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Hanes

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(54) **STIRLING CYCLE CRYOCOOLER WITH OPTIMIZED COLD END DESIGN**

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(21) Appl. No.: **09/558,879**

(22) Filed: **Apr. 26, 2000**

(51) **Int. Cl.**[7] **F25B 9/00**
(52) **U.S. Cl.** **62/6**; 62/51.2
(58) **Field of Search** 62/6, 51.2

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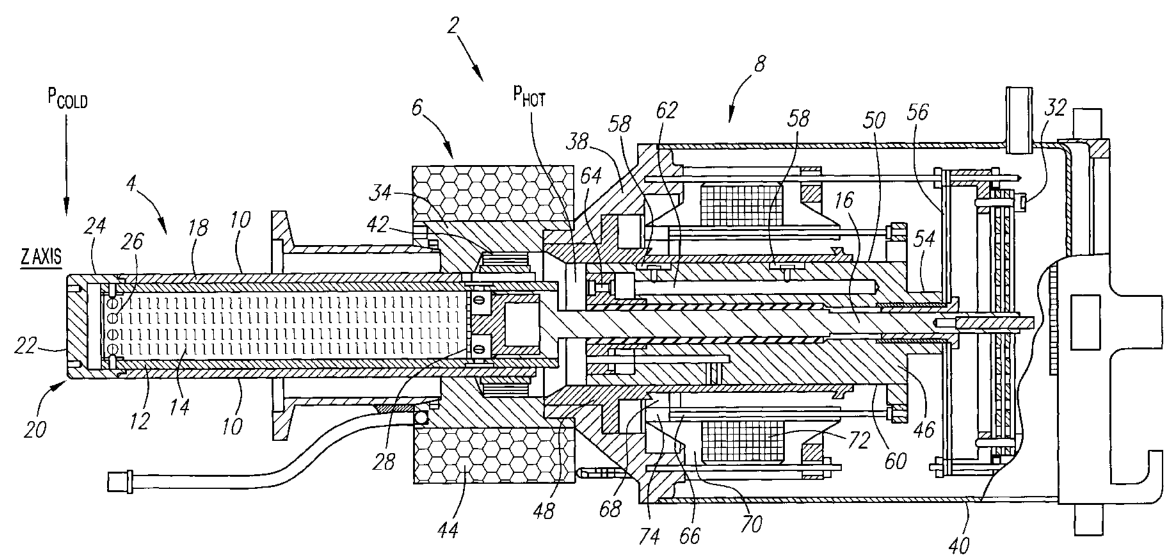
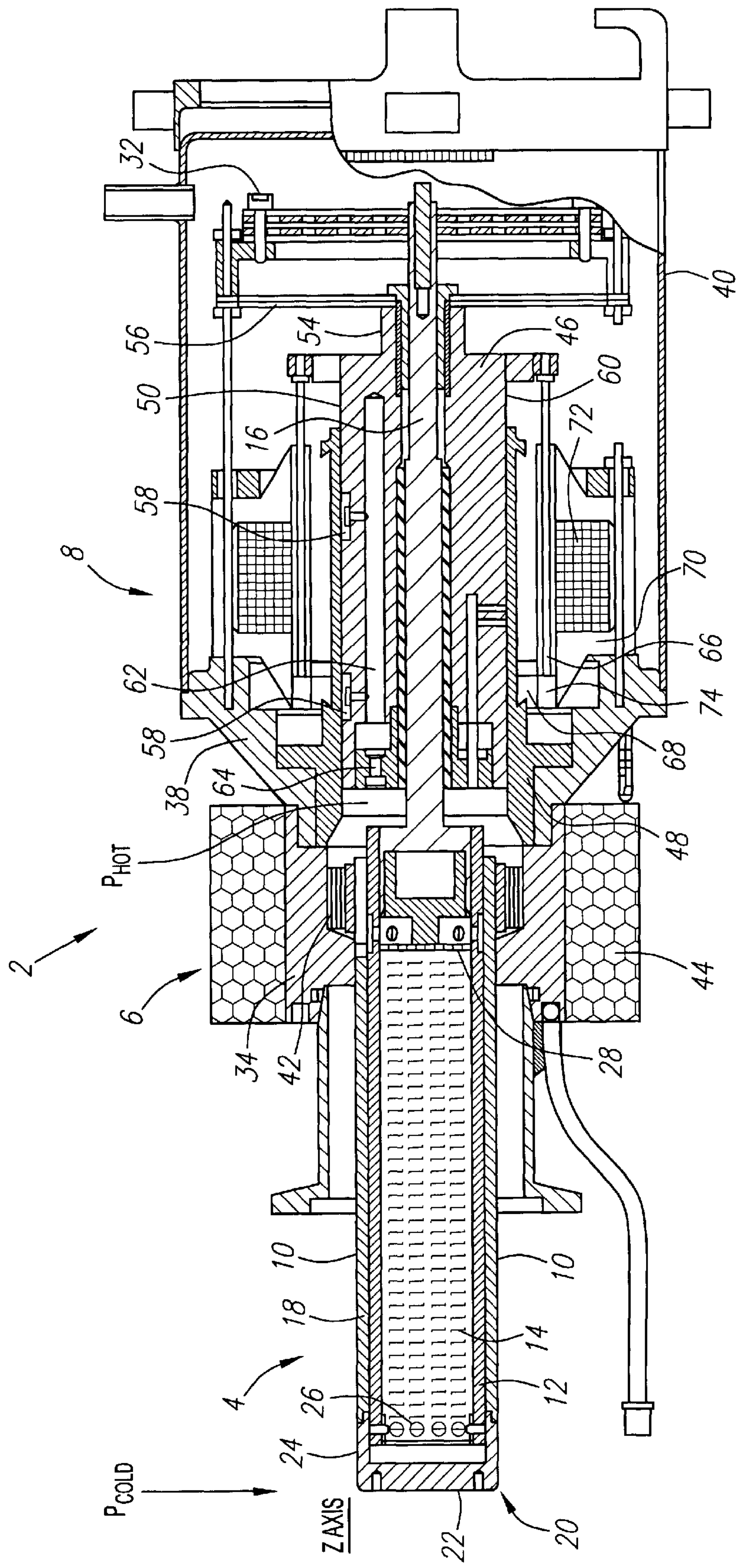
(57) **ABSTRACT**

