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(54) **CRYOCOOLER WITH AMBIENT TEMPERATURE SURGE VOLUME**

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(51) **Int. Cl.**
F25B 9/00 (2006.01)

(52) **U.S. Cl.** **62/6**

(58) **Field of Classification Search** 62/6
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,642,623	A	7/1997	Hiresaki et al.	
5,647,219	A *	7/1997	Rattray et al.	62/6
5,711,157	A	1/1998	Ohtani et al.	
6,167,707	B1 *	1/2001	Price et al.	62/6
6,205,812	B1 *	3/2001	Acharya et al.	62/607
6,256,998	B1 *	7/2001	Gao	62/6
6,330,800	B1	12/2001	Price et al.	
6,374,617	B1 *	4/2002	Bonaquist et al.	62/6
6,378,312	B1 *	4/2002	Wang	62/6
6,666,033	B1 *	12/2003	Swift et al.	62/6
2004/0000149	A1 *	1/2004	Kirkconnell et al.	62/6
2004/0168445	A1 *	9/2004	Kunitani et al.	62/6
2004/0221586	A1 *	11/2004	Daniels	62/6

OTHER PUBLICATIONS

U.S. Appl. No. 10/288,943, filed Nov. 6, 2002, entitled Multi-Nozzle Grid Missile Propulsion System.

* cited by examiner

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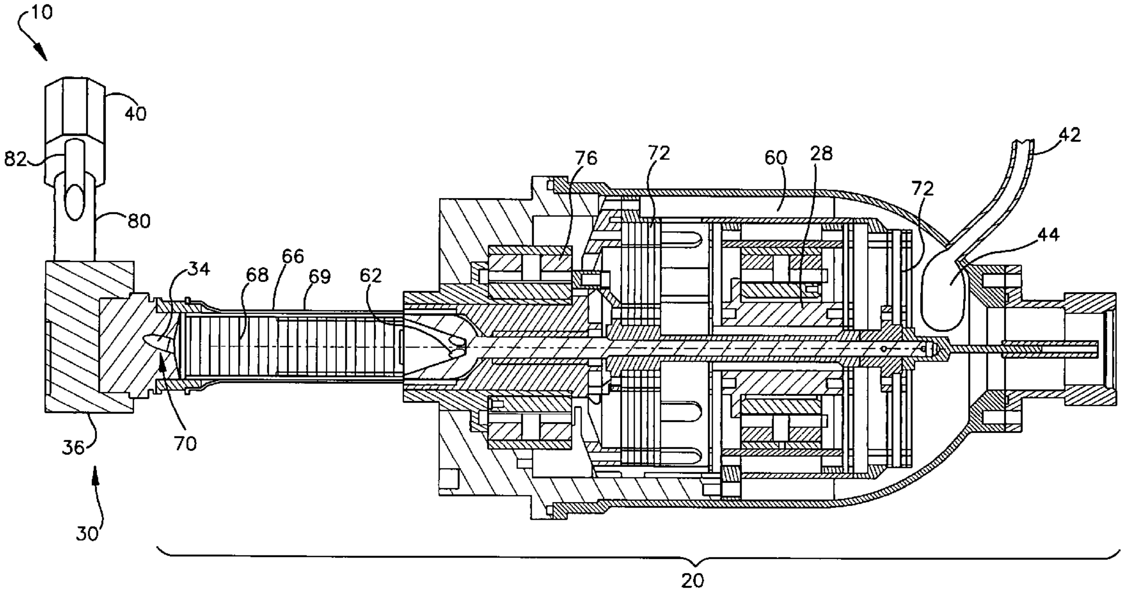
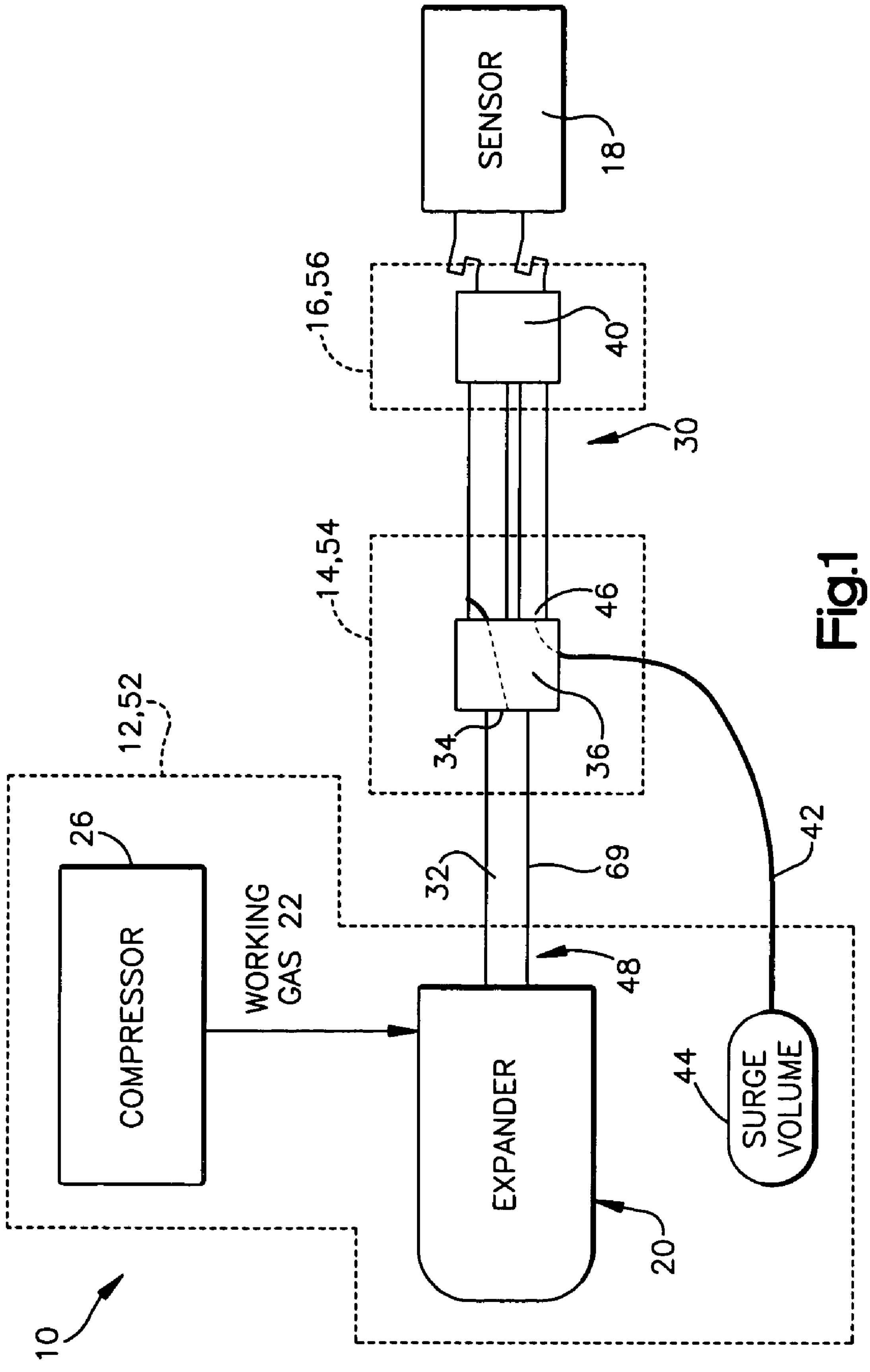
(57) **ABSTRACT**

