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(54) **SOLID-STATE REFRIGERATION DRIVER BASED ON RECOVERY OF MECHANICAL WORK OF UNLOADING, AND REFRIGERATION APPARATUS**

(57) The present disclosure relates to a rotary solid-state cooling actuator based on unloaded mechanical work recovery and a solid-state cooling apparatus. The rotary solid-state cooling actuator includes: a rotary motor, a main transmission shaft driven by the rotary motor to rotate, N eccentric transmission mechanisms installed at different axial positions of the main transmission shaft, N pistons driven by the N eccentric transmission mechanisms to perform reciprocating motion, and N elastocaloric materials periodically loaded and unloaded through the reciprocating motion of the N pistons. The N eccentric transmission mechanisms have different phase angles, so that the N elastocaloric materials are unloaded in different time periods; each elastocaloric material releases its own mechanical work during unloading to provide thrust for rotation of the main transmission shaft; and N is an integer greater than 1.

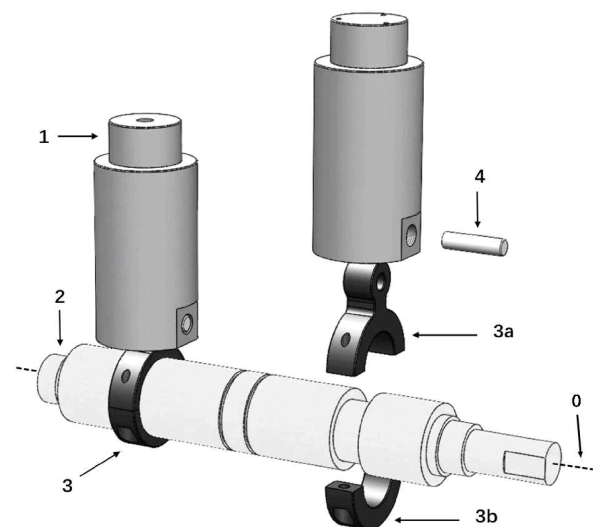


FIG. 2

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Description

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to Chinese Patent Application No. 202311708973.6, filed on December 13, 2023, the contents of which are hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] The present disclosure relates to the technical field of solid-state cooling, and particularly relates to a rotary solid-state cooling actuator (or called "refrigeration driver") capable of realizing recovery of unloaded mechanical work of an elastocaloric material under rotational motion, and a solid-state cooling apparatus (or called "refrigeration apparatus") including the same.

BACKGROUND

[0003] Space cooling is an important guarantee for people to maintain a high quality of life in modern times, and includes the use of air conditioners to reduce indoor temperatures, or the use of refrigerators to preserve food in a specific space at low temperatures. However, with the challenges of sustainable development in the future, the existing refrigeration apparatus based on gas compression expose many problems: firstly, refrigerants used in the gas compression refrigeration apparatus have many problems. Worldwide, the refrigerants (e.g., chlorine-containing refrigerants and bromine-containing refrigerants) in the gas compression refrigeration apparatus are massively manufactured and released into the environment. Although such refrigerants are not toxic to organisms, evaporation of the refrigerants to the atmosphere causes a drastic drop in ozone content of the atmosphere, and the Earth's atmosphere is irreversibly damaged under the chemical action of the refrigerants. Under ozone holes, the surface of the Earth is exposed to a large amount of direct ultraviolet radiation, which not only raises global temperatures and induces more extreme weather, but also easily causes adverse effects on organisms (e.g., skin cancer) under excessive ultraviolet radiation. Although new types of refrigerants (e.g., fluorine-containing refrigerants and ammonia-containing refrigerants) have been developed nowadays through technical iterations to reduce harm to the environment, these refrigerants have the disadvantage of being flammable and explosive, presenting a significant safety risk in public use. Secondly, due to the low energy conversion rate of the existing gas compression refrigeration, the electric energy produced by most power stations is not well converted during refrigeration, resulting in great waste of public resources. The current indicator for evaluating energy efficiency performance of a cooler or refrigerator is the energy efficiency ratio (based on a

ratio of output cooling power to input electrical power). For example, the energy efficiency ratio of common commercial air conditioners is generally about 2.3 to 3.5. If an air conditioner with a higher energy efficiency ratio (e.g., greater than 6) could be used for cooling, the same cooling effect could be obtained by use of half of the original electric energy. However, due to low entropy change of gas-liquid phase transition, the improvement of the energy efficiency ratios of those refrigeration apparatuses has encountered a technical bottleneck. In view of the above, the proposal and development of a new generation of environment-friendly and efficient cooling technology have become an important prerequisite for achieving sustainable development of humanity in the future.

[0004] Elastocaloric solid-state cooling technology is a novel cooling technique utilizing first-order phase transitions of solid materials. This technology induces a phase transition in the material by applying mechanical deformation, causing latent heat release and absorption, thereby lowering the temperature of a target object. An elastocaloric cooling cycle generally includes four processes: loading, holding and heat exchange, unloading, and holding and heat exchange. Since the proposal of this new technique by the British scientists in 2004, this new technique has attracted widespread attention from researchers around the world. The most important reason is its high energy conversion rate, safety during use, and no additional environmental emissions. In Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies issued by the U.S. Department of Energy in 2014, the elastocaloric solid-state cooling technology employing materials with elastocaloric properties obtained the highest score and was evaluated as one of the cooling technologies most likely to replace the existing gas compression refrigeration technology. The materials with elastocaloric properties (or called "elastocaloric materials") refer to solid materials with elastocaloric effect. The elastocaloric effect is one of thermal effects of solid materials, and involves the release or absorption of heat caused by the material undergoing strain due to the application of an external stress field. The phase transition-based elastocaloric effect of the materials with elastocaloric properties exhibits high entropy change, which can greatly improve energy conversion rate. There are many materials having elastocaloric properties, including shape memory alloys, natural rubber, synthetic polymers, plastic crystals, etc. Among them, shape memory alloys (such as nickel-titanium alloy, copper-aluminum-manganese alloy, nickel-manganese-copper-cobalt alloy, nickel-iron-gallium alloy, etc.) are widely used in the elastocaloric solid-state cooling technology due to their extremely high phase transition entropy and material energy efficiency ratio. For example, the widely used nickel-titanium alloy can produce an entropy change of 0.32 J/cm³K under adiabatic phase transition, and the entropy change is

much higher than the entropy change ($0.035 \text{ J/cm}^3\text{K}$) of the most widely used gas compression refrigerant R-32 (hydrofluorocarbon) nowadays. Due to the high phase transition entropy, the energy efficiency ratio of shape memory alloys can be greater than 30. In recent years, the research on elastocaloric solid-state cooling has yielded a plurality of research results in the development of prototypes, particularly in terms of cooling effect, a large temperature difference of 50 K and a specific cooling power of 6 W/g are realized. However, an actual operating energy efficiency ratio (around 1) of prototypes is far lower than the material energy efficiency ratio. Problems in energy utilization and conversion severely hinder further commercialization of this technology.