A Stirling cycle cryocooler is disclosed that includes a displacer unit having a cold end and a hot end. The displacer unit includes a cold cylinder housing and a displacer liner disposed on the inner surface of the housing. A displacer assembly lies within the displacer liner and is slidable with respect to the lengthwise axis of the housing. The displacer unit also includes a regenerator unit. A heat acceptor is affixed to the cold end of the displacer unit. The heat acceptor transfers heat from a device such as a High Temperature Superconducting Filter to a gas such as helium located within the displacer unit. The heat acceptor preferably includes a radial component and an annular component. The heat acceptor advantageously decreases the heat transfer resistance between the heat acceptor and the helium gas. The Stirling cycle cryocooler is thus able to operate with reduced input power to achieve a desired lift level.

15 Claims, 2 Drawing Sheets

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48
50
54
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60
62
64
66
68
70
72
74
P_{HOT}
P_{COLD}
Z AXIS

FIG. 1

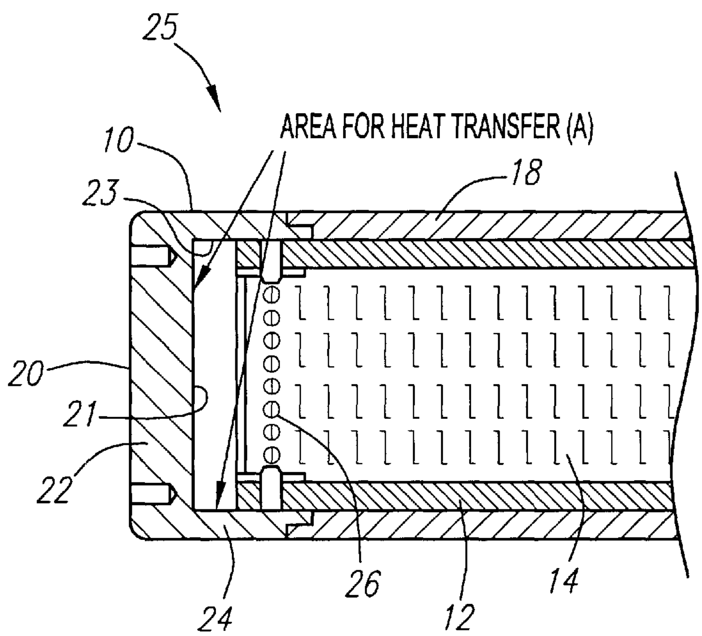
25
AREA FOR HEAT TRANSFER (A)
10
18
23
20
21
22
24
26
12
14