A two-stage cryocooler (**10**) includes an ambient temperature portion (**12**), a first-stage temperature portion (**14**), and a second-stage temperature portion (**16**). The ambient temperature portion includes a surge volume (**44**) that is coupled to and in communication with the first-stage temperature portion. The surge volume may be coupled to a first-stage interface (**36**) of the first-stage temperature portion by use of an inertance tube (**42**). Locating the surge volume in the ambient temperature portion may advantageously reduce size and mass of the first-stage temperature portion. Also, thermal losses may be reduced by maintaining the surge volume at ambient temperature. Space and structural requirements for maintaining the system may be met more easily with the surge volume maintained in the ambient temperature portion of the two-stage cooler. The surge volume may be a separate unit, or may be a plenum or other chamber within an expander in the ambient temperature portion.

21 Claims, 8 Drawing Sheets

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EXPANDER
44
SURGE VOLUME
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10

Fig.1

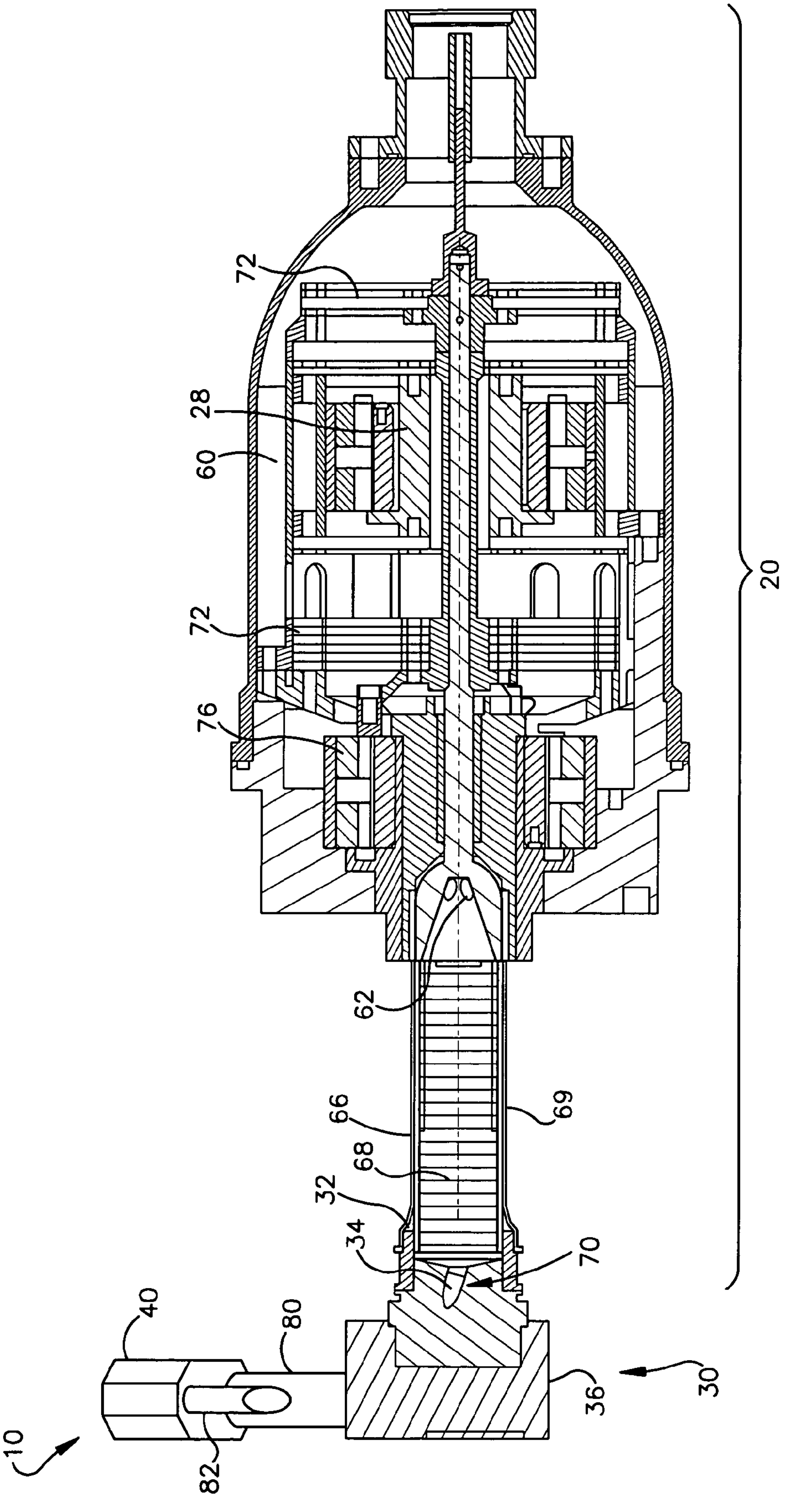

Fig.2
PRIOR ART

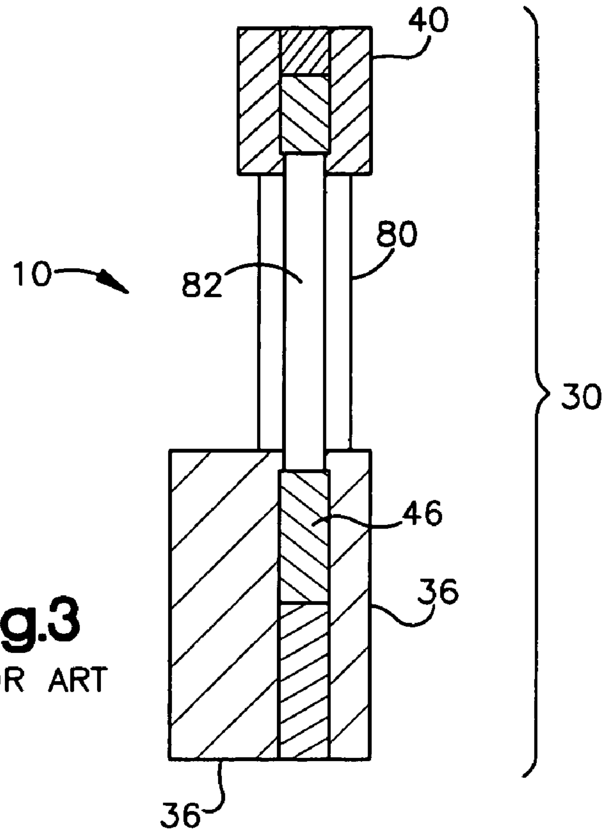

Fig.3
PRIOR ART

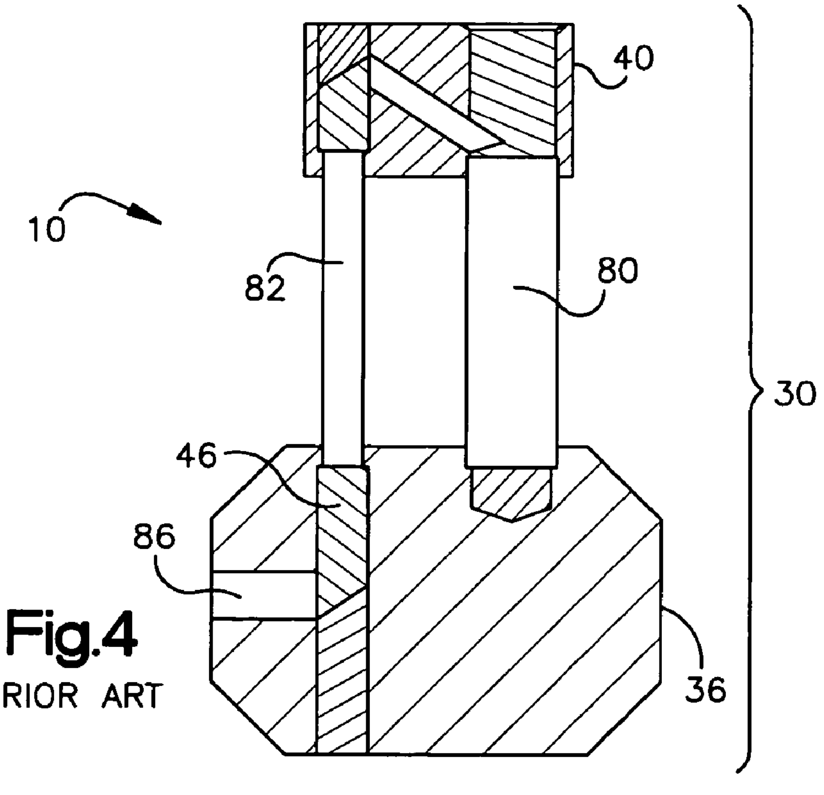

Fig.4
PRIOR ART

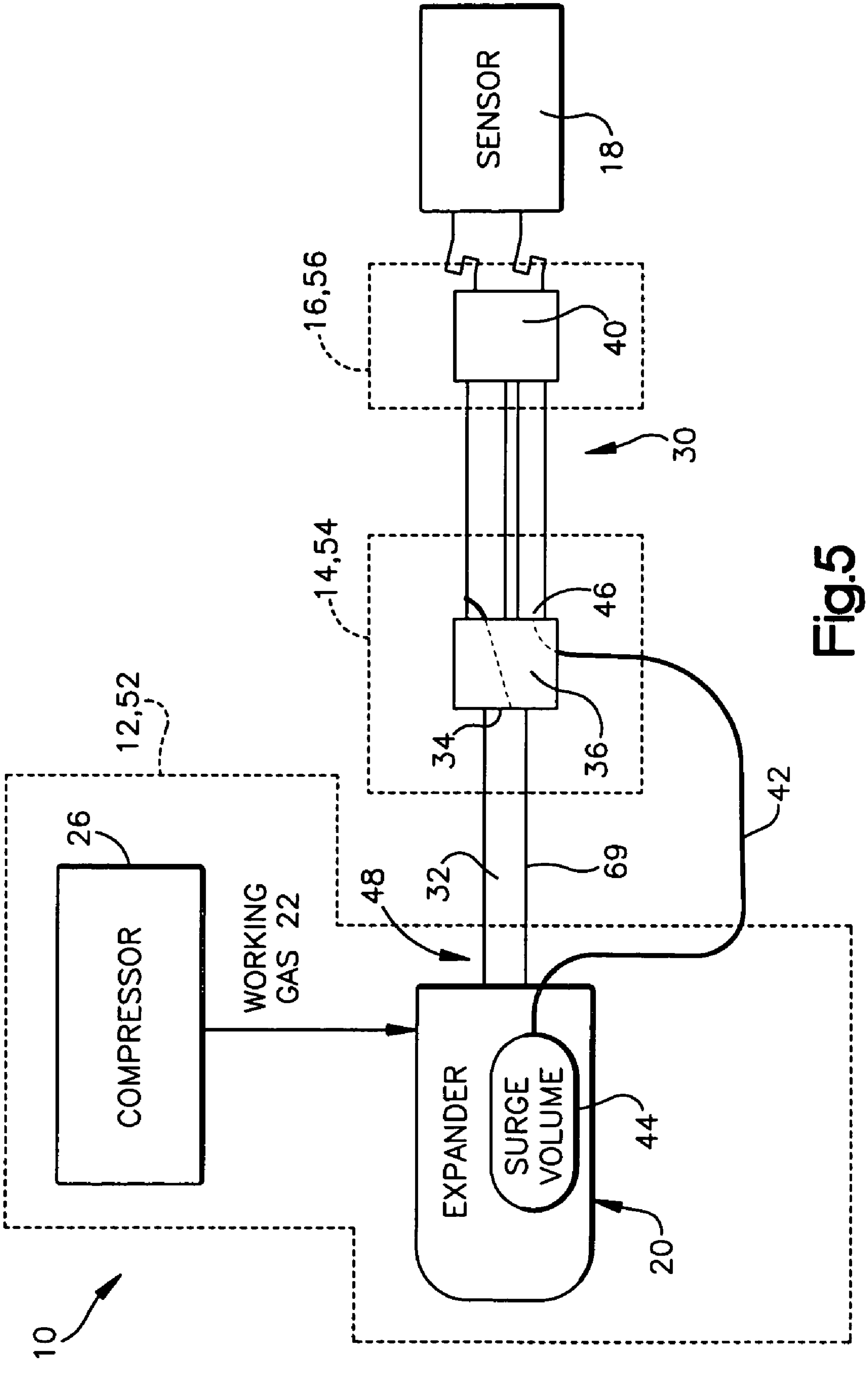
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Fig.5

