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(54) **HYBRID CRYOCOOLER WITH MULTIPLE PASSIVE STAGES**

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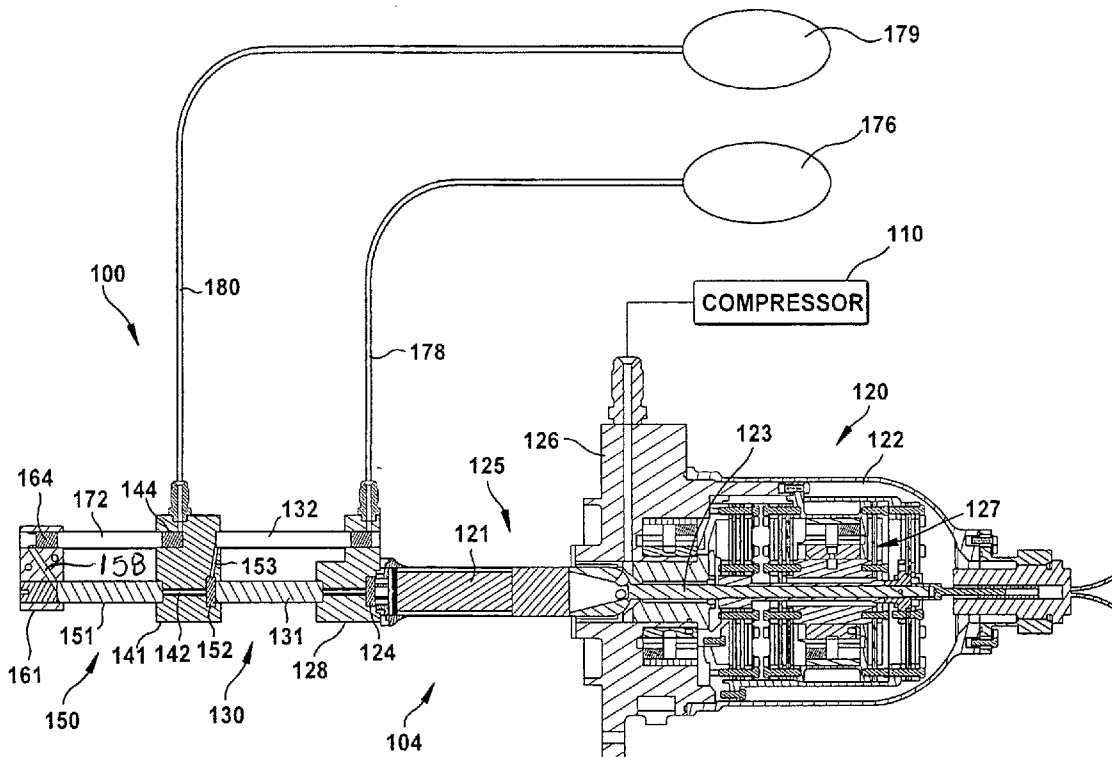
(57) **ABSTRACT**

A multi-stage cryocooler has three or more stages, including an active first stage and passive second and third stages. The active stage may include a Stirling expander, and the passive second and third stages may be pulse tube coolers. The cryocooler may provide cooling at three different temperatures. The coldest cooling temperature may be at or below 10 K, and may be at or below 5 K. The system may provide cooling at such low temperatures while still operating at a relatively high frequency, for example, at a frequency of at least about 20 Hertz.

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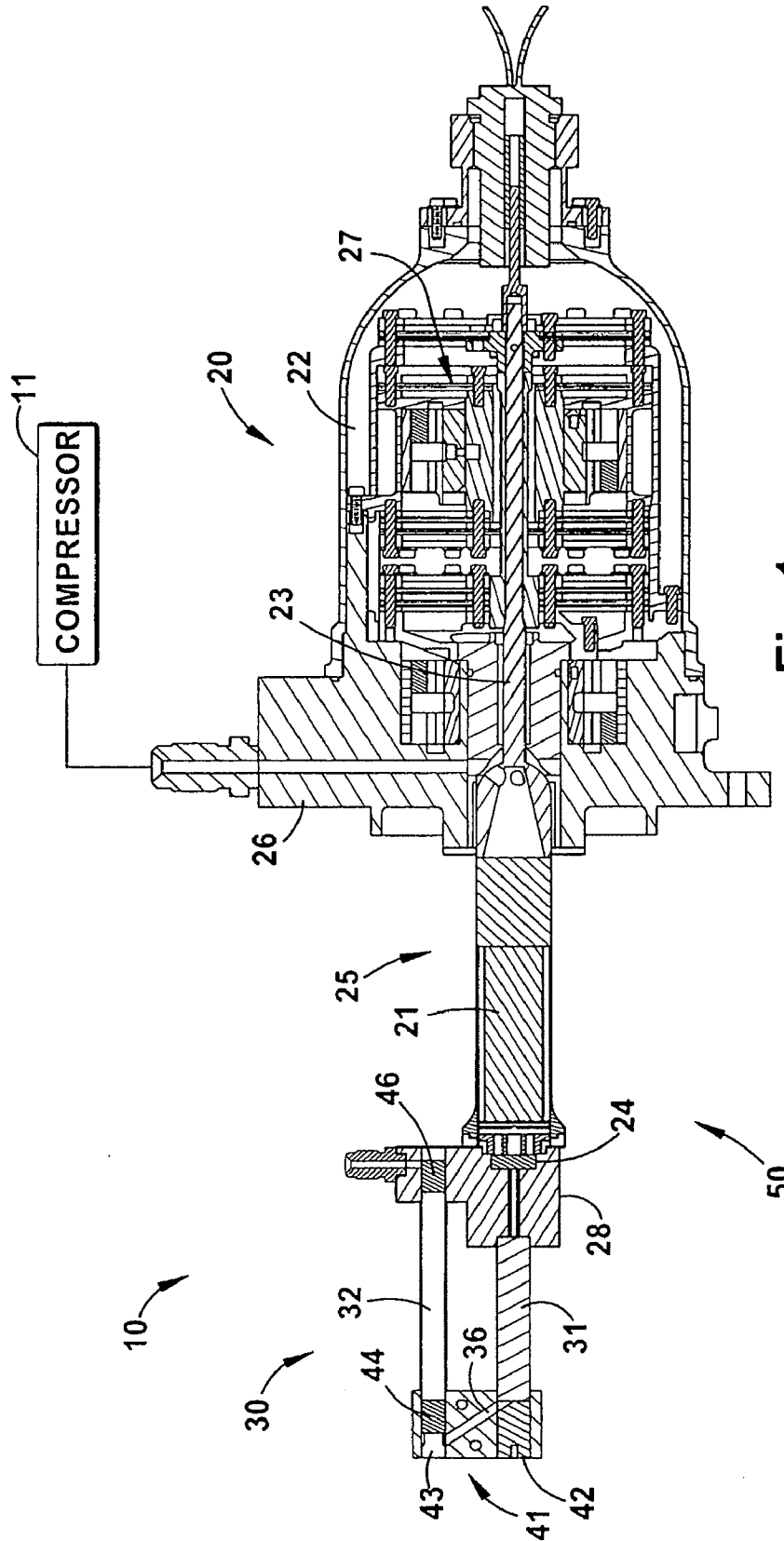