[0005] Inefficient use of unloaded mechanical work of the elastocaloric materials when the materials return from deformation to their original state is one of the main reasons for the low system energy efficiency ratio of the elastocaloric solid-state cooling prototype. When an elastocaloric material is in a deformed state, the material is in an energy-storing state; and if external constraints are removed, the elastocaloric material could release the internally stored mechanical energy. If this part of mechanical work can be utilized, power requirements for external actuators can be greatly reduced, thereby achieving a higher system energy efficiency ratio. The existing elastocaloric cooling prototypes generally adopt linear drive structures (e.g., a hydraulic push rod and a linear push rod). For example, a research team from the University of Michigan designed and developed a cooling prototype taking a hydraulic push rod as an actuator, operating based on compression of a nickel-titanium alloy tube, and using water as a heat exchange medium. The cooling prototype achieved a maximum temperature difference of 20 K, and the result was published in the international academic journal *Science*; A research team from the University of Ljubljana also used a hydraulic push rod as an actuator of a prototype and used a sleeve structure to compress a nickel-titanium alloy tube to achieve the elastocaloric effect, and the result was published in the international academic journal *Nature Energy*. Chinese Patent No. CN201810660524.1 (Publication No. CN108954901A, published on December 7, 2018) proposed an elastocaloric cooling apparatus utilizing compressive deformation of a nickel-titanium alloy tube, in which water is used as a heat transfer medium, the nickel-titanium alloy tube is compressed to undergo compressive deformation through axial reciprocating motion of a linear motor, and an external water pump is used to drive water to circulate to perform convective heat transfer on the nickel-titanium alloy tube. Although the linear drive is conceptually feasible, when there is no external power supply, the ram is locked due to mechanical constraint, whether a linear motor or a hydraulic device is used. In an actual unloading process, electric energy still needs to be input to the actuator for

retracting the ram, which may increase power consumption of the actuator. If the ram is not a moving part, the mechanical energy released by a material during unloading cannot be transferred to another stage to drive the next loading. In contrast, the mechanical energy can be easily transferred by rotation. During the unloading process, a linear motion of the material may be used to drive rotation of a shaft in a tangential direction and maintain the rotation of the shaft; and the rotating shaft can keep driving the compression of the next stage. In addition, a rotary drive system has high mechanical efficiency (a ratio of electric energy input power to mechanical output power) due to fewer mechanisms and components. An efficient rotary drive system has the mechanical efficiency of 90%, which can greatly reduce electricity waste during its own energy conversion. Despite the great application potential of the rotary drive system in elastocaloric cooling, the existing literatures and patents have not provided any clear technical route or structural design for drive systems to date.

SUMMARY

[0006] In order to solve at least one of the above problems, the present disclosure provides a rotary solid-state cooling actuator based on unloaded mechanical work recovery, and a solid-state cooling apparatus including the same.

[0007] In a first aspect of the present disclosure, there is provided a rotary solid-state cooling actuator based on unloaded mechanical work recovery, including: a rotary motor, a main transmission shaft driven by the rotary motor to rotate, N eccentric transmission mechanisms installed at different axial positions of the main transmission shaft and driven by the main transmission shaft, N pistons respectively driven by the N eccentric transmission mechanisms to perform reciprocating motion, and N elastocaloric materials periodically loaded and unloaded through the reciprocating motion of the N pistons, wherein N is an integer greater than 1; the N eccentric transmission mechanisms have different phase angles relative to the main transmission shaft, so that the N elastocaloric materials are unloaded in different time periods; and each elastocaloric material releases its own mechanical work during unloading to provide thrust for the rotation of the main transmission shaft.

[0008] Optionally, along an axial direction of the main transmission shaft, a difference between the phase angles of any two adjacent eccentric transmission mechanisms in the N eccentric transmission mechanisms is $360/N$ degrees.

[0009] Optionally, each of the eccentric transmission mechanisms cooperates with the main transmission shaft and a corresponding piston to form an eccentric linkage mechanism, an eccentric cam mechanism, an eccentric bearing mechanism, or a crank-connecting

rod mechanism.

[0010] Optionally, at each of the different axial positions of the main transmission shaft, a cross section of the main transmission shaft is in a shape of a circle, and a center of the circle does not coincide with a rotation axis of the main transmission shaft; and the eccentric transmission mechanism includes a connecting rod part and a pin, an end of the connecting rod part away from the corresponding piston includes an annular portion, the annular portion is sleeved over an outer circumferential surface of the main transmission shaft and is capable of sliding circumferentially relative to the outer circumferential surface of the main transmission shaft, and the other end of the connecting rod part is hinged to an end of the piston away from the elastocaloric material through the pin.

[0011] Optionally, the connecting rod part includes a connecting rod upper part and a connecting rod lower part, the annular portion is formed by the connecting rod lower part and the lower part of the connecting rod upper part, and the connecting rod upper part and the connecting rod lower part are screwed together.

[0012] Optionally, the rotary solid-state cooling actuator further includes: linear bearings, which are sleeved over the respective pistons, for limiting the direction of the reciprocating motion of the pistons and reducing radial friction.

[0013] Optionally, the rotary solid-state cooling actuator further includes: first external racks, which support the respective pistons and the respective elastocaloric materials, two ends of each elastocaloric material being fixed between a corresponding piston and a corresponding first external rack by means of direct contact, threaded connection, welding, or bonding.

[0014] Optionally, the rotary solid-state cooling actuator further includes: an upper housing part and a lower housing part, which are configured to bear the pistons and the main transmission shaft, respectively.

[0015] Optionally, the rotary motor is selected from the group consisting of a servo motor, a stepper motor, a torque motor, a switched reluctance motor, and a brushless direct current motor.

[0016] Optionally, the rotary solid-state cooling actuator further includes a speed reducer for increasing the torque of the rotary motor.

[0017] Optionally, the rotary motor drives the main transmission shaft to rotate through the speed reducer.

[0018] Optionally, the rotary solid-state cooling actuator further includes a second external rack for fixing the speed reducer and the eccentric transmission mechanisms.

[0019] Optionally, a geometric shape of the elastocaloric material is selected from: cylindrical, cubic, cuboid, circular tubular, and rectangular tubular.

[0020] Optionally, the elastocaloric material is selected from the group consisting of shape memory alloys, natural rubber, synthetic polymers, and plastic crystals.

[0021] Optionally, the elastocaloric material is selected from nickel-titanium alloy, copper-aluminum-manganese alloy, nickel-manganese-titanium alloy, nickel-titanium-cobalt alloy, nickel-titanium-copper-cobalt alloy, and nickel-iron-gallium alloy.

[0022] Optionally, the deformation mode of the loading-unloading process of the elastocaloric material is uniaxial linear deformation, wherein the uniaxial linear deformation includes linear compression and linear tension.

[0023] In a second aspect of the present disclosure, there is provided a solid-state cooling apparatus. The solid-state cooling apparatus includes: the rotary solid-state cooling actuator based on unloaded mechanical work recovery described in the first aspect of the present disclosure; and a heat exchange structure, which is configured to exchange heat with the elastocaloric materials to transfer heat and cold energy generated by the elastocaloric materials.

[0024] Compared to existing technology, the rotary solid-state cooling actuator and the solid-state cooling apparatus of the present disclosure have the following advantages.

1. Adopting rotary loading: Compared to the existing hydraulic or linear motor drives, the present disclosure greatly reduces the number of mechanical transmission devices, and further reduces mechanical and electric energy losses.

2. Realizing recovery of unloaded mechanical work: The present disclosure adopts a multi-cylinder structure including a plurality of eccentric transmission mechanisms and a plurality of pistons, allowing the unloaded mechanical work of one elastocaloric material to be recovered and utilized for loading another elastocaloric material, thereby achieving energy recovery and utilization and reducing energy consumption.

3. Large and adjustable temperature drop of solid refrigerants: By adjusting the eccentricity (eccentric distance), a single temperature drop of the elastocaloric material of up to 30 degrees can be achieved.

4. Continuous output of cold energy: Compared to traditional technologies where the cold energy cannot be utilized until heat dissipation of the elastocaloric materials, the present disclosure adopts a multi-cylinder design, so that the intermittent cooling of the plurality of elastocaloric materials can be superimposed into a continuous cooling, greatly improving efficiency and cooling power.