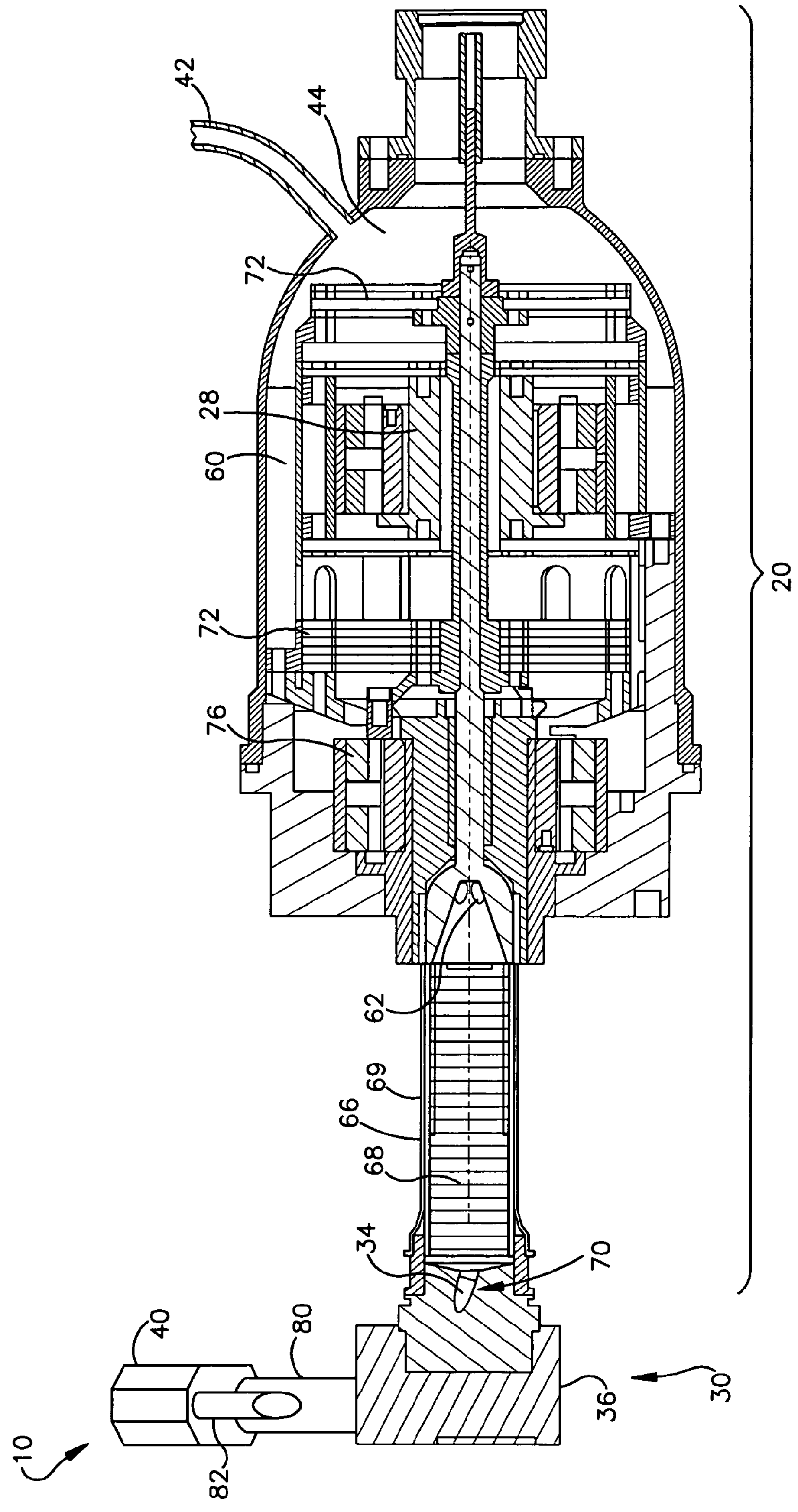


Fig.6

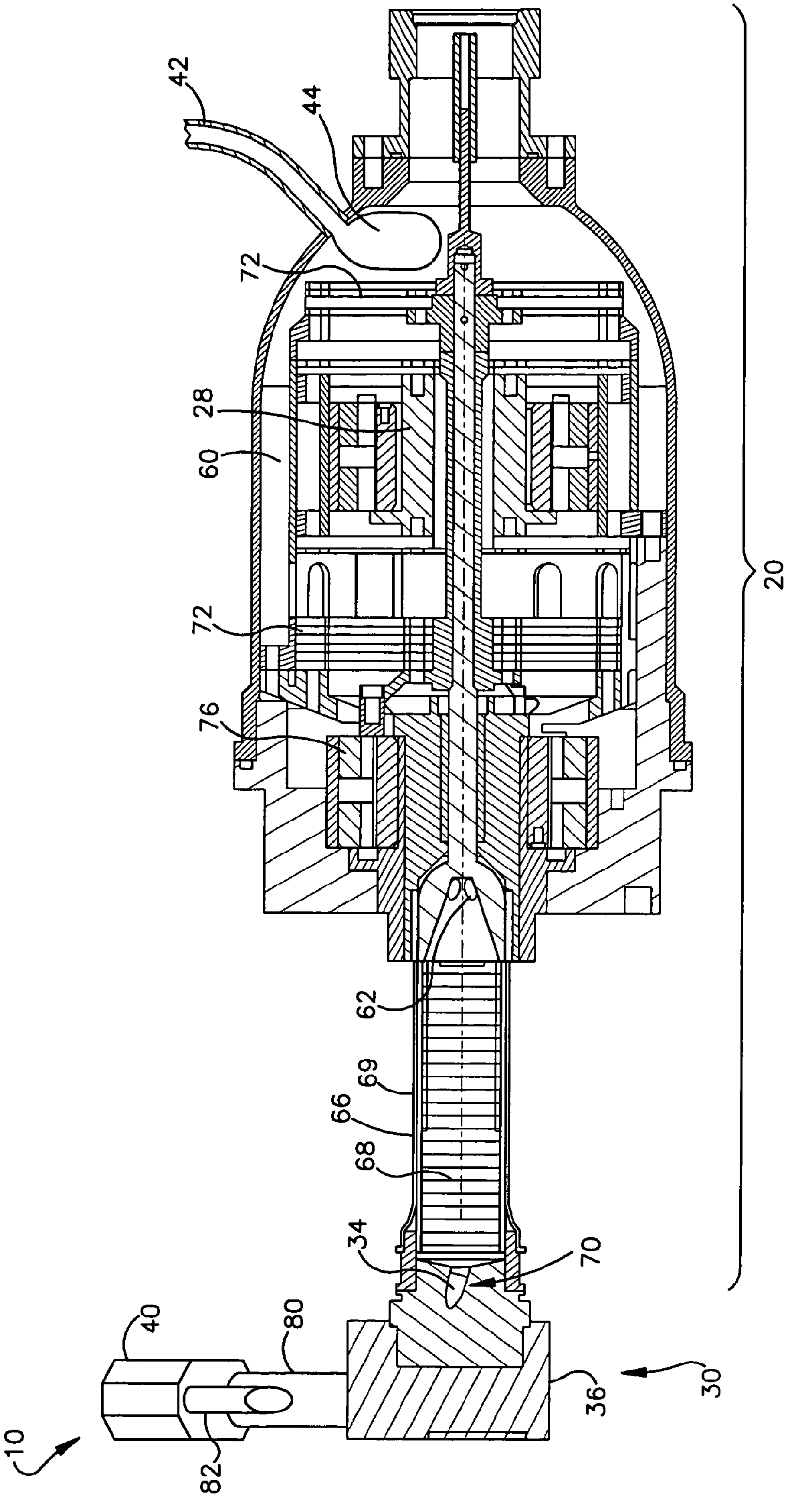
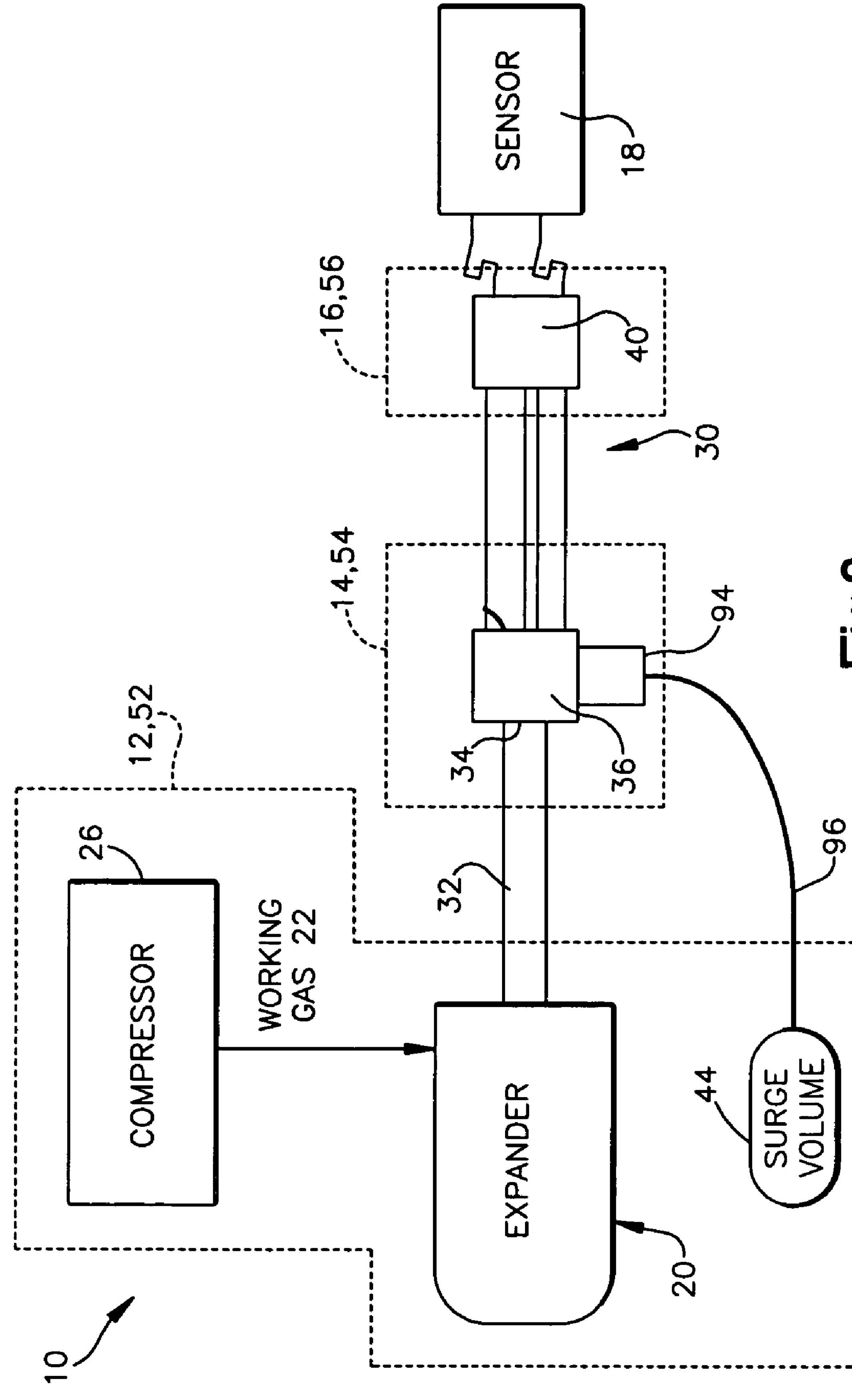


Fig.7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EXPANDER
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SURGE VOLUME