Fig.1
(PRIOR ART)

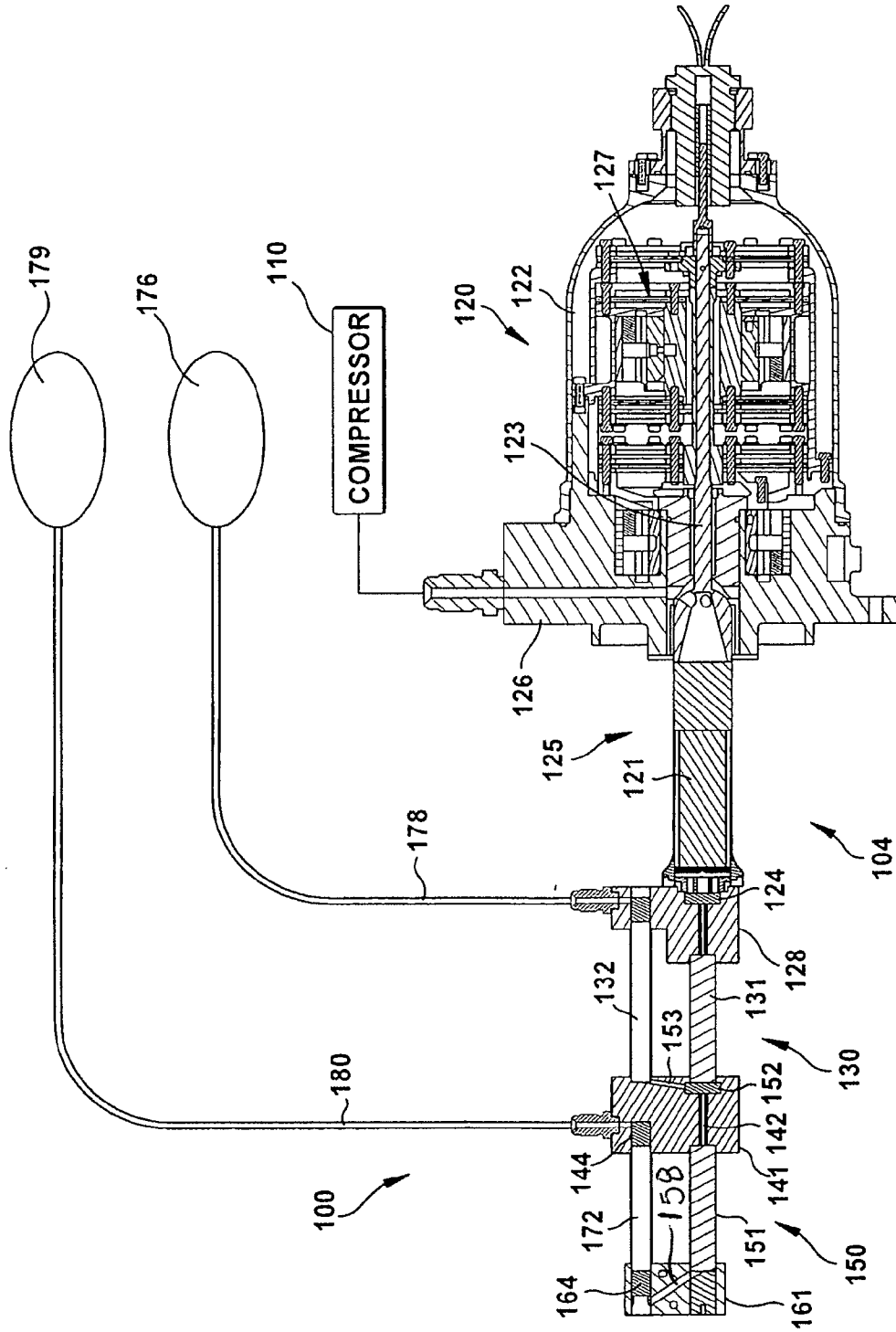


Fig.2A

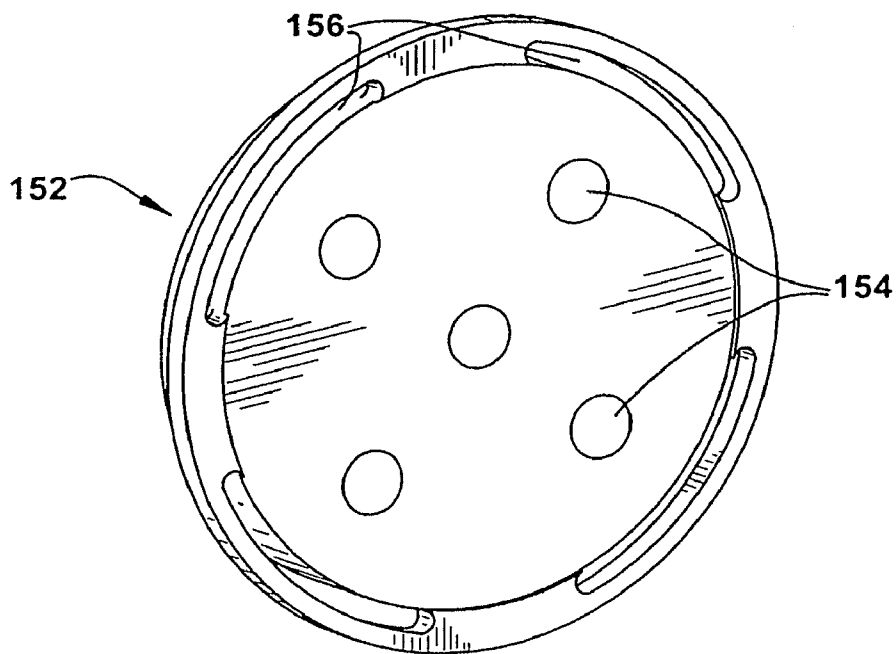


Fig. 2B

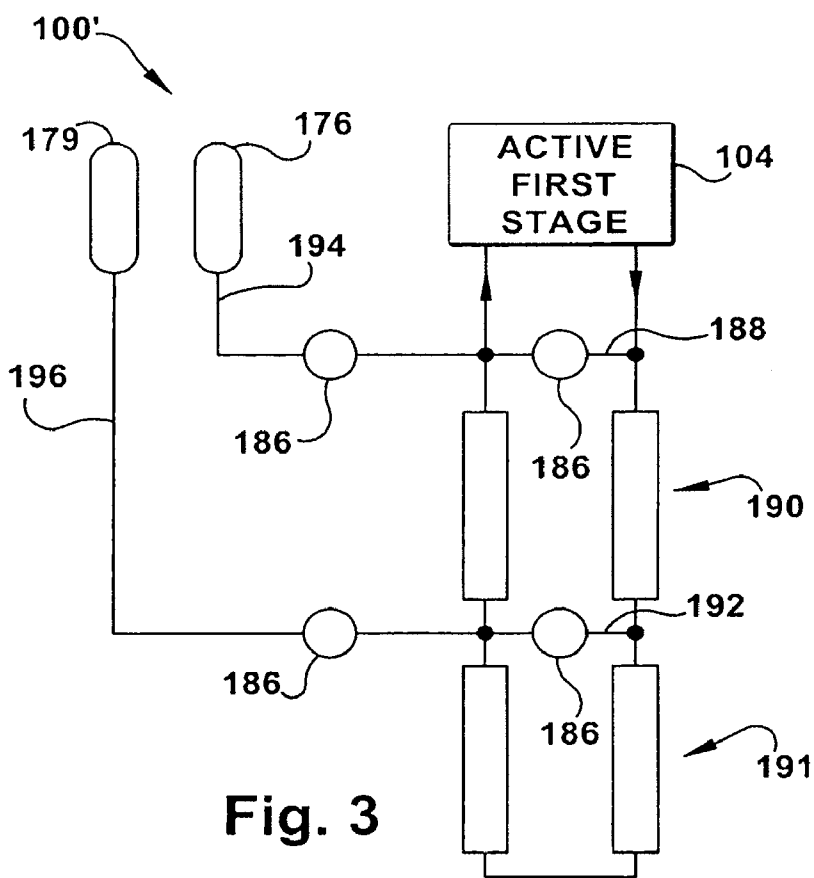


Fig. 3

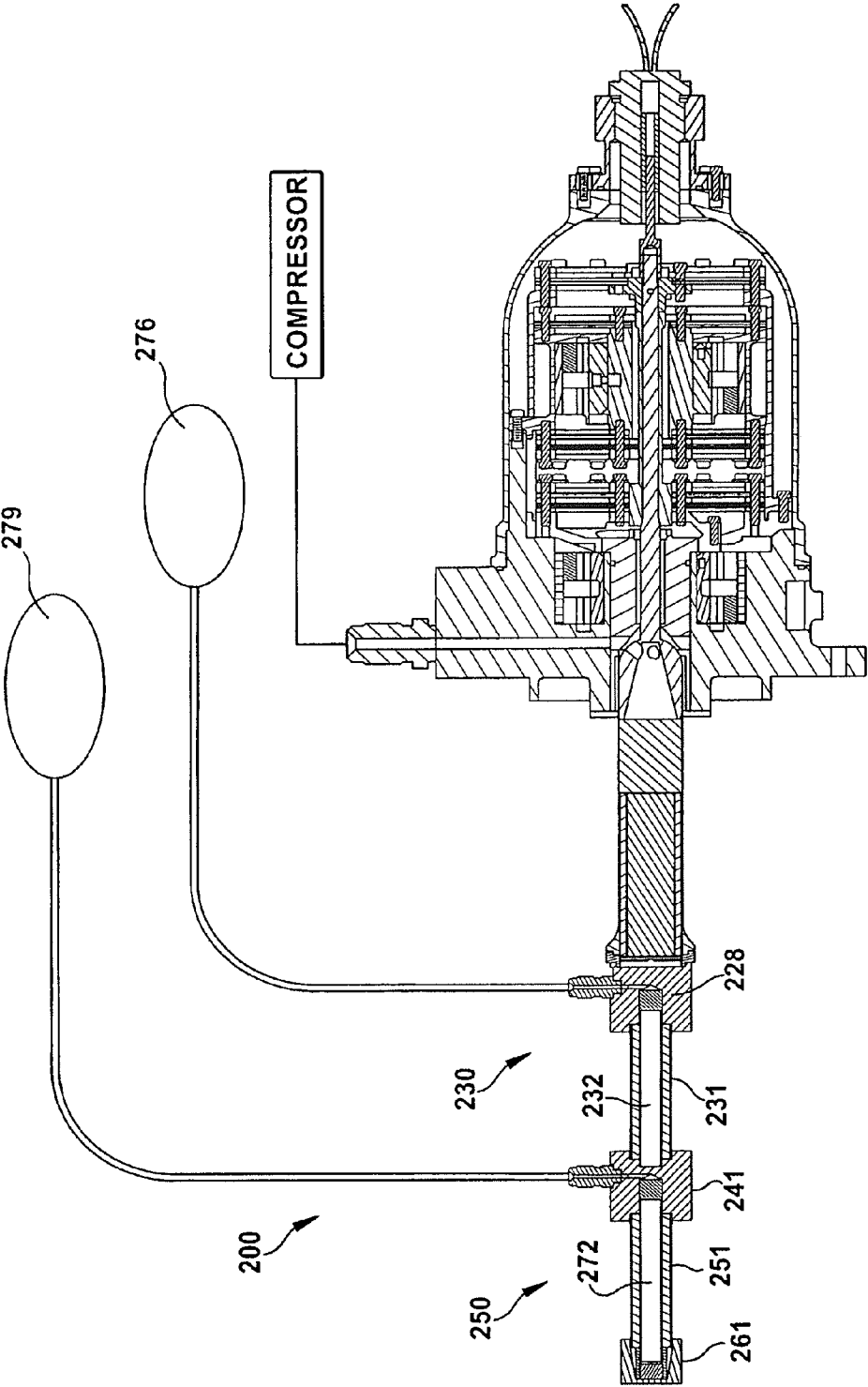


Fig.4