5. Miniaturization and commercialization: Compared to existing hydraulic or linear motor drive, the overall weight and volume are greatly reduced, improving safety and portability.

6. High-frequency operation: An operation frequency of up to 5 Hz can be reached, improving the cooling power.

BRIEF DESCRIPTION OF DRAWINGS

[0025]

FIG. 1 is a schematic view illustrating the principle of unloaded mechanical work recovery according to the present disclosure;

FIG. 2 is a perspective view illustrating a part of a rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure;

FIG. 3 is a front schematic view illustrating the structure and the installation process of a part of the rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure;

FIG. 4 is a front schematic view illustrating a part of the rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure;

FIG. 5 is a perspective view illustrating a part of the rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure;

FIG. 6 is a graph illustrating changes in torque on the main transmission shaft relative to rotation angles according to an exemplary embodiment of the present disclosure and a comparative example.

[0026] Reference numerals are defined as follows:

1 - piston; 2 - main transmission shaft; 3 - connecting rod part;
3a - connecting rod upper part; 3b - connecting rod lower part; 4 - pin;
5a - upper housing part; 5b - lower housing part; 6 - linear bearing;
7a - second external rack; 7b - first external rack; 8 - speed reducer;
9 - rotary motor; 10 - elastocaloric material; O - rotation axis.

DETAIL DESCRIPTION OF EMBODIMENTS

[0027] In order to enable those of ordinary skill in the art to better understand the technical solutions of the present disclosure, the mode of the unloaded mechanical work recovery and the structure of the unloaded mechanical work recovery-based actuator employing the principle of unloaded mechanical work recovery according to the present disclosure are described in detail below with reference to the drawings.

[0028] The terms used herein are just used to describe specific embodiments, and are not intended to limit the present disclosure. The term "and/or" used herein includes any and all combinations of one or more associated listed items. The terms "a" and "the" used herein which indicate a singular form are intended to include a plural form, unless expressly stated in the context. The terms "include" and "be made of" used

herein indicate the presence of the described features, integers, steps, operations, elements and/or components, but do not exclude the presence or addition of one or more other features, integers, steps, operations, elements, components and/or combinations thereof.

[0029] In the description of the present disclosure, it should be noted that the orientations or positional relationships indicated by the terms "top", "bottom", "up", "down", "left", "right", "inside", "outside" and the like refer to the orientations or positional relationships based on the drawings, or the orientations or positional relationships in which the product is commonly arranged in use, and these terms are used simply for convenience of description and simplification of description, rather than indicating or implying that the device or element referred to must have a particular orientation or must be constructed and operated in a particular orientation, and therefore, these terms should not be construed as limiting the present disclosure.

[0030] Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by those of ordinary skill in the art. It should be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with a meaning in the context of the related art and the present disclosure, and should not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

[0031] FIG. 1 illustrates the principle of unloaded mechanical work recovery according to the present disclosure. Based on the principle of object deformation, when an object is deformed (stretched, compressed, twist or bent), the object stores elastic deformation mechanical energy. As the deformation is completed, the object releases the stored mechanical energy to the outside. The same also applies to the elastocaloric materials. In general, materials used for elastocaloric cooling have superelasticity (or pseudoelasticity), that is, the materials can undergo large elastic deformation and recover to their original states without residual strain. Based on such characteristic, the present disclosure adopts an eccentric transmission mechanism to drive the elastocaloric materials to deform, and utilizes elastic deformation mechanical energy stored in the elastocaloric material to drive the transmission shaft of the eccentric mechanism to rotate in turn; meanwhile, when being deformed by external force, the elastocaloric material will undergo phase transition to release or absorb heat, thereby performing cooling.

[0032] For simplifying the description, an eccentric wheel is taken as an example of the eccentric transmission mechanism in FIG. 1. When a distal portion of the eccentric wheel rotates to below the elastocaloric material (elastocaloric material member), the distal portion of the eccentric wheel presses the elastocaloric material, so that the elastocaloric material releases heat while undergoing compressive deformation; as the eccentric

wheel continues to rotate, the elastocaloric material enters an unloading process after passing the highest point of the distal portion, and releases elastic deformation mechanical energy and absorbs heat from the surrounding environment. The mechanical energy released by the elastocaloric material can be transmitted to the eccentric wheel, thereby further driving the eccentric wheel to rotate. The inventors also found that, since the transmission shaft needs to be connected to a motor, the gear structure of the motor itself may experience self-locking and cannot change speed instantaneously to rotate (that is, cannot keep rotating through inertia). If a single-cylinder design is adopted, that is, the cooling apparatus is provided with only one elastocaloric material, unloaded mechanical work instantaneously transferred to the transmission shaft cannot be stored and transferred for loading of the same elastocaloric material in a next time period. In view of the above, the present disclosure adopts a multi-cylinder mechanism design (including at least two cylinders), and through design of phase angles of eccentric positions, it is satisfied that the loading of one material and the unloading of the other material occur at the same time, and the torque on the transmission shaft is reduced due to the simultaneous action of the two materials. That is, the torque required for simultaneously driving two materials is less than the sum of torques required for separately driving the two materials, the reason being the occurrence of unloaded work recovery. Based on the above principle, the unloaded work recovery ratio of the actuator may be roughly calculated by the following formula:

$$\text{work recovery ratio} = \frac{nW_2 - W_{in}}{nW_1}$$

where W_1 refers to mechanical work required for loading and deforming a single elastocaloric material without unloaded work recovery; n represents the number of cylinders in an actuator (that is, how many materials there are in the actuator); W_{in} refers to total mechanical work (a measured value) required to achieve a driving process under actual operating conditions using the rotary solid-state cooling actuator of the present disclosure; and W_2 refers to unloaded mechanical work of a single material under the operating conditions. In general, for materials such as springs with a constant modulus of elasticity, W_1 is equal to W_2 . Under actual operating conditions, since a shape memory alloy undergoes two-phase transformation during phase transition, the Young's modulus of the shape memory alloy continuously changes, so that hysteresis is caused, and a part of the unloaded mechanical work is converted into hysteresis heat and is dissipated; therefore, for system analysis related to shape memory alloy, W_1 is greater than W_2 .

[0033] Based on the above principle, exemplary em-

bodiments of the present disclosure provides a rotary solid-state cooling actuator capable of achieving unloaded mechanical work recovery of an elastocaloric material under rotational motion (hereinafter referred to as a rotary solid-state cooling actuator). As shown in FIG. 2 to FIG. 5, the rotary solid-state cooling actuator includes: a rotary motor 9, a main transmission shaft 2, two eccentric transmission mechanisms, two pistons 1, and two elastocaloric materials 10.

[0034] The rotary motor 9 is configured to drive the main transmission shaft 2 to rotate. The two eccentric transmission mechanisms are installed at different axial positions of the main transmission shaft 2. The eccentric transmission mechanisms function to convert rotational motion of the main transmission shaft 2 into linear reciprocating motion of the pistons 1, and the two elastocaloric materials 10 are periodically loaded and unloaded through the reciprocating motion of the two pistons 1, respectively. Phase angles of the two eccentric transmission mechanisms relative to the main transmission shaft 2 (rotation axis O) differ by 180 degrees, so that time periods during which the two elastocaloric materials 10 are unloaded (or loaded) are staggered from each other. In other words, when one elastocaloric material 10 is loaded, the other elastocaloric material 10 is unloaded. Each elastocaloric material 10 may apply, in its unloading process, downward thrust to one of the pistons 1, the thrust may drive the piston 1 to move downwards and thus drive the eccentric transmission mechanism to move downwards at the same time, and the transmitted thrust may act on the main transmission shaft 2 in a tangential direction to provide thrust for rotation of the main transmission shaft 2. Since the two elastocaloric materials 10 do not provide thrust to the main transmission shaft 2 simultaneously, the thrust promotes the rotation of the main transmission shaft 2 instead of hindering the rotation of the main transmission shaft 2, thereby reducing input work of the rotary motor 9.