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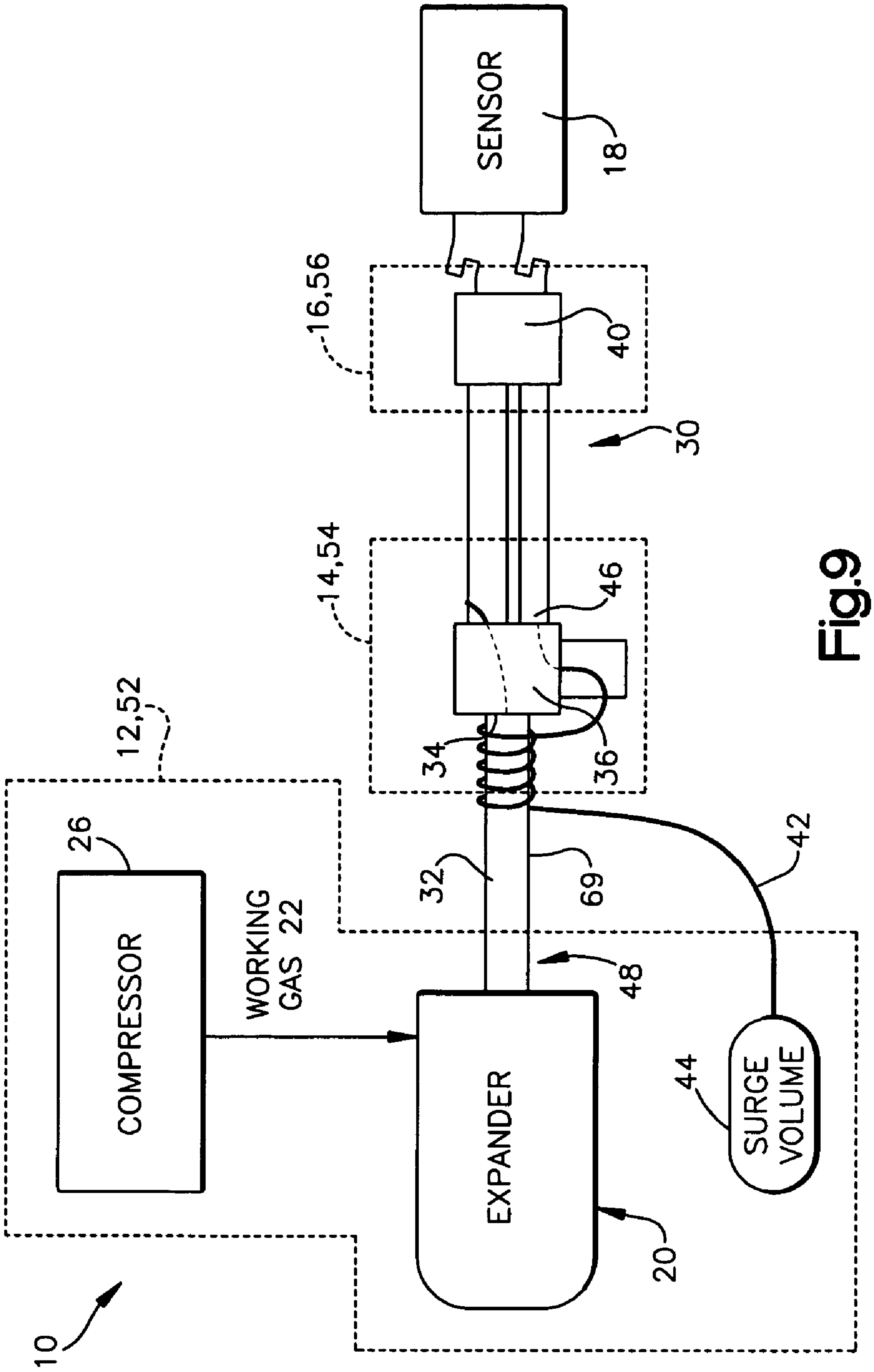
Fig.8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EXPANDER
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SURGE VOLUME
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Fig.9