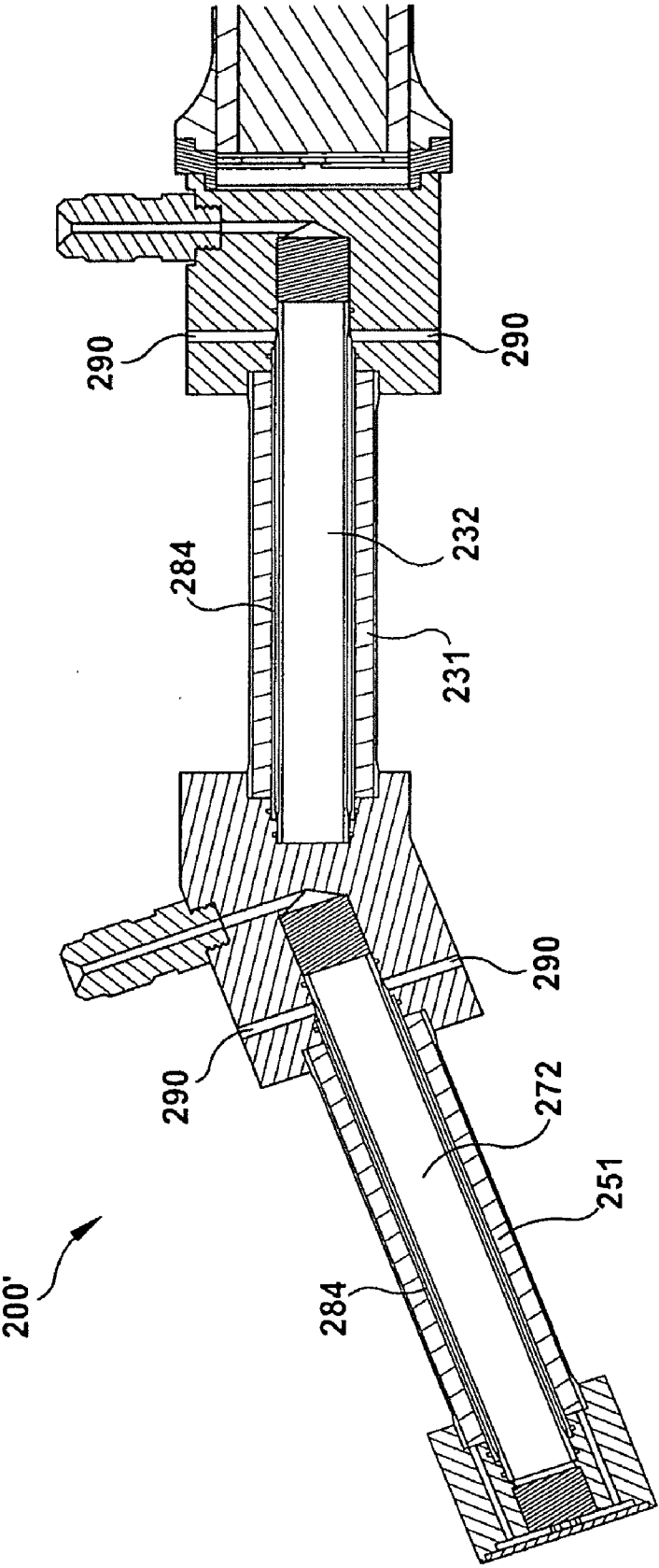


Fig.5

HYBRID CRYOCOOLER WITH MULTIPLE PASSIVE STAGES

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of U.S. application Ser. No. 11/432,058, filed on May 11, 2006, the contents of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] 1. Technical Field of the Invention

[0003] This invention is in the field of cryocoolers, and more particularly in the field of regenerative cryocoolers.