[0035] Specifically, as shown in FIG. 2, the main transmission shaft 2 can rotate around the rotation axis O. Cross sections of portions of the main transmission shaft 2 where the eccentric transmission mechanisms are installed are in a shape of a circle, but the center of the circle does not coincide with the rotation axis O. In other words, the portions of the main transmission shaft 2 where the eccentric transmission mechanisms are installed are of an eccentric circular structure relative to the rotation axis O of the main transmission shaft 2, that is, the main transmission shaft 2 is of a (partially) eccentric shaft structure. The two eccentric circular portions have an angular deviation of 180 degrees in the radial direction, that is, phase angles of the two eccentric circular portions differ by 180 degrees. In addition, eccentricity of each eccentric circular portion may be set to 1.5 mm, that is, the radial distance between the centers of the two eccentric circular portions is 3 mm.

[0036] As shown in FIG. 2, each eccentric transmission mechanism includes a connecting rod part 3 and a pin 4, and the connecting rod part 3 includes a connecting rod upper part 3a and a connecting rod lower part 3b which are screwed together. The connecting rod lower part 3b and the lower end of the connecting rod upper part 3a form an annular portion. The inner diameter of the annular portion matches the outer diameter of the eccentric circular structure, so that the annular portion may be sleeved over the outer circumferential surface of the eccentric circular portion of the main transmission shaft 2, and slide (rotate) circumferentially relative to the outer circumferential surface. The other end of the connecting rod part 3, i.e., the upper end of the connecting rod upper part 3a, is hinged to the lower end of the piston 1 through the pin 4, so as to constrain the piston 1 from moving back and forth or moving left and right. In addition, since the annular portion of the connecting rod part 3 is sleeved over the eccentric circular portion having the eccentricity of 1.5 mm, when the main transmission shaft 2 rotates, the connecting rod part 3 may swing about the pin 4 relative to the piston 1, and meanwhile, the upper end of the connecting rod part 3 drives the piston 1 through the pin 4 to perform reciprocating motion with a stroke of about 3 mm.

[0037] As shown in FIG. 3 and FIG. 5, the rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure may further include two linear bearings 6. Each linear bearing 6 is sleeved outside the corresponding piston 1 for to providing constraint for the piston 1 and reducing friction loss generated during upward and downward motion of the piston 1.

[0038] As shown in FIG. 5, the rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure may further include two first external racks 7b. The first external rack 7b is a support structure for supporting the corresponding piston 1 and the corresponding elastocaloric material 10. The first external rack 7b may be further configured to fix the corresponding elastocaloric material 10. Both ends of the elastocaloric material 10 are fixed between the corresponding piston 1 and the first external rack 7b by means of direct contact, threaded connection, welding, or bonding. The first external rack 7b may be installed on the linear bearing 6, and may include: a plurality of screws fixed to the top surface of the linear bearing 6, and a top cover fixed to the screws by nuts. The position of the top cover may be adjusted through the nuts, and the bottom surface of the top cover and the top surface of the piston 1 may be provided with blind holes or screw holes for receiving the ends of the elastocaloric material 10.

[0039] As shown in FIG. 4, the rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure may further include a speed reducer 8. The rotary motor 9 is connected to the main

transmission shaft 2 through the speed reducer 8. The speed reducer 8 is axially connected to the rotary motor 9 and the main transmission shaft 2, and is configured to increase torque on the main transmission shaft 2. In addition, the rotary motor 9 in the rotary solid-state cooling actuator according to the exemplary embodiments of the present disclosure may adopt a servo motor, a stepper motor, a torque motor, a switched reluctance motor, or a brushless direct current motor, or may adopt a mechanical device capable of performing rotational motion.

[0040] As shown in FIG. 3 and FIG. 4, the rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure may further include a second external rack 7a for fixing the speed reducer 8 and the eccentric transmission mechanisms.

[0041] Further, as shown in FIG. 3, the rotary solid-state cooling actuator according to an exemplary embodiment of the present disclosure may further include an upper housing part 5a and a lower housing part 5b. The upper housing part 5a and the lower housing part 5b serve as housing supports to bear the pistons 1 and the main transmission shaft 2, respectively. The linear bearings 6 may be fixed to the upper housing part 5a. The lower housing part 5b may be fixedly connected to the second external rack 7a.

[0042] It should be noted that, although the rotary solid-state cooling actuator according to the above exemplary embodiments of the present disclosure adopts a two-cylinder structure, that is, each of the number of eccentric transmission mechanisms, the number of pistons, and the number of elastocaloric materials is two, the present disclosure is not limited thereto, and the rotary solid-state cooling actuator may adopt a three-cylinder structure, a four-cylinder structure, or a structure with more cylinders. Optionally, in a case where an N-cylinder structure is adopted, where $N > 2$, the difference between the phase angles of any two adjacent eccentric transmission mechanisms is $360/N$ degrees. In other words, for any intermediate eccentric transmission mechanism, if the phase angle of the intermediate eccentric transmission mechanism is α , the phase angle of an adjacent eccentric transmission mechanism before the intermediate eccentric transmission mechanism and the phase angle of an adjacent eccentric transmission mechanism after the intermediate eccentric transmission mechanism may be $\alpha - 360/N$ and $\alpha + 360/N$ respectively; or, the phase angles of the plurality of eccentric transmission mechanisms may not have an increasing/decreasing relationship as long as the phase angles of the plurality of eccentric transmission mechanisms are uniformly distributed within a range of 360 degrees.

[0043] Under operating conditions, the rotary motor 9 drives the main transmission shaft 2 to rotate through the speed reducer 8. Each eccentric circular portion of the main transmission shaft 2 and its corresponding connecting rod part 3, pin 4, and piston 1 form a crank-

connecting rod structure. When the main transmission shaft 2 rotates, each eccentric circular portion drives the connecting rod part 3 to vibrate up and down and swing left and right through the annular portion. Meanwhile, since the upper ends of the connecting rod parts 3 are connected to the respective pistons 1 and the pistons 1 are constrained by the respective linear bearings 6, the rotation of the main transmission shaft 2 is converted into the linear reciprocating motion of the pistons 1. The pistons 1 load and unload the elastocaloric materials 10 disposed thereon through this reciprocating motion, thereby inducing the elastocaloric effect. The elastocaloric effect refers to the elastocaloric materials 10 releasing heat to the environment when being compressed, and absorbing heat from the environment when recovering from deformation. Due to the different phase angles of the plurality of eccentric transmission mechanisms relative to the main transmission shaft 2, non-simultaneous linear reciprocating motion of the plurality of pistons 1 is achieved, so that the elastocaloric materials 10 are unloaded (or loaded) by the pistons 1 in different time periods, that is, the elastocaloric materials 10 are in different deformation stages. During the unloading process, that is, in a deformation stage from compressive deformation to deformation recovery, each elastocaloric material 10 applies downward thrust to the piston 1, and the thrust drives the piston 1 to move downwards and thus drives the eccentric transmission mechanism to move downwards at the same time. The transmitted thrust acts on the main transmission shaft 2 in a tangential direction to provide thrust for rotation of the main transmission shaft 2. Since the plurality of elastocaloric materials 10 do not provide thrust to the main transmission shaft 2 simultaneously, this thrust can reduce the torque required for loading other elastocaloric materials, achieving work recovery, promoting uniform rotation of the main drive shaft 2, reducing the input work of the rotary motor 9, and achieving power and energy saving.

