the magnetic field applied to the regenerator bed allows the maximum amplitude of the magnetocaloric effect in the anisotropically-shaped magnetocaloric material.

5 **DESCRIPTION OF THE FIGURES**

Figure 1 illustrates a schematic of the high (left-hand side) and low (right-hand side) demagnetizing-field configurations in a magnetic sample with a high aspect-ratio shape. The demagnetizing-field (H_d) will be greatest when the applied external magnetic field (H_a) is parallel to the shortest dimension, and thus the total internal magnetic field lower. Conversely, when the applied external magnetic field is parallel to the longest dimension, the demagnetizing field will be lowest. Thus, the internal magnetic field on any high-aspect ratio sample can be altered via rotation. The arrow density and length are not indicative of the magnetic field strength.

Figure 2 illustrates the magnetocaloric effect amplitude ($\Delta T(T)$) as a function of the starting temperature for the three distinct cases: applying the field parallel to the longest dimension of the magnetocaloric material (length – d_1), the shortest dimension of the magnetocaloric material (thickness – d_3), and rotating between the two orientations.

Figure 3 illustrates the magnetic entropy difference, as an indirect estimate of the magnetocaloric effect obtained through magnetic measurements, associated with field rotation. This was estimated by subtracting the entropy difference along the length (d_1) and the width (d_2) of the magnetocaloric material.

DETAILED DESCRIPTION

The more general and advantageous configurations of the present invention are described in the Summary of the Invention. Such configurations are detailed below in

accordance with other advantageous and/or preferred embodiments of implementation of the present invention.

In a preferred embodiment of the present invention, the magnetocaloric material is comprised of a plurality of sets of rectangular prism-shaped plates, comprising facets with dimensions length d_1 , width d_2 , and thickness d_3 , being $d_1 > d_2 > d_3$ for each separate rectangular prism-shaped plate. The anisotropic shape of the rectangular prism-shaped plates allows the occurrence of a magnetocaloric effect in the magnetocaloric material when subjected to a rotating magnetic field.

In a preferred aspect of the present invention, the rectangular prism-shaped plates of the magnetocaloric material are parallel to each other along d_2 , with the $d_1 \times d_3$ planes being parallel, and within each set of parallel plates, each pair of adjacent plates are spaced by a constant value s . The same orientation of each plate and the even spacing between plates contribute to the maximization of the magnetocaloric effect within the set of plates.

Preferably, each parallel rectangular prism-shaped plate of the magnetocaloric material has a length d_1 oriented along the direction of the flow of heat exchange fluid in the tubing circuit, being the magnetic field oriented parallel to the length d_1 of the magnetocaloric material. The alignment of the length d_1 of the magnetocaloric material with the flow of heat exchange fluid in the tubing circuit maximizes the heat exchange as the temperature of the magnetocaloric material increases or decreases upon the rotation of the magnetic field, being the length d_1 the longest dimension of the rectangular prism-shaped plate of the magnetocaloric material. In addition, the amplitude of the magnetocaloric effect is greater when the applied magnetic field is oriented parallel to the longest dimension of the magnetocaloric material, as illustrated in Figure 2.

In addition, the means of rotation are configured to rotate the magnetic field in such way that the magnetic field is either oriented parallel to the width d_2 of the magnetocaloric material, or oriented parallel to the thickness d_3 of the magnetocaloric

material. The rotation of the magnetic field applied to the magnetocaloric material induces the magnetocaloric effect which leads to a change in the temperature of the material, wherein effect is dependent of the change in amplitude of the magnetic field, which is different when the magnetic field is rotated to become oriented parallel to the width d_2 or to the of the magnetocaloric material thickness d_3 of the magnetocaloric material. The dependence of the magnetocaloric effect is shown in Figure 3, where it is possible to see how the peak effect of the rotating magnetocaloric effect does not occur for the maximum applied magnetic field (1 T) but instead occurs for an applied magnetic field with an intermediate value between 0.3 and 0.6 T.

This advantageous effect of the present invention, allows the use of weaker magnets as external magnetic field source of the magnetocaloric refrigeration apparatus, instead of using powerful magnets capable to generate magnetic fields of 1T or above, such as NdFeB magnets, which are more expensive.