[0004] 2. Background of the Related Art

[0005] Multi-stage cryocoolers are of fundamental interest for many applications in which cryogenic cooling is required. For example, some applications require the simultaneous cooling of two or more objects to cryogenic, but different, temperatures. In the case of a long wave infrared sensor, for instance, the focal plane assembly may require an operating temperature of around 40 K, while the optics may need to be maintained at a different temperature, such as about 100 K. One approach for such situations is to use a single-stage cooler and extract all of the refrigeration at the coldest temperature. However, this is thermodynamically inefficient. Another approach is to use two single-stage cryocoolers with one each at the two temperature reservoirs. This approach has the disadvantage of being expensive and large in size. A better approach that has been done in the past is to use a two-stage cryocooler with the first-stage cooling the higher operating temperature component, and the second stage cooling the lower operating temperature component. Multi-stage cryocoolers are generally more efficient than single-stage coolers, because a portion of the internal parasitic thermal losses can be removed from the system at higher temperatures, thus producing less entropy generation.

[0006] FIG. 1 shows a portion of a prior art cryocooler 10. The cryocooler 10 includes a compressor 11 that is coupled to a first-stage Stirling expander 20 with a first-stage regenerator 21, a plenum 22, and a piston or displacer 23. The piston 23, which contains the regenerator 21, oscillates within a cold cylinder 25. A wall of the cold cylinder 25 provides first stage pressure containment and thermal isolation from the ambient warm end. The plenum 22 and a motor assembly 27 are contained within an expander housing 26. The first-stage expander 20 also includes a first-stage heat exchanger 24 in a first-stage manifold 28. The piston or displacer 23 is used to expand the working gas, such as helium, downstream of the regenerator 21 such that refrigeration is produced in the first-stage heat exchanger 24. The working gas absorbs the first stage heat load from the environment as it passes through the first-stage heat exchanger 24. The first-stage heat exchanger 24 is in pneumatic communication with a second-stage pulse tube expander 30, where the (colder) second-stage refrigeration is produced. The pulse tube expander 30 includes a second-stage regenerator 31 and a pulse tube 32. The second-stage regenerator 31 and the pulse tube 32 may be generally parallel to one another, forming legs of a U-shaped configuration. The second-stage regenerator 31 and the pulse tube 32 are linked together by a flow passage 36 in a second-stage manifold 41. The flow passage 36 links a downstream end of the second-stage regenerator 31 with an upstream end of the pulse tube 32. End caps 42 and 43 close off the respective ends

of the second-stage regenerator 31 and the pulse tube 32, within the second-stage manifold 41. A second-stage cold heat exchanger 44 is at an upstream end of the pulse tube 32, in the second-stage manifold 41. A second-stage warm heat exchanger 46 is at a downstream end of the pulse tube 32, in the first-stage manifold 28. The cryocooler 10 may be used to cool objects thermally coupled to either or both of the manifolds 28 and 41. Objects in thermal communication with the first-stage manifold 28 are cooled at a first cold temperature, and objects in communication with the second-stage manifold 41 are cooled at an even lower cold temperature. Further details regarding prior art cryocoolers may be found in commonly-assigned U.S. Pat. Nos. 6,167,707, and 6,330,800, the descriptions and figures of which are incorporated herein by reference.

[0007] In installation of the prior art cryocooler 10, the cold cylinder 25, the first-stage manifold 28, and the second-stage pulse tube expander 30 (collectively a cold head 50) are often required to be supported only at the expander housing 26. This leaves the second-stage pulse tube expander 30, the second-stage manifold 41, the first-stage manifold 28, and much of the cold cylinder 25, cantilevered off of the housing 26. This has caused difficulties, particularly in space flight applications, where the cooling system must be able to withstand loads and random vibrations generated during launch.

[0008] In order to provide cooling at very low temperatures, for instance at about 10 K or below, multi-stage coolers with three or more stages have been utilized. Improvements are desirable in multi-stage cryocoolers capable of providing cooling at these very low temperatures.

SUMMARY OF THE INVENTION

[0009] According to an aspect of the invention, a cryocooler has three or more stages, at least one of which is an active stage, defined as a stage driven by a moving piston, and at least another of which is a passive stage.

[0010] According to another aspect of the invention, a cryocooler has an active first stage, and two or more passive stages coupled to the active stage. The active stage may be a Stirling expander, and the passive stages may include pulse tubes.

[0011] According to yet another aspect of the invention, a cryocooler has three or more stages, all of which utilize the same working fluid.

[0012] According to still another aspect of the invention, a cryocooler has three or more stages, including an active stage that operates at at least about 20 Hertz.

[0013] According to a still further aspect of the invention, a cryocooler has an active first stage that includes a Stirling expander, passive second and third stages that include pulse tubes, and a pair of surge volumes which are maintained at substantially ambient temperature.

[0014] According to another aspect of the invention, a multi-stage cryocooler includes: an active first stage; and plural passive stages operatively coupled to the active first stage.