FIG. 2

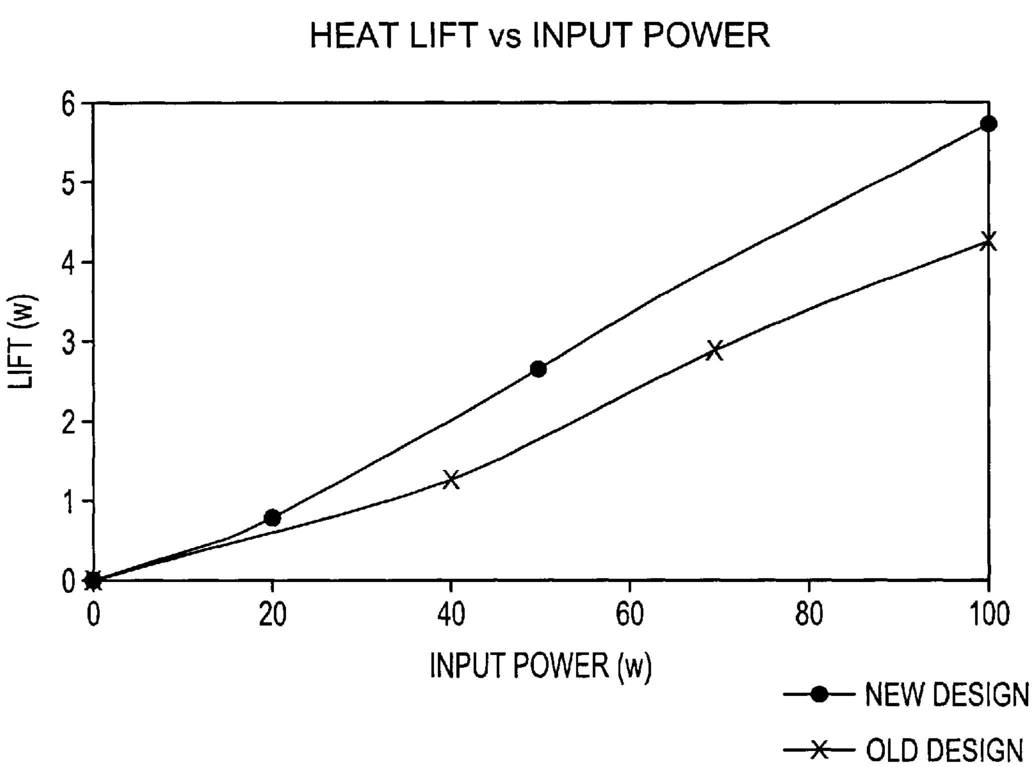
HEAT LIFT vs INPUT POWER
6
5
4
3
2
1
0
LIFT (w)
0
20
40
60
80
100
INPUT POWER (w)
NEW DESIGN
OLD DESIGN

FIG. 3

STIRLING CYCLE CRYOCOOLER WITH OPTIMIZED COLD END DESIGN

FIELD OF THE INVENTION

The field of the invention relates generally to cryocoolers. More particularly, the field of the invention relates to Stirling cycle cryocoolers.

BACKGROUND OF THE INVENTION

Recently, substantial attention has been directed to the field of superconductors and to systems and methods for using such products. Substantial attention also has been directed to systems and methods for providing a cold environment (e.g., 77° K. or lower) within which superconductor products such as superconducting filter systems may function.

One device that has been widely used to produce a cold environment within which superconductor devices may function is the Stirling cycle refrigeration unit or Stirling cycle cryocooler. Such units typically comprise a displacer assembly and a compressor assembly, wherein the two assemblies are in fluid communication and are driven by one or more linear or rotary motors. Conventional displacer assemblies generally have a "cold" end and a "hot" end, the hot end being in fluid communication with the compressor assembly. Displacer assemblies generally include a displacer having a regenerator mounted therein for displacing a fluid, such as helium, from one end, i.e., the cold end of the displacer assembly, to the other end, i.e., the hot end, of the displacer assembly. The piston assembly functions to apply additional pressure to the fluid, when the fluid is located substantially within the hot end of the displacer assembly, and to relieve pressure from the fluid, when the fluid is located substantially within the cold end of the displacer assembly. In this fashion, the cold end of the displacer assembly may be maintained, for example, at 77° K., while the hot end of the displacer assembly is maintained, for example, at 15° K. above ambient temperature. Devices such as superconducting filter systems are then typically placed in thermal contact with the cold end of the displacer assembly.