In a relevant aspect of the present invention, the demagnetizing field-based rotating magnetocaloric effect has a lower amplitude but a more constant profile in temperature (does not fall as rapidly with lowering of temperature). Moreover, rotating the applied magnetic field can be energetically less demanding as compared to modulating its amplitude, as well as more efficient with respect to amount of magnet material to use as external magnetic field source.

In a preferred embodiment of the present invention, each set of parallel rectangular prism-shaped plates is encased within the tubing circuit, and have varying width d_2 depending on the location of the tubing circuit. The different width d_2 values may also affect the overall magnetocaloric effect, allowing different configurations of the tubing circuit to generate different magnetocaloric effect within the regenerator bed.

In more preferred embodiment of the present invention, the magnetocaloric refrigeration apparatus comprises at least one peripheral magnetic field source arranged to envelop the tubing circuit. The peripheral magnetic field sources are configured to generate an homogeneous magnetic field and may comprise electromagnets or permanent magnets configured as hollow cylinder-shaped Halbach

arrays. The peripheral magnetic field sources, by enveloping the tubing circuit, generate an additional homogeneous magnetic that amplifies the amplitude of the magnetocaloric effect in the anisotropically-shaped magnetocaloric material through a change of internal demagnetization field for the anisotropically-shaped magnetocaloric material at the steady-state operation temperature of the peripheral magnetic field sources.

In another embodiment of the present invention, the external magnetic field source comprises permanent magnets or electromagnets.

In another embodiment of the present invention, the means of rotation comprise a motor and the flow control device comprises a pump.

A preferred embodiment of the present invention comprises a housing made of thermal insulating material to prevent unintended heat exchange with the environment.

It is also an object of the present invention a method of refrigeration performed by the magnetocaloric refrigeration apparatus comprising the following steps:

- i) exposing a refrigerator bed containing magnetocaloric material to a constant magnetic field generated by an external magnetic field source;
- ii) rotating the magnetic field by an angle within the range of 0° to 180° by rotating the magnetocaloric material or rotating the magnetic field source or rotating both the magnetocaloric material and the magnetic field source;
- iii) exchanging heat between the magnetocaloric material and the low-temperature side of the heat exchange unit;
- iv) rotating the magnetic field by an angle within the range of 0° to 180° by rotating the magnetocaloric material or rotating the external magnetic field source or rotating both the magnetocaloric material and the external magnetic field source;
- v) exchanging heat between the magnetocaloric material and the high-temperature side of the heat exchange unit;
- vi) repeat the steps ii – v until a preset temperature is reached.

In the first step, the regenerator bed comprising the magnetocaloric material is subjected to a constant magnetic field, being at a constant temperature. As the magnetic field is rotated, either by rotating the magnetocaloric material, or rotating the external magnetic field source, or both, the temperature of the magnetocaloric material decreases, which results in the heat exchange between the magnetocaloric material of the regenerator bed and the low-temperature side the heat exchange unit, wherein the heat exchange is facilitated by the heat exchange fluid being circulated in the tubing circuit. When the temperature reaches an equilibrium, the magnetic field is rotated again, thereby inducing an increase of the temperature of the magnetocaloric material. The heat is then exchanged between the magnetocaloric material of the regenerator bed and the high-temperature side of the heat exchange unit, until the temperature reaches an intermediate temperature and the cycle can be repeated. The number of repeated cycles depends on the defined preset temperature, which corresponds to the desired temperature to be achieved by the refrigeration method.

In a preferred method of refrigeration performed by the magnetocaloric refrigeration apparatus, the magnetic field is rotated by an angle of 90° .

In another preferred method of refrigeration, the regenerator bed containing a magnetocaloric material is exposed to a constant magnetic field aligned with the length d_1 of the magnetocaloric material.

Furthermore, the magnetic field is rotated 90° by rotating the magnetocaloric material or rotating the magnetic field source or rotating both the magnetocaloric material and the magnetic field source, being the magnetic field either aligned with the width d_2 of the magnetocaloric material or being magnetic field aligned with the thickness d_3 of the magnetocaloric material.