[0015] To the accomplishment of the foregoing and related ends, the invention comprises the features hereinafter fully described and particularly pointed out in the claims. The following description and the annexed drawings set forth in detail certain illustrative embodiments of the invention. These embodiments are indicative, however, of but a few of the various ways in which the principles of the invention may be employed. Other objects, advantages and novel features of

the invention will become apparent from the following detailed description of the invention when considered in conjunction with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] In the accompanying drawings, which are not necessarily to scale:

[0017] FIG. 1 is a cross-sectional view of a prior art multi-stage cryocooler;

[0018] FIG. 2A is a cross-sectional side view of a multi-stage cryocooler in accordance with an embodiment of the present invention;

[0019] FIG. 2B is an oblique view of a flow plug that is part of the cryocooler of FIG. 2A;

[0020] FIG. 3 is a schematic illustration of an alternate embodiment of a multi-stage cryocooler in accordance with the present invention, utilizing microelectromechanical systems (MEMS) devices;

[0021] FIG. 4 is a cross-sectional view of a multi-stage cryocooler in accordance with an alternate embodiment of the present invention, including concentric pulse tube stages; and

[0022] FIG. 5 is a cross-sectional view of a second stage of a multi-stage cryocooler in accordance yet another alternate embodiment of with the present invention.

DETAILED DESCRIPTION

[0023] A multi-stage cryocooler has three or more stages, including an active first stage and passive second and third stages. The active stage may include a Stirling expander, and the passive second and third stages may be pulse tube coolers. The cryocooler may provide cooling at three different temperatures. The coldest cooling temperature may be at or below 10 K, and may be at or below 5 K. The system may provide cooling at such low temperatures while still operating at a relatively high frequency, for example, at a frequency of at least about 20 Hertz.

[0024] With reference initially to FIG. 2A, details are now discussed of a multi-stage cryocooler 100. The cooler 100 includes an active first stage 104, with a compressor 110 coupled to a first-stage expander 120, such as a Stirling expander. The expander 120 may be substantially identical to the expander 20 of the prior art cryocooler 10 (FIGS. 1), and may include such parts as a first-stage regenerator 121, a plenum 122, and a piston or displacer 123, a cold cylinder 125, an expander housing 126, and a motor assembly 127. Working fluid exiting the first-stage regenerator 121 proceeds into a first-stage heat exchanger 124 that is in a first-stage manifold 128. The first-stage heat exchanger 124 includes through holes proceeding through the first-stage manifold 128, for allowing flow of the working fluid into a second-stage pulse tube expander 130. The first-stage manifold 128 may be maintained at a first-stage cold temperature, and may be linked to heat-producing items via suitable thermal straps (not shown) to cool or maintain temperature of the heat-producing items.

[0025] The cold cylinder 125 (and its contents) and the second-stage pulse-tube expander 130 are parts of a cold head. The cold head is mechanically coupled to the expander housing 126.

[0026] The second-stage pulse tube expander 130 is in many respects similar to the pulse tube expander 30 shown in FIG. 1. The second-stage pulse tube expander 130 includes a second-stage regenerator 131 and a second-stage pulse tube

132, which may be generally parallel to one another, forming legs of a U-shaped configuration. A second-stage manifold 141 provides a flow passage 142 that links the second-stage pulse tube expander 130 with an upstream end of the third-stage pulse tube expander 150. A second-stage heat exchanger 144 is located at an upstream end of the second-stage pulse tube 132. Flow proceeds from the second-stage regenerator 131 through the flow passage 142 and into a third-stage regenerator 151.

[0027] The second-stage manifold also contains a flow plug 152, shown in detail in FIG. 2B, that diverts some of entering flow through a passage 153, to the second-stage pulse tube 132. The flow plug 152 includes a set of central holes 154 that allow flow to pass through to the third-stage pulse tube expander 150. The flow plug also contains a set of circumferential slots 156 that allow flow to be diverted, via the flow passage 153, directly to the upstream end of the second-stage pulse tube 132.

[0028] It will be appreciated that a wide variety of alternative configurations are possible for the flow plug 152. The flow plug 152 may divert a relatively fixed amount of flow away from the third stage 150 of the cryocooler 100. Alternatively, the amount of flow diverted by the flow plug may be controllable.

[0029] A flow passage 158 in a third-stage manifold 161 is used to turn the flow from a downstream end of the third-stage regenerator 151. Within the third-stage manifold 161, the flow passes through a third-stage heat exchanger 164, and into a third-stage pulse tube 172. Return flow of the working fluid passes from the third-stage pulse tube 172 into the second-stage manifold 141 and the second-stage heat exchanger 144.

[0030] The outlet from the second-stage pulse tube 132 may be coupled to a surge volume 176, via an inertance tube 178 coupled to the first-stage manifold 128. In addition, the outlet from the third-stage pulse tube 172 may be coupled to a second surge volume 179 via an inertance tube 180 coupled to the second-stage manifold 141. The surge volumes 176 and 179 may be maintained at an ambient warm temperature, or alternatively one or both of the surge volumes may be maintained at a cooler temperature. Further details regarding configuration and use of an ambient-temperature surge volume may be found in commonly-assigned U.S. application Ser. No. 10/762,867, titled "Cryocooler With Ambient Temperature Surge Volume" filed Jan. 22, 2004, the description and figures of which are incorporated herein by reference.

[0031] The cryocooler 100 provides an efficient means for getting to very low cryogenic temperatures. In one example, the Stirling first stage may cool to about 80 K, the pulse tube second stage may cool to about 20 K, and the pulse tube third stage may cool to about 10 K. For lower objective temperatures, alternative temperature arrangements are achievable, such as a first stage cooling to about 50 K, the second stage cooling to about 12 K, and the third stage cooling to about 5 K. These lower temperatures may be desirable for some installations, such as cooling of niobium superconducting electronics. It will be appreciated that a wide variety of other cooling temperatures may be produced using various embodiments of the cryocooler 100. For example, temperatures in ranges between the above specific examples may be achievable. Also, temperatures warmer or colder than the above temperatures may be achievable.