CRYOCOOLER WITH AMBIENT TEMPERATURE SURGE VOLUME

BACKGROUND OF THE INVENTION

1. Technical Field

The present invention relates generally to cryocoolers, and more particularly, to two-stage cryocoolers having a Stirling/pulse tube hybrid configuration.

2. Description of the Related Art

Multistage cryocoolers are of fundamental interest for many applications in which cryogenic cooling is required. For example, some applications require the simultaneous cooling of two 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 of the higher operating temperature component, and the second stage cooling the lower operating temperature component. Multistage cryocoolers are generally more efficient than single-stage coolers, because a portion of the internal parasitic thermal losses can occur at higher temperatures, thus producing less entropy generation.

Space-based cryocooler requirements put a high premium upon small volume, low weight, and high reliability. One approach that has been taken in the past is to use a two-stage cryocooler with a first-stage Stirling cryocooler, and a second-stage pulse tube cryocooler. Such an arrangement provides high efficiency, long life, and compact size for the system. Examples of such systems may be found in co-owned U.S. Pat. Nos. 6,167,707 and 6,330,800. Other and viable multistage configurations include multistage Stirling cryocoolers and multistage pulse tubes.

While some success has been achieved with the prior approaches described above, it will be appreciated that improvements may be desirable, as is generally the case in the vast majority of technical areas.

SUMMARY OF THE INVENTION

According to an aspect of the invention, a cryocooler includes a surge volume that is maintained at a temperature while being in communication with an interface maintained at another, lower temperature. The surge volume may be maintained at ambient temperature while the interface may be maintained at a temperature below ambient.

According to another aspect of the invention, a hybrid multistage cryocooler includes: a first-stage expander having a first-stage expander outlet; a first-stage thermal interface; a second-stage expander in communication with the first-stage expander outlet, via the first-stage thermal interface; and a surge volume in gaseous communication with the second-stage expander outlet. The surge volume is maintained at an ambient temperature.

According to yet another aspect of the invention, a hybrid multistage cryocooler includes: a first-stage expander having a first-stage expander outlet; a first-stage thermal interface; a second stage in communication with the first-stage expander outlet, via the first-stage thermal interface; a surge volume in gaseous communication with the second-stage expander; and an inertance tube coupling the surge volume to the second-stage outlet. The surge volume is maintained at an ambient temperature. A first end of the inertance tube is at the ambient temperature. A second end of the inertance tube is at a first-stage temperature, which is lower than the ambient temperature. The first-stage expander is a Stirling expander. The first-stage thermal interface is coupled to an expansion volume of the first-stage expander. The first-stage thermal interface is cantilevered from a first-stage cold cylinder.

According to a further aspect of the invention, a method of cooling includes the steps of providing a first-stage expander having a first-stage expander outlet; providing a first-stage thermal interface; providing a second stage in communication with the first-stage expander outlet, via the first-stage thermal interface; and coupling a surge volume in communication with the second-stage expander outlet, wherein the coupling includes placing the surge volume such that the surge volume is maintained at an ambient temperature.

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 DRAWINGS

In the annexed drawings, which are not necessarily to scale:

FIG. **1** is a schematic diagram of a cryocooler in accordance with the present invention;

FIG. **2** is a sectional view of details of a prior art Stirling expander and pulse tube expander;

FIG. **3** is a sectional view of details of a prior art pulse tube expander;

FIG. **4** is another sectional view of the pulse tube expander of FIG. **3**;

FIG. **5** is a schematic diagram of an alternate embodiment cryocooler in accordance with the invention;

FIG. **6** is a cross-sectional view of one specific embodiment of a Stirling expander for the cryocooler of FIG. **5**;

FIG. **7** is a sectional view of another specific embodiment of a Stirling expander for use in the cryocooler of FIG. **5**;

FIG. **8** is a schematic diagram of yet another embodiment of a cryocooler in accordance with the present invention; and

FIG. **9** is a schematic diagram of still another embodiment of a cryocooler in accordance with the present invention.

DETAILED DESCRIPTION

A two-stage cryocooler includes an ambient temperature portion, a first-stage temperature portion, and a second-stage temperature portion. The ambient temperature portion includes a surge volume that is gaseously coupled to a second-stage outlet, and thus in thermal communication with the first-stage temperature portion. The surge volume may be coupled to the second-stage outlet by use of an inertance tube. Locating the surge volume in the ambient temperature portion may advantageously reduce the size and mass of the first-stage temperature portion. Also, thermal losses may be reduced by maintaining the surge volume at ambient temperature. Space and structural requirements for maintaining the system may be met more easily with the surge volume maintained in the ambient temperature portion of the two-stage cooler. The surge volume may be a separate unit, or may be a plenum or other chamber within an expander in the ambient temperature portion.

FIG. **1** schematically illustrates a two-stage cryocooler. Certain aspects of the cryocooler **10** may be similar to corresponding aspects described in U.S. Pat. Nos. 6,167,707 and 6,330,800, the descriptions of which are incorporated herein by reference. The cryocooler **10** includes an ambient temperature portion **12**, a first-stage temperature portion **14**, and a second-stage temperature portion **16**. The second-stage temperature portion is coupled to a component to be cooled, such as a sensor **18**. The first-stage of the cryocooler **10** includes a Stirling expander **20** for providing cooling by expanding a working gas **22** compressed by a compressor **26**. The second stage of the cryocooler **10** is a pulse tube expander **30**.