Current Stirling cycle cryocooler designs employ a heat acceptor positioned at the cold end of the displacer assembly. The heat acceptor is typically in thermal contact with the device that is to be cooled, such as a High Temperature Superconducting Filter (HTSF) system. Heat is transferred from the device and to the heat acceptor. The heat transferred to the heat acceptor then passes to the helium gas contained in the displace assembly. The transfer of heat from the heat acceptor to the helium gas typically is the most difficult since the resistance to heat transfer is greatest in this step.

In current cryocooler designs, the ineffective transfer of heat from the heat acceptor to the helium gas results in additional power requirements. In essence, a greater amount of input power is needed to achieve the desired refrigeration lift. The lower heat transfer rate is due, in large part, to the relatively small surface area and low convective heat transfer coefficient.

There is a need for a cryocooler design that decreases the heat transfer resistance between the heat acceptor and the helium gas. The cryocooler design would advantageously require less input power to provide an equivalent amount of refrigeration as compared to prior designs.

SUMMARY OF THE INVENTION

In a first aspect of the invention, a displacer unit for use in a Stirling cycle cryocooler is disclosed. The displacer

includes a housing, a displacer liner adjacent to the inside of the housing, a displacer assembly, a regenerator unit, and a heat acceptor. The displacer assembly is located inside the displacer liner and is axially slidable with respect to the housing. The heat acceptor includes a radial component and an annular component. The heat acceptor is affixed to the cold end of the displacer unit.

In a second separate aspect of the invention, a heat acceptor for use on the cold end of a displacer unit is disclosed. The heat acceptor includes a radial component including a radially located inner face that is perpendicular to the long axis of the displacer unit. In addition, the heat acceptor includes an annular component including an inner circumferential face.

In a third aspect of the invention, the displacer unit according the first aspect of the invention further includes a plurality of radial holes in the displacer assembly.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a side view of the Stirling cycle cryocooler.

FIG. **2** shows an enlarged side view of the cold end of the displacer unit.

FIG. **3** shows a graph illustrating the heat lift vs. input power for the present cryocooler and the conventional cryocooler.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** illustrates a Stirling cycle cryocooler **2** in accordance with a preferred form of the present invention. As seen in FIG. **1**, the Stirling cycle cryocooler **2** preferably includes a displacer unit **4**, a heat exchanger unit **6**, a compressor and a linear motor assembly **8**.

The displacer unit **4** preferably includes a cold cylinder housing **10**, a displacer assembly **12**, a regenerator unit **14**, and a displacer rod assembly **16**. A displacer liner **18** is positioned circumferentially about the displacer assembly **12** and inward of the cold cylinder housing **10**. The displacer assembly **12** is slidably mounted in the axial direction within the cold cylinder housing **10**. Preferably, the displacer liner **18** is affixed to the inner surface of the cold cylinder housing **10**.

The displacer unit **4** also includes a heat acceptor **20**. Preferably, as shown in FIGS. **1** and **2**, the heat acceptor **20** includes a radial component **22** and an annular component **24**. The radial component **22** is generally perpendicular to the long axis of the displacer unit **4**. The long axis lies between the hot and cold ends of the displacer unit **4**. The annular component **24** lies along a circumferential annulus of the displacer unit **4**. Preferably, the annular component **24** extends from the radial component **22** to beyond the edge of the displacer assembly **12**. Even more preferably, the annular component **24** extends axially beyond the edge of the displacer assembly **12** and abuts against a distal end of the displacer liner **18**. The heat acceptor **20** is preferably brazed to the cold cylinder housing **10** to provide a hermetically sealed environment. The annular component **24** opposes, in a co-axial-type manner with the displacer liner **18**. In this regard, the total area of the heat acceptor **20** available for heat transfer is increased.

Referring now to FIG. **2**, the radial component **22** of the heat acceptor **20** includes a radially located inner face **21**. The radially located inner face **21** is preferably perpendicular to the long axis of the displacer unit **4**. The annular component **24** includes an inner circumferential face **23**.

While the heat acceptor **20** has been described as containing two separate components, i.e., a radial component **22** and an annular component **24**, it should be understood that the heat acceptor **20** can be a single unitary component. Preferably, the heat acceptor **20** is made of thermally conductive metal such as copper. Even more preferably, the heat acceptor **20** is made from high purity copper or oxygen-free-high-conductivity (OFHC) copper.