[0032] The temperatures described above may be achievable with operation at higher frequencies than have been used in previous cryocooler systems for achieving such low tem-

peratures. For example, the cryocooler **100** may operate at a frequency of at least about 20 Hertz. Systems for achieving such low temperatures have previously operated at much lower frequencies (5-10 Hertz), which requires a large moving assembly for an active device such as a Stirling expander. By operating at low frequencies, such expanders must have a moving portion that is relatively large. In contrast, the high-frequency operation of the cryocooler **100** allows reduction of the physical size and weight of the cryocooler. The cryocooler **100** advantageously is able to operate at a higher frequency at least because the active-passive-passive configuration of the stages of the cryocooler **100** is more efficient. Control of the phase angle in the active first stage allows optimization in the amount of refrigeration provided by each stage.

[0033] Overall refrigeration capacity may be shifted between the active first stage and the passive second and third stages simply by changing the phase angle of the active stage displacer relative to the pressure wave generated by a mated compressor.

[0034] One advantage of the cryocooler **100** is that use of passive second and third stages reduces the need for moving parts and cryogenic moving seals, relative to three-stage Stirling or other active cryocoolers. This simplifies the system and reduces cost. Relative to systems involving only three or more pulse tubes, the efficiency of the active first stage has the advantage of reducing the cooling burden required from the passive second and third stages. Efficient single-stage Stirling coolers may achieve cooling temperatures as low as 35 K, for instance. In contrast, single-stage pulse tubes often may provide competitive cooling only down to substantially higher temperatures, such as about 60 K. By combining an active first stage with passive or pulse-tube second and third stages, the cooling burden on the passive stages is reduced, and the need to add additional stages may be avoided.

[0035] Another advantage of the cryocooler **100** is that the same working fluid is used for all three stages.

[0036] Microelectromechanical systems (MEMS) devices may be incorporated at various positions within the cryocooler **100** to control flow within the cryocooler **100**.

[0037] Such MEMS devices may be used to control any of a variety of flow parameters, for example, providing suitable flow rate, dynamic response, power efficiency, and/or other operating characteristics for MEMS devices or flow controllers. A schematic illustration of use of MEMS devices is shown in FIG. 3, in which a cryocooler **100'** has MEMS devices **186** located 1) in a bypass line **188** (allowing flow from an active first stage **104** to bypass a passive second stage **190** and a passive third stage **191**); 2) in a bypass line **192** (allowing flow from the second stage **190** to bypass the third stage **191**); and 3) in fluid lines **194** and **196** leading to respective surge volumes **176** and **179**. The MEMS devices may be located in any of these locations, or in other suitable locations within a multi-stage cryocooler. The MEMS pulse tube phase shifters in flow tubes **194** and **196** provide improved control over the expansion phase angle in the pulse tubes, which enables increased refrigeration capacity in either the second or third stages. The MEMS valve in bypass line **192** is a particularly attractive embodiment for the Hybrid Cryocooler with Multiple Passive Stages because it enables load shifting between the second and third stages, and/or because it enables the elimination of DC flow patterns within the cold head. Adjustment of the first stage Stirling piston phase angle provides load shifting between the first stage and the pulse tube stages. The coupling of these two effects pro-

vides a broad range of operational flexibility in that the refrigeration capacity can now be shifted between all three stages for nominally constant input power. Further information regarding such MEMS devices may be found in U.S. patent application Ser. No. 10/974,154, titled "PULSE TUBE COOLER WITH INTERNAL MEMS FLOW CONTROLLER," filed Oct. 14, 2005, the description and drawings of which are herein incorporated by reference.

[0038] FIG. 4 illustrates another embodiment, a cryocooler **200** that utilizes a concentric second-stage pulse tube expander **230**, and a concentric third-stage pulse tube expander **250**. A first-stage manifold **228** is upstream of the second-stage pulse tube expander **230**. The second-stage pulse tube expander **230** has a second-stage regenerator **231** that surrounds a second-stage pulse tube **232**. Similarly, the third-stage pulse tube expander **250** may have a third-stage regenerator **251** that surrounds and may be concentric with a third-stage pulse tube **272**. The flow passages in a second-stage manifold **241** and a third-stage manifold **261** may be somewhat different than the passages in the manifolds **141** and **161** (FIG. 2), which have been described above. Some of these flow passages are shown in the illustrated view, while other flow passages (such as passages in the second-stage manifold **241**, connecting the regenerators **231** and **251**) are not shown. The manifolds **241** and **261** may be coupled to respective surge volumes **276** and **279**, which may be maintained at ambient temperature.

[0039] FIG. 5 shows a portion of a variation on the cooler **200**, a cryocooler **200'** in which vacuum gaps **284** are placed between the walls of the second-stage regenerator **231** and the second-stage pulse tube **232**, and between the third-stage regenerator **251** and the third-stage pulse tube **272**. The configuration in FIG. 5 also shows the third-stage pulse tube expander **250** at an angle to the second-stage pulse tube expander **230**. This angle may be substantially a right angle, or may be at any of a variety of other suitable angles. The vacuum gaps **284** may be in fluid communication with an ambient atmosphere through external passages **290**.