Of course, the preferred embodiments shown above are combinable, in different possible configurations, being the present invention not limited to the embodiments previously described.

CLAIMS

1. A magnetocaloric refrigeration apparatus comprising:
 - at least one external magnetic field source configured to produce a magnetic field;
 - at least one regenerator bed containing a magnetocaloric material, being said at least one regenerator bed disposed within the magnetic field;
 - means of rotation configured to change the relative orientation of the magnetic field by either rotating the magnetocaloric material or rotating the magnetic field source or rotating both the magnetocaloric material and the magnetic field source by an angle within the range of 0° to 180° ;
 - a tubing circuit arranged to encompass the at least one regenerator bed and connecting the at least one regenerator bed to a low-temperature side and to a high-temperature side of a heat exchange unit;
 - heat exchange fluid, being said heat exchange fluid inside the tubing circuit;
 - a flow control device configured to control and direct the flow of heat exchange fluid through the tubing circuit;

wherein the magnetocaloric material of the at least one regenerator bed comprises an anisotropic shape.

2. A magnetocaloric refrigeration apparatus according to the previous claim wherein the means of rotation are configured to change the relative orientation of the magnetic field by either rotating the magnetocaloric material or rotating the magnetic field source or rotating both the magnetocaloric material and the magnetic field source by an angle of 90° .

3. A magnetocaloric refrigeration apparatus according to any of the previous claims wherein the magnetocaloric material is comprised of a plurality of sets of rectangular prism-shaped plates, comprising facets with dimensions length d_1 , width d_2 , and thickness d_3 , being $d_1 > d_2 > d_3$ for each separate rectangular prism-shaped plate.

4. A magnetocaloric refrigeration apparatus according to claim 3 wherein the rectangular prism-shaped plates are parallel to each other along d_2 , with the $d_1 \times d_3$ planes being parallel, and within each set of parallel plates, each pair of adjacent plates are spaced by a constant value s .
5. A magnetocaloric refrigeration apparatus according to claim 4 wherein each parallel rectangular prism-shaped plate of the magnetocaloric material has a length d_1 oriented along the direction of the flow of heat exchange fluid in the tubing circuit, being the magnetic field oriented parallel to the length d_1 of the magnetocaloric material.
6. A magnetocaloric refrigeration apparatus according to claims 4 – 5 wherein the means of rotation are configured to rotate the magnetic field in such way that the magnetic field is oriented parallel to the width d_2 of the magnetocaloric material.
7. A magnetocaloric refrigeration apparatus according to claims 4 – 5 wherein the means of rotation are configured to rotate the magnetic field in such way that the magnetic field is oriented parallel to the thickness d_3 of the magnetocaloric material.
8. A magnetocaloric refrigeration apparatus according to claims 4 – 7 wherein each set of parallel rectangular prism-shaped plates is encased within the tubing circuit, and have varying width d_2 depending on the location of the tubing circuit.
9. A magnetocaloric refrigeration apparatus according to any of the previous claims comprising at least one peripheral magnetic field source arranged to envelop the tubing circuit, being said at least one peripheral magnetic field source configured to generate an homogeneous magnetic field.
10. A magnetocaloric refrigeration apparatus according to claim 9 wherein at least one peripheral magnetic field source comprises electromagnets or permanent magnets configured as hollow cylinder-shaped Halbach arrays.

11. A magnetocaloric refrigeration apparatus according to any of the previous claims wherein the least one external magnetic field source comprises permanent magnets or electromagnets.
12. A magnetocaloric refrigeration apparatus according to any of the previous claims wherein the means of rotation comprise a motor and the flow control device comprises a pump.
13. A magnetocaloric refrigeration apparatus according to any of the previous claims comprising a housing made of thermal insulating material.
14. A method of refrigeration performed by the magnetocaloric refrigeration apparatus of claims 1 – 13 comprising the following steps:
 - vii) exposing a refrigerator bed containing magnetocaloric material to a constant magnetic field generated by an external magnetic field source;
 - viii) rotating the magnetic field by an angle within the range of 0° to 180° by rotating the magnetocaloric material or rotating the external magnetic field source or rotating both the magnetocaloric material and the external magnetic field source;
 - ix) exchanging heat between the magnetocaloric material and the low-temperature side the heat exchange unit;
 - x) rotating the magnetic field by an angle within the range of 0° to 180° by rotating the magnetocaloric material or rotating the external magnetic field source or rotating both the magnetocaloric material and the external magnetic field source;
 - xi) exchanging heat between the magnetocaloric material and the high-temperature side the heat exchange unit;
 - xii) repeat the steps ii – v until a preset temperature is reached.
15. A method of refrigeration to claim 14 wherein the magnetic field is rotated by an angle of 90°.