[0044] Optionally, although the eccentric transmission mechanism according to the present disclosure preferably has the structure described in the above embodiments, it can also have other structures. For example, the eccentric transmission mechanism may cooperate with the main transmission shaft 2 and the piston 1 to form an eccentric linkage mechanism, an eccentric cam mechanism, an eccentric bearing mechanism, or a crank-connecting rod mechanism. For example, when the eccentric cam mechanism is adopted, the main transmission shaft 2 may not be provided with the eccentric circular portions, and the connecting rod part 3 may be directly replaced with a cam fixed to the main transmission shaft 2, the cam surface of the cam is in contact with the bottom of the piston 1 (so as to push and press the piston 1 when the elastic material is loaded, or be pushed and pressed by the piston 1 when the elastic material is unloaded), with each cam having a different phase angle.

[0045] Optionally, the elastocaloric material 10 is selected from shape memory alloys, natural rubber, synthetic polymers, and plastic crystals. When the elastocaloric material 10 is a shape memory alloy, the elastocaloric material 10 may be selected from nickel-titanium alloy, copper-aluminum-manganese alloy, nickel-manganese-titanium alloy, nickel-titanium-cobalt alloy, nickel-titanium-copper-cobalt alloy, and nickel-iron-gallium alloy.

[0046] Optionally, the eccentric transmission mechanisms, the pistons 1, the main transmission shaft 2, the linear bearings 6, the upper housing part 5a, and the lower housing part 5b are made of plastic, metal, resin, or other materials by additive manufacturing (e.g., 3D printing) or subtractive manufacturing (e.g., wire cutting).

[0047] Optionally, the rotation mode of the main transmission shaft 2 may be uniform rotation, differential rotation, or intermittent rotation.

[0048] Optionally, the deformation mode of the loading-unloading process of each elastocaloric material 10 is uniaxial linear deformation including linear compression and linear tension.

[0049] The rotary solid-state cooling actuator of the present disclosure is further described below in conjunction with a test.

Related Test

[0050] The structure of the rotary solid-state cooling actuator adopted in the present test is shown in FIG. 2 to FIG. 5. The linear bearings 6, the second external rack 7a, the first external rack 7b, the speed reducer 8, and the elastocaloric materials 10 used in this test are commercial standard parts; and the pistons 1, the main transmission shaft 2, the connecting rod upper parts 3a, the connecting rod lower parts 3b, the pins 4, the upper housing part 5a, and the lower housing part 5b are machined alloy components. The components are connected to each other by screws. The rotary motor 9 is a servo motor. In order to achieve a better demonstration effect in the test, the elastocaloric materials 10 are replaced with springs.

[0051] The rotary solid-state cooling actuator operates as shown in FIG. 1. The main transmission shaft 2 is driven to rotate through the rotation of the rotary motor 9, and the eccentric transmission mechanisms convert the rotation into the linear reciprocating motion of the pistons 1, thereby compressing the springs. Reverse recovery of unloaded elastic mechanical work refers to the spring pushing the main transmission shaft 2 to rotate after being unloaded, thereby reducing the torque required to load the other spring.

[0052] A torque sensor is axially installed between the main transmission shaft 2 and the speed reducer 8 for measuring a change of the torque on the main transmission shaft 2. The two springs in place of the elastocaloric materials 10 are installed in the two cylin-

ders of the rotary solid-state cooling actuator of the present disclosure, respectively. Initially, one spring is in a compressed state, that is, in a loaded state; and the other spring is in an undeformed state, that is, in an unloaded state. After the springs are installed, the rotary motor 9 is started and set to operate in a uniform rotation mode with a rotation speed set to 16 revolutions per minute. The torque data on the transmission shaft as a function of the rotation angle of the transmission shaft is collected and recorded by the torque sensor. As a comparison, torque change of a solid-state cooling actuator provided with a single spring is collected.

[0053] The result of the test is shown in FIG. 6, area of regions enclosed by the on-shaft torque variation curves and the horizontal axis indicating the rotation angle represents the input work of the rotary motor 9. It can be seen that the input work required for driving two materials simultaneously while using the unloaded elastic work of one material to drive the other material is smaller than the input work required for driving the two materials separately (twice the torque curve-enclosed area for the single material is greater than the torque curve-enclosed area for the two materials). According to the principle described above, the unloaded work recovery ratio of the actuator can be roughly calculated by the following formula:

$$\text{work recovery ratio} = \frac{2W_1 - W_{in}}{2W_2}$$

where W_1 refers to the mechanical work required for loading and deforming a single elastocaloric material without unloaded work recovery, here referring to the torque curve-enclosed area for the single material; the number 2 represents the number of cylinders in the actuator (that is, how many materials there are in the actuator); W_{in} refers to the total mechanical work (a measured value) required to achieve a driving process under actual operating conditions using the rotary solid-state cooling actuator of the present disclosure, here referring to the torque curve-enclosed area for the two materials; and W_2 refers to the unloaded mechanical work of a single material under the operating conditions. In general, W_1 is equal to W_2 for the materials having a constant elastic modulus, such as a spring. Through calculation, the work recovery ratio is found to be 53%, which indicates that the rotary solid-state cooling actuator of the present disclosure has an unloaded work recovery function. By recovering the unloading elastic mechanical work of the material, the input work required by the rotary motor can be reduced to maintain system operation, thereby reducing energy consumption.

[0054] Therefore, compared to the existing technology, the rotary solid-state cooling actuator of the present disclosure has the following advantages.

1. In the aspect of structural design: The present disclosure adopts a rotary loading method, which greatly reduces the number of mechanical transmission devices compared to the existing hydraulic or linear motor drives, thereby reducing loss of mechanical energy and electric energy. By adopting the multi-cylinder arrangement, an overall length is greatly reduced, which makes an overall structure compact.

2. In the aspect of energy utilization: The rotary solid-state cooling actuator of the present disclosure achieves recovery of unloaded mechanical work, recovering the unloaded mechanical work of one elastocaloric material and then utilizing the recovered unloaded mechanical work to load another elastocaloric material, so that energy recovery and utilization are realized, and energy consumption is reduced. Compared to traditional technologies where the cold energy cannot be utilized until heat dissipation of the elastocaloric materials, the actuator of the present disclosure adopts the multi-cylinder design, so that the intermittent coolings of the plurality of elastocaloric materials can be superimposed into a continuous cooling, greatly improving efficiency and cooling power. By adjusting the eccentricity, a single temperature drop of the elastocaloric materials of up to 30 degrees can be achieved. The unloaded mechanical work recovery requires no additional waiting time, so that the overall driving operating frequency can be increased, reaching up to 5 Hz, thereby realizing high cooling power.

3. In the aspect of commercial application: Compared to the existing hydraulic or linear motor drives, the rotary solid-state cooling actuator of the present disclosure has the advantages of greatly reduced overall weight and volume and improved safety and portability; meanwhile, since the actuator only involves rotational motion when operating, the actuator needs no additional mechanical transmission device, and thus has high overall mechanical stability, and has high safety factor during operation. Most importantly, by achieving the unloaded mechanical work recovery, the energy consumption coefficient of an elastocaloric solid-state cooler can exceed that of the conventional air conditioners, which can not only reduce power expenditure of consumers but also meet requirements of environmental protection and carbon neutrality.