[0040] Features of the embodiment shown in FIGS. 4 and 5 may be combinable with one another. For example, multiple pulse tube stages having vacuum gaps may be arrayed in a straight line, or multiple pulse tube stages without vacuum gaps may be angled relative to one another. In addition, it will be appreciated that a concentric pulse tube may be combined in the same cryocooler with a non-concentric pulse tube, if desired. It will be appreciated that other features of other embodiments may also be combinable in a single cryocooler.

[0041] The use of concentric pulse tube stages may have the advantage of providing better mechanical integrity. In addition, use of the vacuum gap may advantageously reduce heat transfer between parts of the same pulse tube expander stage. Further details regarding concentric pulse tube expanders may be found in U.S. Pat. No. 5,680,768, and in U.S. patent application Ser. No. 11/038,833, titled "MULTI-STAGE CRYOCOOLER WITH CONCENTRIC SECOND STAGE," filed Jan. 19, 2005. The description and figures of the above patent and patent application are herein incorporated by reference.

[0042] Although the invention has been shown and described with respect to a certain preferred embodiment or embodiments, it is obvious that equivalent alterations and modifications will occur to others skilled in the art upon the reading and understanding of this specification and the annexed drawings. In particular regard to the various func-

tions performed by the above described elements (components, assemblies, devices, compositions, etc.), the terms (including a reference to a “means”) used to describe such elements are intended to correspond, unless otherwise indicated, to any element which performs the specified function of the described element (i.e., that is functionally equivalent), even though not structurally equivalent to the disclosed structure which performs the function in the herein illustrated exemplary embodiment or embodiments of the invention. In addition, while a particular feature of the invention may have been described above with respect to only one or more of several illustrated embodiments, such feature may be combined with one or more other features of the other embodiments, as may be desired and advantageous for any given or particular application.

What is claimed is:

- 1. A multi-stage cryocooler comprising:
 - an active first stage;
 - first and second passive stages, wherein the first passive stage is operatively coupled to the active first stage, and the second passive stage is operatively coupled to the first passive stage; and
 - a manifold coupled between the first passive stage and the second passive stage,
 - wherein the active first stage includes a compressor and an active expander, and
 - wherein at least one of the passive stages comprises a concentric pulse tube expander.
- 2. The cryocooler of claim 1, wherein both of the first and second passive stages comprise a concentric pulse tube expander.
- 3. The cryocooler of claim 1, wherein the concentric pulse tube expander includes a vacuum gap.
- 4. The cryocooler of claim 3, wherein the concentric pulse tube expander comprises a pulse tube and a regenerator, and wherein the vacuum gap is between the pulse tube and the regenerator.
- 5. The cryocooler of claim 1, wherein the manifold is a second stage manifold, and further comprising a first stage manifold coupled between the active first stage and the first passive stage.
- 6. The cryocooler of claim 5, further comprising a third stage manifold coupled to the second passive stage opposite the first passive stage.
- 7. The cryocooler of claim 6, further comprising respective surge volumes mechanically coupled to the respective second and third stage manifolds.
- 8. The cryocooler of claim 5, wherein the second stage manifold includes a passage for diverting flow, to bypass the second passive stage.
- 9. The cryocooler of claim 1, wherein the first passive stage includes the concentric pulse tube expander, and wherein the second passive stage includes a U-shaped pulse tube expander.
- 10. The cryocooler of claim 1, wherein the cryocooler provides three different temperature outputs, and wherein one of the temperature outputs is below 10 K.

11. The cryocooler of claim 2, wherein the concentric pulse tube expanders of the first and second passive stages are oriented at a nonzero angle relative to one another.

12. The cryocooler of claim 1, further comprising a microelectromechanical system (MEMS) flow controller fluidically coupled to at least one of the active first stage, the first passive stage, or the second passive stage, for controlling flow of a working fluid within the cryocooler.

13. The cryocooler of claim 12, wherein the MEMS flow controller is located in a bypass line between the active first stage and the first passive stage.

14. The cryocooler of claim 12, wherein the MEMS flow controller is located in a bypass line between the first passive stage and the second passive stage.

15. The cryocooler of claim 12, further comprising respective first and second surge volumes mechanically coupled to the respective first and second passive stages, and wherein the MEMS flow controller is located in a fluid line coupled to one of the first or second surge volume.

16. The cryocooler of claim 1, wherein the cryocooler operates at a frequency of at least about 20 Hertz.

17. A multi-stage cryocooler comprising:

- an active first stage comprising a compressor and an active expander coupled to the compressor, the active expander including a piston;
- a first passive stage comprising a first concentric pulse tube expander including a pulse tube and a regenerator; and
- a second passive stage comprising a second concentric pulse tube expander including a pulse tube and a regenerator,

wherein the first passive stage is coupled to the active first stage at a first stage manifold, and

wherein the second passive stage is coupled to the first passive stage at a second stage manifold.

18. The multi-stage cryocooler of claim 17, wherein the first and second passive stages are cantilevered from the active first stage.

19. The multi-stage cryocooler of claim 17, wherein the second concentric pulse tube expander is coupled at a nonzero angle relative to the first concentric pulse tube expander.

20. A multi-stage cryocooler comprising:

- an active first stage comprising a compressor and an active expander coupled to the compressor, the active expander including a piston;
- a first passive stage comprising a first pulse tube and a first regenerator that surrounds the first pulse tube, and a first vacuum gap between the first pulse tube and the first regenerator;
- a second passive stage comprising a second pulse tube and a second regenerator that surrounds the second pulse tube, and a second vacuum gap between the second pulse tube and the second regenerator,

wherein the first passive stage is coupled to the active first stage at a first stage manifold,

wherein the second passive stage is coupled to the first passive stage at a second stage manifold, and

wherein the first and second passive stages are cantilevered from the active first stage.

* * * * *