16. A method of refrigeration according to claims 14 – 15 wherein the regenerator bed containing a magnetocaloric material is exposed to a constant magnetic field aligned with the length d_1 of the magnetocaloric material.

17. A method of refrigeration according to claim 14 – 16 wherein the magnetic field is rotated 90° by rotating the magnetocaloric material or rotating the magnetic field source or rotating both the magnetocaloric material and the magnetic field source, being the magnetic field aligned with the width d_2 of the magnetocaloric material.

18. A method of refrigeration according to claim 14 – 16 wherein the magnetic field is rotated 90° by rotating the magnetocaloric material or rotating the magnetic field source or rotating both the magnetocaloric material and the magnetic field source, being the magnetic field aligned with the thickness d_3 of the magnetocaloric material.

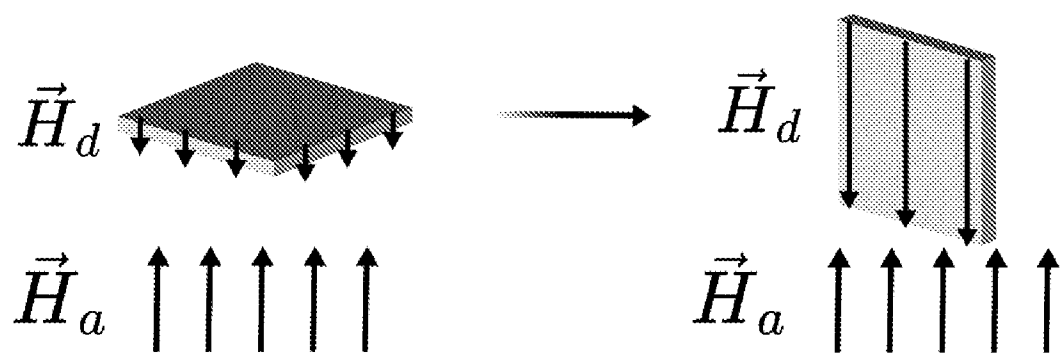


Figure 1

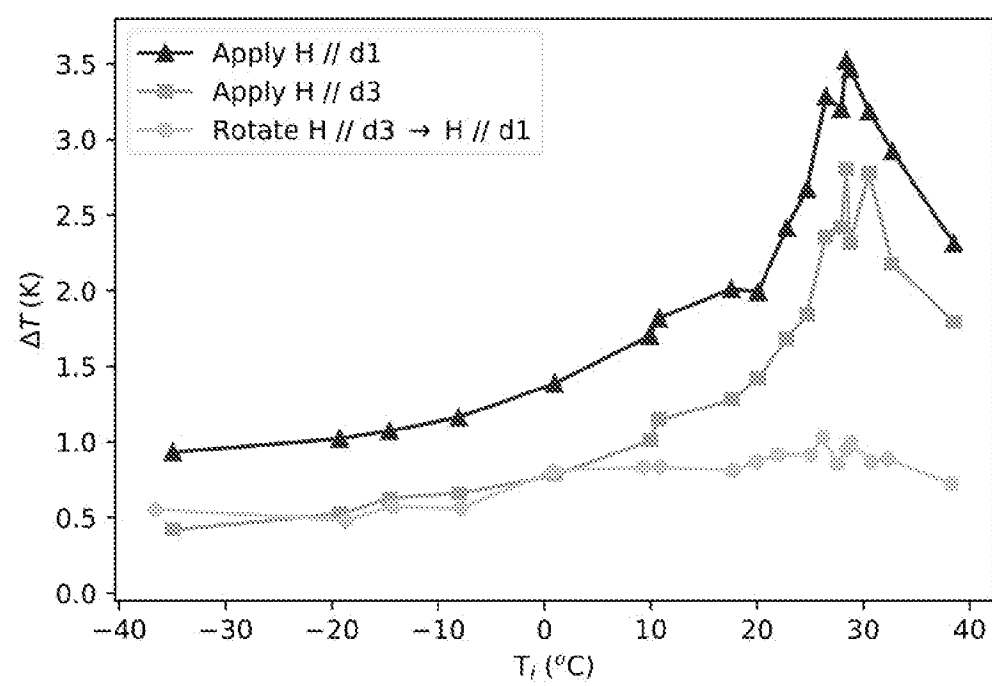