[0055] In summary, the rotary solid-state cooling actuator of the present disclosure utilizes the elastic mechanical energy stored in the elastocaloric materials during the unloading process, achieves recovery and utilization of the unloaded mechanical work, reduces electric energy consumption required by the whole actuator, improves energy consumption ratio and stability of the actuator during operation, and provides new pos-

sibility for developing a light-weight and commercial elastocaloric solid-state cooling apparatus.

[0056] In a second aspect, the present disclosure further provides a solid-state cooling apparatus, which includes the above rotary solid-state cooling actuator based on unloaded mechanical work recovery, and further includes a heat exchange structure for exchanging heat with the elastocaloric materials to transfer heat and cold energy generated by the elastocaloric materials.

[0057] Optionally, the heat exchange structure may be a solid heat exchanger (which directly transfer the heat by means of solid-solid contact) or a fluid heat exchanger (which performs solid-liquid convective heat transfer using a gas, a liquid, or a liquid metal).

[0058] Since the solid-state cooling apparatus includes the above rotary solid-state cooling actuator, the solid-state cooling apparatus has all the advantages of the rotary solid-state cooling actuator.

[0059] It should be understood that the above embodiments are just exemplary embodiments adopted to illustrate the principle of the present disclosure, and the present disclosure is not limited thereto. Various modifications and improvements can be made by those of ordinary skill in the art without departing from the spirit and essence of the present disclosure, and those modifications and improvements are also considered to fall within the scope of the present disclosure.

Claims

1. A rotary solid-state cooling actuator based on unloaded mechanical work recovery, wherein:

the rotary solid-state cooling actuator comprises a rotary motor, a main transmission shaft driven by the rotary motor to rotate, N eccentric transmission mechanisms installed at different axial positions of the main transmission shaft and driven by the main transmission shaft, N pistons respectively driven by the N eccentric transmission mechanisms to perform reciprocating motion, and N elastocaloric materials periodically loaded and unloaded through the reciprocating motion of the N pistons, wherein

N is an integer greater than 1;

the N eccentric transmission mechanisms have different phase angles relative to the main transmission shaft, so that the N elastocaloric materials are unloaded in different time periods; and

each elastocaloric material releases its own mechanical work during unloading to provide thrust for rotation of the main transmission shaft.

2. The rotary solid-state cooling actuator according to claim 1, wherein:

along an axial direction of the main transmission shaft, a difference between the phase angles of any two adjacent eccentric transmission mechanisms in the N eccentric transmission mechanisms is $360/N$ degrees.

3. The rotary solid-state cooling actuator according to claim 1 or 2, wherein:

each of the eccentric transmission mechanisms cooperates with the main transmission shaft and a corresponding piston to form an eccentric linkage mechanism, an eccentric cam mechanism, an eccentric bearing mechanism, or a crank-connecting rod mechanism.

4. The rotary solid-state cooling actuator according to claim 1 or 2, wherein, at each of the different axial positions of the main transmission shaft:

a cross section of the main transmission shaft is in a shape of a circle, and a center of the circle does not coincide with a rotation axis of the main transmission shaft; and

the eccentric transmission mechanism comprises a connecting rod part and a pin, an end of the connecting rod part away from the piston comprises an annular portion, the annular portion is sleeved over an outer circumferential surface of the main transmission shaft and is capable of sliding circumferentially relative to the outer circumferential surface of the main transmission shaft, and the other end of the connecting rod part is hinged to an end of the piston away from the elastocaloric material through the pin.

5. The rotary solid-state cooling actuator according to claim 4, wherein:

the connecting rod part comprises a connecting rod upper part and a connecting rod lower part, the annular portion is formed by the connecting rod lower part and a lower portion of the connecting rod upper part, and the connecting rod upper part and the connecting rod lower part are screwed together.

6. The rotary solid-state cooling actuator according to claim 5, further comprising:

linear bearings, which are sleeved over the respective pistons, for limiting a direction of the reciprocating motion of the pistons;

first external racks, which support the respective pistons and the respective elastocaloric materials, both ends of each elastocaloric material being fixed between a corresponding pis-

ton and a corresponding first external rack by means of direct contact, threaded connection, welding, or bonding; and/or an upper housing part and a lower housing part, which are configured to bear the pistons and the main transmission shaft, respectively.

7. The rotary solid-state cooling actuator according to claim 1 or 2, wherein:

the rotary motor is selected from a group consisting of a servo motor, a stepper motor, a torque motor, a switched reluctance motor, and a brushless direct current motor, and the rotary solid-state cooling actuator further comprises a speed reducer, the rotary motor driving the main transmission shaft to rotate through the speed reducer.

8. The rotary solid-state cooling actuator according to claim 7, further comprising a second external rack for fixing the speed reducer and the eccentric transmission mechanisms.

9. The rotary solid-state cooling actuator according to claim 1 or 2, wherein:

the elastocaloric material has a geometric shape selected from a group consisting of cylindrical, cubic, cuboid, circular tubular, and rectangular tubular; and the elastocaloric material is selected from a group consisting of shape memory alloys, natural rubber, synthetic polymers, and plastic crystals.

10. The rotary solid-state cooling actuator according to claim 1 or 2, wherein: a deformation mode of a loading-unloading process of the elastocaloric material is uniaxial linear deformation, wherein the uniaxial linear deformation comprises linear compression and linear tension.

11. A solid-state cooling apparatus, comprising:

the rotary solid-state cooling actuator according to any one of claims 1 to 10; and a heat exchange structure, which is configured to exchange heat with the elastocaloric materials to transfer heat and cold energy generated by the elastocaloric materials.