In an outline of general operation of the system, the compressor **26** supplies the compressed working gas **22** such as helium, to the first-stage Stirling expander **20**. The working gas is expanded into an expansion volume **32**. The working gas flows from the expansion volume **32** through a Stirling expander outlet **34**, through a first-stage interface **36**, and into the second-stage pulse tube expander **30**. A second-stage thermal interface **40** is provided between the second-stage pulse tube expander **30** and a heat load in the form of the component to be cooled, such as the sensor **18**.

An inertance tube **42** is coupled on one end to the first-stage interface **36**, and on another, opposite end to a surge volume **44** that is a part of the ambient temperature portion **12**. The first-stage interface **36** is in gaseous communication with a second-stage outlet **46**. The inertance tube **42** and the surge volume **44** provide modulation and control in the operation of the cryocooler **10**. The inertance tube **42** and the surge volume **44** combine to reduce a phase shift in the operation of the cryocooler **10**, to reduce the phase angle between a pressure wave and the cold end flow rate in the pulse tube expander **30**. The characteristics of the inertance tube **42**, such as the diameter and length of the inertance tube **42**, may be selected so as to achieve a desired performance within the cryocooler. The desired performance may include a goal of minimizing the phase angle between the mass flow rate and the pressure wave at the cold end of the pulse tube **30**, with an ultimate objective of optimizing thermodynamic efficiency.

The ambient temperature portion **12** includes a warm end **48** of the Stirling expander **20**, as well as the compressor **26** and the surge volume **44**. The components of the ambient temperature portion **12** may be coupled to an ambient temperature structure **52**. The first-stage temperature portion **14** includes the first-stage interface **36**, which may be coupled to a first-stage structure **54**. The second-stage portion **16** includes the second-stage thermal interface **40**, which may be coupled to a second-stage temperature structure **56**. The first-stage interface **36** may be supported in a cantilevered structure by the thin-walled tube of the expansion volume **32**.

Referring now to FIGS. **2**–**4**, some details are shown of the structure of the Stirling expander **20** and the second-stage pulse tube expander **30**. The Stirling expander **20** has a plenum **60** and a cold head that includes a thin-walled cold cylinder, an expander inlet **62** disposed at a warm end of a first-stage regenerator **68**, a moveable piston or displacer **66** disposed within a cold cylinder **69**, and a heat exchanger **70**. The displacer **66** is suspended on fore and aft flexures **72**. The displacer **66** is controlled and moved by using a motor **76** located at a fore end of the plenum **60**. A flexure-suspended balancer **78** may be used to provide internal reaction against the inertia of the moving displacer **66**.

The second-stage pulse tube expander **30** includes a second-stage regenerator (regenerative heat exchanger) **80**, and a pulse tube **82**. The second-stage regenerator **80** and the pulse tube **82** are gaseously coupled at one end to the second-stage interface **40**. Both the second-stage regenerator **80** and the pulse tube **82** are physically connected to the first-stage interface **36** at an opposite end, but are not in direct communication with each other. The first-stage interface **36** has a port **86** that is connected to the second-stage outlet **46**. One end of the inertance tube **42** is coupled to the port **86**.

In operation of the cryocooler **10**, a gas, for instance helium, flows into the expander inlet **62**, and into the first-stage regenerator **68** and the heat exchanger **70**. Gas flowing into the cold volume within the expander **20** is regenerated by the first-stage regenerator **68**. A portion of the gas remains in the first-stage expansion volume of the first-stage regenerator **68**. Progressively smaller portions of the gas continue to the second-stage regenerator **80**, the pulse tube **82**, and the inertance tube **42** in the surge volume **44**.

The use of a relatively long inertance tube **42** allows the advantage of moving the surge volume **44** to the ambient temperature portion **12** of the cryocooler **10**, while simultaneously providing the required fluidic resistance and inductance to achieve the desired phase shift. In the past, surge volumes in Stirling/pulse tube hybrid cryocoolers have been maintained at a cold temperature, and have been mounted more or less directly on structure of a cold stage. Since the cold stages of a cryocooler may be suspended in an essentially cantilevered configuration, with the expander **20** supported, and other components of the cryocooler having to support their own weight in a cantilevered configuration, it is highly advantageous to shift the surge volume to the ambient portion of the cryocooler, where it is much more easily supported. The cantilevered structure of the cryocooler **10** may involve use of a fairly long, thin-walled tube (e.g., the cold cylinder **69**) as a support. It will be appreciated that the greater amount of mass on the cantilevered structure, the greater the amount of stress that is put at the joint at the base of the thin-walled tube. Thus, by reducing the mass on the cantilevered structure, mechanical stresses in the cryocooler **10** may be reduced. Reducing the mass at the end of the cold cylinder **69** increases the natural frequency of the thin-walled tube that is the cold cylinder, which tends to make the dynamic response of the cryocooler **10** to loads such as vibrations from a space launch less severe. In addition, reducing the amount of size that must be maintained at the cryogenic first-stage temperature decreases the parasitic radiative load on the first stage, and thus increases the system cooling of objects or components to be cooled, that the cryocooler **10** may provide.

In addition, moving the surge volume from the first-stage temperature portion to the ambient temperature portion may be advantageous from the point of view of packaging volume. Often, there is a tight constraint on the amount of available packaging volume within a cryogenic space. Volume availability of ambient space is almost always less constraining. Moving the surge volume to the ambient temperature portion of a cryocooler, where volume is much less constrained, may be a major benefit in the design process.

Further, as pointed out above, moving the surge volume to the first-stage temperature portion reduces the cryogenic surface area, which may thereby reduce radiative parasitic losses.

Another potential benefit of the cryocooler **10** is that entropy generated due to frictional loss in the inertance tube **42** may also be reduced. It will be appreciated that the inertance tube **42** is not maintained at a single temperature. One end of the inertance tube **42** is coupled to the first-stage interface **36**, at the first-stage temperature. The opposite end of the inertance tube **42** is coupled to the surge volume **44**, at an ambient temperature. Therefore, at least part of the inertance tube **42** is at a higher temperature than the first-stage temperature portion **14**, due to the shifting of the surge volume **44** from the first-stage temperature portion **14** to the ambient temperature portion **12**. Operation of the cryocooler **10** involves frictional losses within the inertance tube **42**. These frictional losses generate entropy. Since the amount of entropy generated for a given amount of heating is inversely proportional to the temperature, it will be appreciated that raising the operating temperature of at least a portion of the inertance tube **42** reduces the amount of entropy created.

In addition, heat generated due to friction within the inertance tube **42** has multiple thermal paths through which it may be removed. One thermal path is at the first-stage temperature, by coupling to the first-stage interface **36**. Another thermal path is to the ambient surroundings. Providing multiple thermal paths, including a path to remove friction-generated heat at ambient temperature, may also be advantageous in terms of efficiently using the cooling generated by the cryocooler **10**.