Figure 2

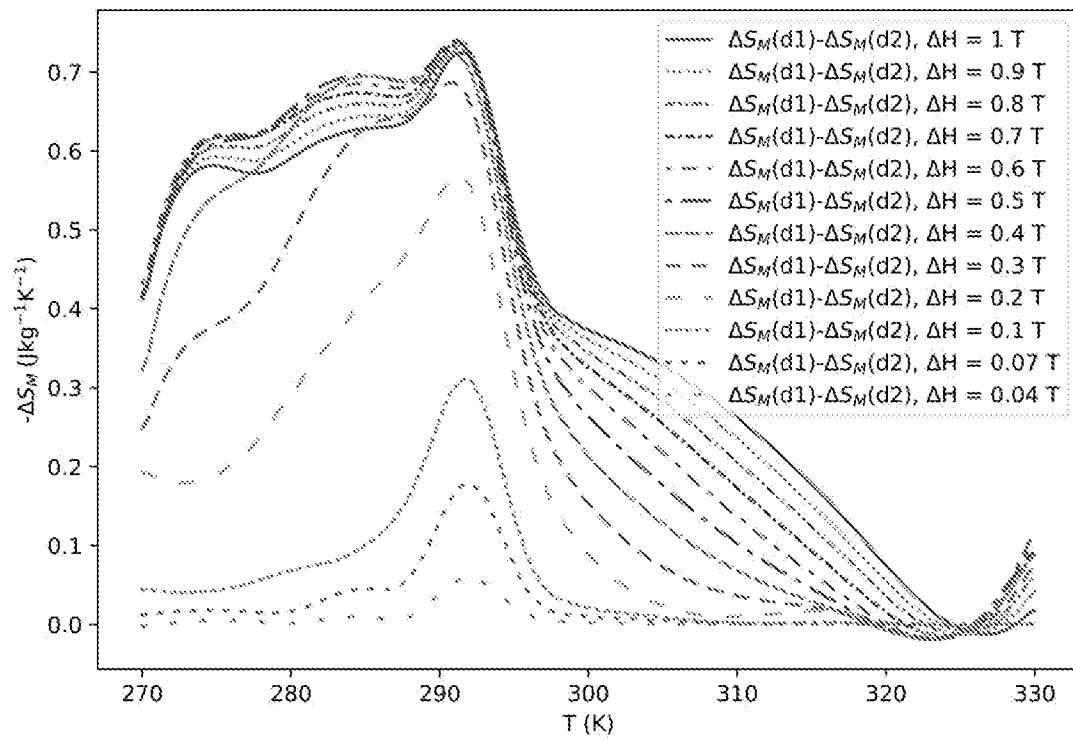


Figure 3

INTERNATIONAL SEARCH REPORT

International application No

PCT/IB2024/055783

A. CLASSIFICATION OF SUBJECT MATTER

INV. F25B21/00 H10N15/00

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F25B H02N H10N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2022/015128 A1 (UNIV INT RABAT [MA]) 20 January 2022 (2022-01-20)	1,2,9-18
A	the whole document -----	3-8
X	US 2013/019610 A1 (ZIMM CARL B [US] ET AL) 24 January 2013 (2013-01-24)	1,2,9-18
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X	EP 2 796 811 A1 (UNIV DENMARK TECH DTU [DK]) 29 October 2014 (2014-10-29)	1,2,9-18
A	the whole document -----	3-8

☐

Further documents are listed in the continuation of Box C.

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See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search

28 August 2024

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
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