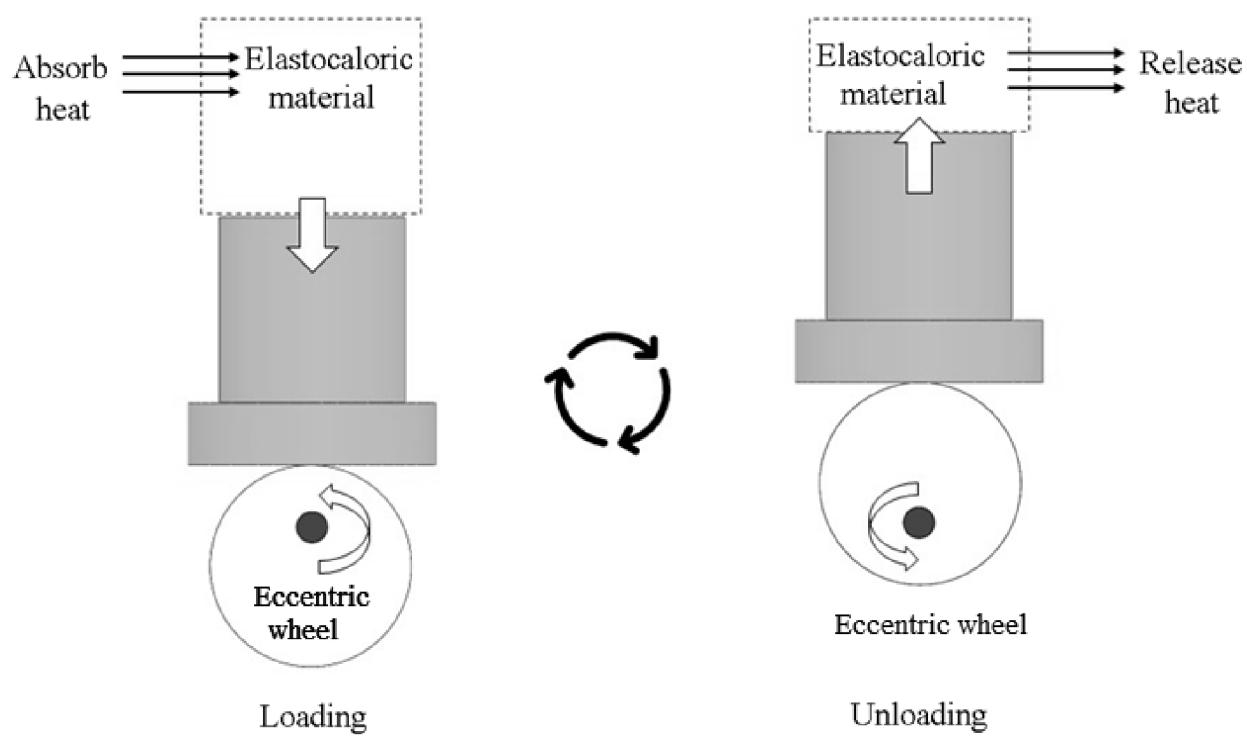


FIG. 1

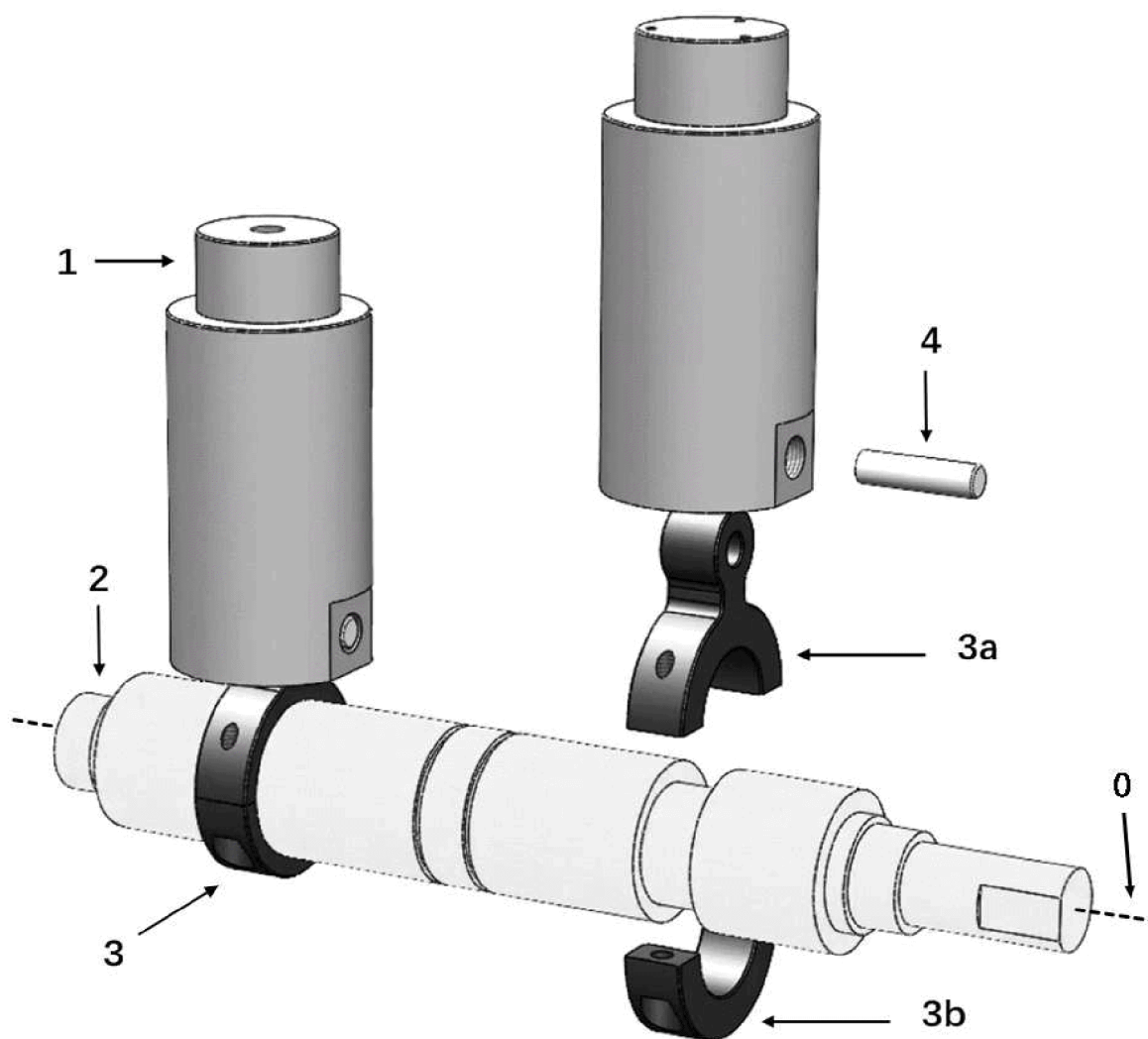


FIG. 2

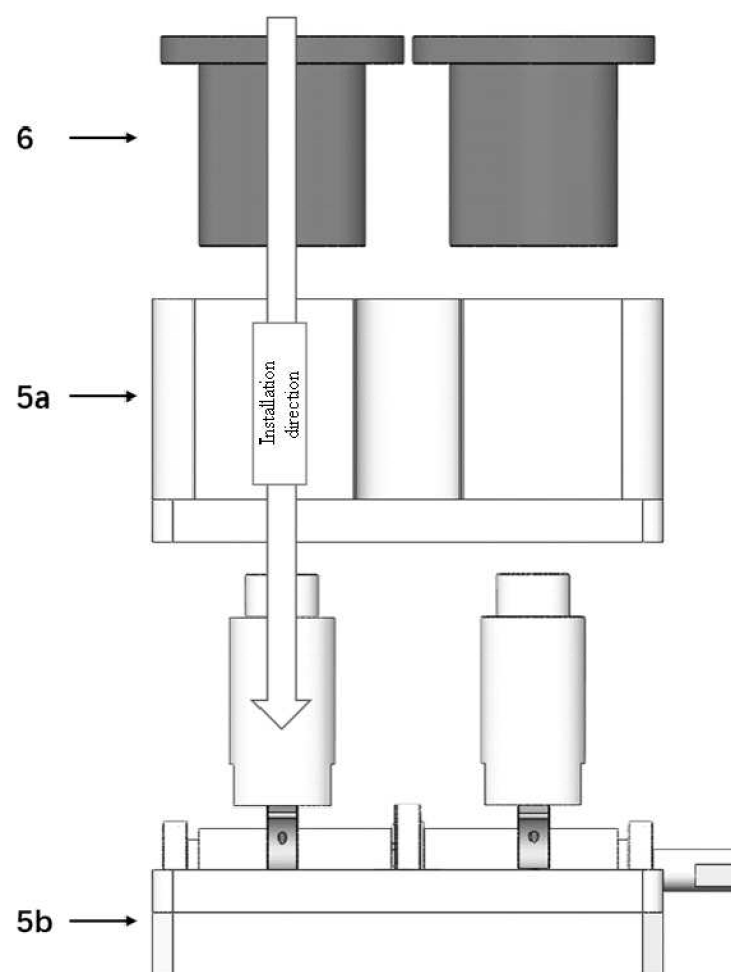


FIG. 3

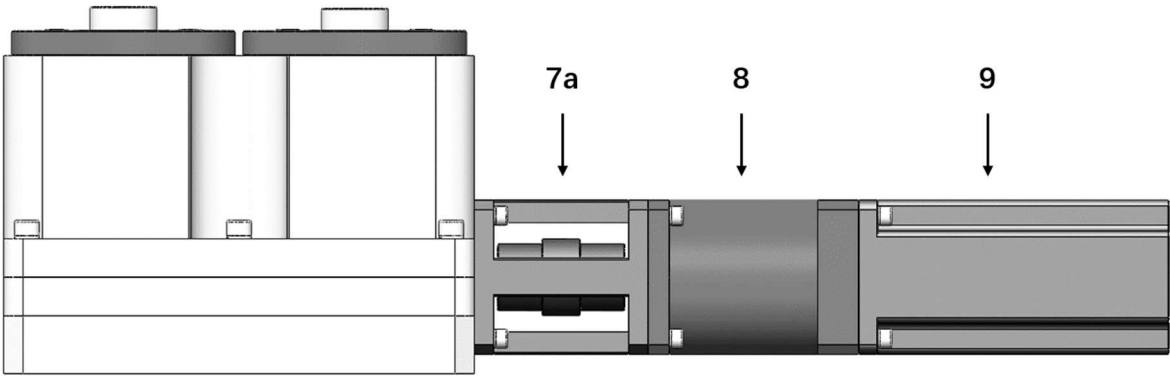


FIG. 4

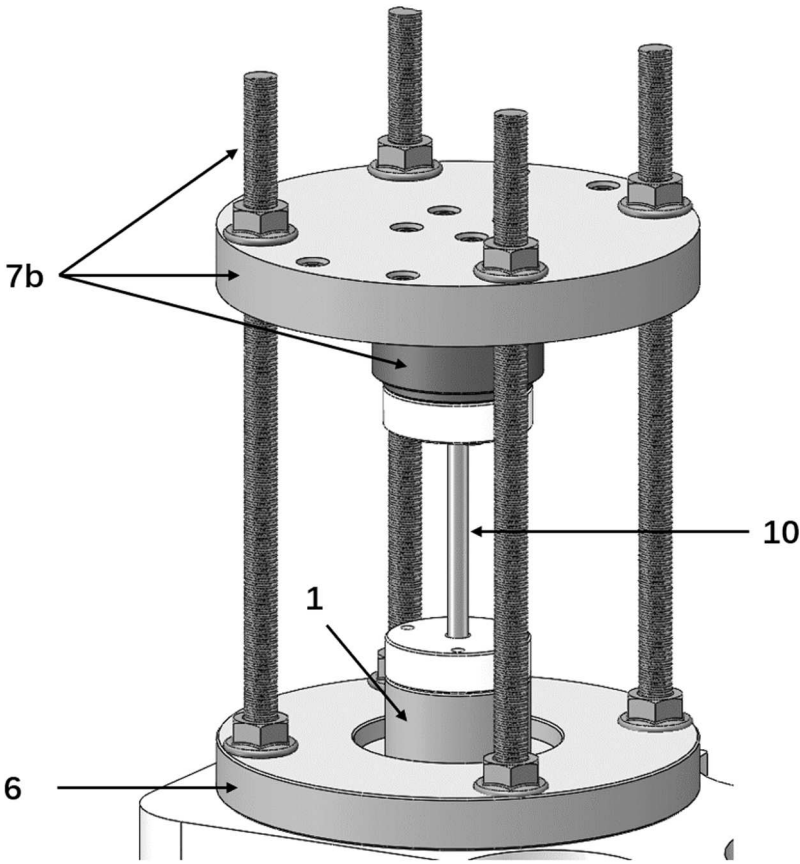


FIG. 5

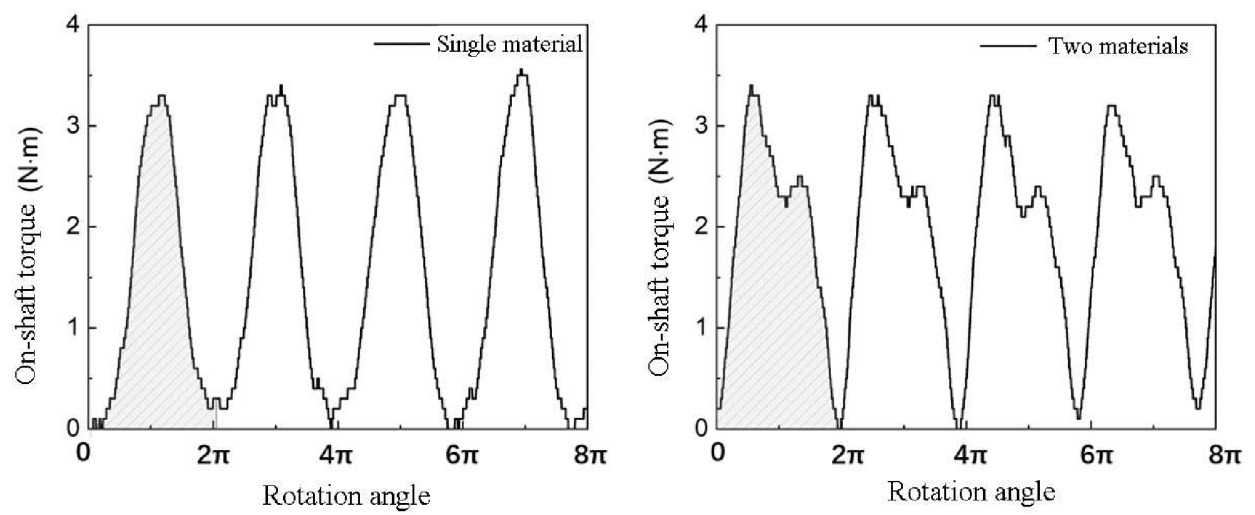


FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2024/074956

A. CLASSIFICATION OF SUBJECT MATTER

F25B23/00(2006.01)i; F25B17/08(2006.01)i; F28D17/00(2006.01)i; F25D31/00(2006.01)i

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)

IPC:F25B; F28D; F25D

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)

CNTXT; ENTXT; WPABS; 中国期刊网全文数据库, CJFD; PATENTICS; CJFD: 固态制冷, 固态相变, 弹卡, 偏心, 凸轮, 活塞, 马达, 相位, solid+, refrigerat+, phase w transit+, off w centre+, cam?, piston+, motor+

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	CN 115930479 A (HONG KONG UNIVERSITY OF SCIENCE & TECHNOLOGY) 07 April 2023 (2023-04-07) description, specific embodiments sections, and figures 1-6	1-11
A	CN 108954901 A (SHANGHAI JIAO TONG UNIVERSITY) 07 December 2018 (2018-12-07) entire document	1-11
A	CN 116839243 A (HEBEI UNIVERSITY OF SCIENCE AND TECHNOLOGY) 03 October 2023 (2023-10-03) entire document	1-11
A	CN 114992978 A (HONG KONG UNIVERSITY OF SCIENCE & TECHNOLOGY) 02 September 2022 (2022-09-02) entire document	1-11
A	CN 110285516 A (CHONGQING UNIVERSITY) 27 September 2019 (2019-09-27) entire document	1-11

☒ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"E" earlier application or patent but published on or after the international filing date	"&" document member of the same patent family
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search 31 July 2024	Date of mailing of the international search report 15 August 2024
Name and mailing address of the ISA/CN China National Intellectual Property Administration (ISA/CN) China No. 6, Xitucheng Road, Jimenqiao, Haidian District, Beijing 100088	Authorized officer Telephone No.

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Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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				JP	2012220184	A	12 November 2012
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