FIG. **5** shows an alternate embodiment of the cryocooler **10**. In an embodiment shown in FIG. **5**, the surge volume **44** is placed at least partially within the Stirling expander **20**. For instance, the plenum **60** (FIG. **2**) may itself be utilized as the surge volume **44**, as illustrated in FIG. **6**. Alternatively, the surge volume **44** may be an isolated structure, taking up part of the plenum **60**, within a pressure containment housing **90** of the Stirling expander **20**. This configuration is illustrated in FIG. **7**.

It will be appreciated that, as another alternative, the surge volume **44** may placed at least partially within the compressor **26**. The placement of the surge volume **44** within the compressor **26** or the expander **20** may facilitate meeting design and/or packaging requirements.

Another alternative for the cryocooler **10** is shown in FIG. **8**. As shown therein, the inertance tube **42** (FIG. **1**) is replaced by a phase shifter **94** and a connecting flow line **96**. The phase shifter may be any of a variety of suitable devices, such as an orifice, a porous plug, or an active device, to provide the desired phase shift between the mass flow rate and the pressure wave at the cold end of the pulse tube **30**.

The phase shifter **94** alters mass flow distribution to the surge volume **44**. It will be appreciated that by varying the stroke and/or phase angle of the displacer **66** in the first-stage expander **20**, and by means of the inertance tube **42** and/or the phase shifter **94** (in conjunction with the surge volume **44**), performance may be optimized at any operating point, including on orbit and in an actual thermal environment of a space craft, for example.

FIG. **9** shows another embodiment of the cryocooler **10**. In the embodiment shown in FIG. **9**, the inertance tube **42** is thermally coupled to the cold cylinder **69**, for example by being wrapped around the cold cylinder **69**. This thermal coupling between the inertance tube **42** and the cold cylinder **69** may reduce heat transfer from the warm end of the inertance tube **42** to the cold end of the inertance tube **42**, which may be caused by oscillatory movement of gas in the inertance tube **42**. The thermal coupling between the inertance tube **42** and the cold cylinder **69** may be accomplished by any of a variety of ways. For example, the heat sinking between the inertance tube **42** and the cold cylinder **69** may be accomplished by coupling them together at one point, at several distinct points, or essentially continuously along at least part of the length of the inertance tube **42** (as with the embodiment shown in FIG. **9**).

From the foregoing, it will be appreciated that placing a surge volume in the ambient temperature portion of a multistage cryocooler results in several benefits, such as increasing performance, reducing mechanical stresses, and allowing easier integration of the cryocooler into systems such as space craft. In addition, the combination of an inertance tube for phase shifting and a surge volume for achieving thermal isolation may itself be beneficial for multistage cryocoolers that utilize a Stirling expander and a pulse tube expander.

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 functions 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 hybrid multistage cryocooler comprising:

a first-stage expander having a first-stage expander outlet;

a first-stage thermal interface;

a second-stage expander in communication with the first-stage expander outlet, via the first-stage thermal interface; and

a surge volume in communication with a second-stage expander outlet of the second-stage expander, via the first-stage thermal interface;

wherein the surge volume is maintained at an ambient temperature.

2. The cryocooler of claim **1**, further comprising an inertance tube coupling the surge volume to the first-stage thermal interface.

3. The cryocooler of claim **2**, wherein a first end of the inertance tube is at the ambient temperature, and wherein a second end of the inertance tube is at a first-stage temperature that is lower than the ambient temperature.

4. The cryocooler of claim **2**, wherein the inertance tube is thermally coupled to a cold cylinder surrounding an expansion volume that is in gaseous communication with the first-stage expander outlet.

5. The cryocooler of claim **1**, wherein the first-stage expander is a Stirling expander.

6. The cryocooler of claim **5**, wherein the Stirling expander includes:

a cold cylinder surrounding an expansion volume that is in gaseous communication with the first-stage expander outlet;

a displacer which forces a working gas through the expansion volume and a first-stage regenerator; and

a motor that drives the displacer.

7. The cryocooler of claim **1**, wherein the second-stage expander is a pulse tube expander.

8. The cryocooler of claim **7**, wherein the pulse tube expander includes:

a pulse tube inlet;

a pulse tube gas volume in gaseous communication with the pulse tube inlet, the gas volume including a second-stage regenerator and a pulse tube gas column; and

a second-stage heat exchanger in thermal communication with the second-stage regenerator and the pulse tube gas column.

9. The cryocooler of claim **1**, wherein the first-stage thermal interface is maintained at a first-stage cold temperature that is lower than the ambient temperature.

10. The cryocooler of claim **9**, wherein the first-stage thermal interface is coupled to an expansion volume of the first-stage expander.

11. The cryocooler of claim **10**, further comprising an inertance tube coupling the surge volume to the first-stage thermal interface.

12. The cryocooler of claim **10**, wherein the first-stage thermal interface is cantilevered off the expansion volume.

13. The cryocooler of claim **1**, wherein the surge volume is within the Stirling expander.

14. The cryocooler of claim **1**, wherein the surge volume is inside at least part of a plenum of the Stirling expander.

15. The cryocooler of claim **1**,

further comprising an ambient-stage structure;

wherein the surge volume and at least the first-stage expander are mechanically coupled to the ambient-stage structure.

16. A hybrid multistage cryocooler comprising:

a first-stage expander having a first-stage expander outlet;

a first-stage thermal interface;

a second stage in communication with the first-stage expander outlet, via the first-stage thermal interface;

a surge volume in communication with a second-stage expander, via the first-stage thermal interface; and

an inertance tube coupling the surge volume to the first-stage thermal interface;

wherein the surge volume is maintained at an ambient temperature;

wherein a first end of the inertance tube is at the ambient temperature,

wherein a second end of the inertance tube is at a first-stage temperature that is lower than the ambient temperature;

wherein the first-stage expander is a Stirling expander;

wherein the first-stage thermal interface is coupled to an expansion volume of the first-stage expander; and

wherein the first-stage thermal interface is cantilevered off the expansion volume.

17. The cryocooler of claim **16**, wherein the surge volume is within the Stirling expander.

18. The cryocooler of claim **16**, wherein the surge volume is in at least part of a plenum of the Stirling expander.

19. The cryocooler of claim **16**,

further comprising an ambient-stage structure; and

wherein the surge volume and at least the first-stage expander are mechanically coupled to the ambient-stage structure.

20. A method of cooling, comprising:

providing a first-stage expander having a first-stage expander outlet;

providing a first-stage thermal interface;

providing a second-stage cooler in communication with the first-stage expander outlet, via the first-stage thermal interface; and

coupling a surge volume in communication with the first-stage expander outlet and the second-stage cooler, via the first-stage thermal interface, wherein the coupling includes placing the surge volume such that the surge volume is maintained at an ambient temperature.

21. The cryocooler of claim **1**, wherein the first-stage thermal interface is at a first-stage temperature that is lower than the ambient temperature.

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