In one aspect of the invention, the displacer assembly **12** includes a plurality of radial holes **26**. The radial holes **26** permits additional flow of helium within the cold end **25** of the displacer unit **4**. The helium flowing through the holes **26** will impinge directly on the heat acceptor **20**. The area available for heat transfer, shown by arrow A in FIG. **2**, is thus increased. The radial holes **26** assist in decreasing the convective resistance between the heat acceptor **20** and the helium gas within the cryocooler **2**.

Still referring to FIG. **1**, the displacer rod assembly **16** is coupled at one end to a base section **28** of the displacer assembly **12** and coupled at the other end to a displacer spring assembly **32**.

The heat exchanger unit **6**, which is located between the displacer unit **4** and the compressor and linear motor assembly **8**, preferably includes a heat exchanger block **34**, a flow diverter or equivalent structure, and a heat exchanger mounting flange **38**. The heat exchanger mounting flange **38** preferably is coupled to a distal end of a pressure housing **40** of the compressor and linear motor assembly **8**. The heat exchanger block **34** preferably includes a plurality of internal heat exchanger fins **42** and a plurality of external heat rejector fins **44**. Thus, the heat exchanger unit **6** is designed to facilitate heat dissipation from a gas, such as helium, that is compressed in the region P_{HOT} located at the juncture between the displacer unit **4** and the compressor and linear motor assembly **8** (the region P_{HOT} also is referred to herein as the compression chamber of the compressor and linear motor assembly **8**). Preferably, the heat exchanger block **34**, internal heat exchanger fins **42** and external heat rejector fins **44** are made from a thermally conductive metal such as high purity copper.

The compressor and linear motor assembly **8** preferably includes a pressure housing **40** that has a piston assembly **46** mounted therein. The piston assembly **46** includes a cylinder **48**, a piston **50**, a piston assembly mounting bracket **54** and a spring assembly **56**. The piston assembly mounting bracket **54** provides a coupling between the piston **50** and the spring assembly **56**. The piston **50** is thus adapted for reciprocating motion within the cylinder **48**. A plurality of gas bearings **58** are provided within the exterior wall **60** of the piston **50**, and the gas bearings **58** receive gas, e.g., helium, from a sealed cavity **62** that is provided within the piston **50**. A check valve **64** provides a unidirectional fluid communication conduit between the sealed cavity **62** and the region P_{HOT} of the cylinder **48** (i.e., the compression chamber of the cylinder **48**) when the pressure of the gas within that region exceeds the pressure within the cavity **62** (i.e., exceeds the piston reservoir pressure).

The piston **50** preferably has mounted thereon a plurality of magnets **66**. Internal laminations **68** are secured to the outside of the cylinder **48**. External laminations **70** are secured within the pressure housing **40** and are located outward of the magnets **66**. The external laminations **70** are preferably secured to a mounting flange **38**. The internal and external laminations **68**, **70** are preferably made of an iron-containing material. A motor coil **72** preferably lies within the external laminations **70** and surrounds the piston **50**. The motor coil **72** is preferably located outward of the magnets **66** and within recesses formed within the external laminations **70**. Thus, it will be appreciated that, as the piston **50** moves within the cylinder **48**, the magnets **66** move within a gap **74**.

During operation, the piston **50** and displacer assembly **12** preferably oscillate at a resonant frequency of approximately 60 Hz and in such a manner that the oscillation of the displacer assembly **12** is approximately 90° out of phase with the oscillation of the piston **50**. Stated somewhat differently, it is preferred that the motion of the displacer assembly **12** will "lead" the motion of the piston **50** by approximately 90°.

Those skilled in the art will appreciate that, when the displacer assembly **12** moves to the "cold" end P_{COLD} of the displacer housing **10**, most of the fluid, e.g. helium, within the system is displaced to the warm end P_{HOT} of the displacer housing **10** and/or moves around the flow diverter or similar device and through the internal heat exchanger fins **42** into the compression area P_{HOT} of piston assembly **46**. Due to the phase difference between the motion of the displacer assembly **12** and the piston **50**, the piston **50** should be at mid-stroke and moving in a direction toward the heat acceptor **20** when displacer assembly **12** is located at the cold end of the displacer housing **10**. This causes the helium in the areas P_{HOT} to be compressed, thus raising the temperature of the helium. The heat of compression is transferred from the compressed helium to the internal heat exchanger fins **42** and from there to the heat exchanger block **34** and external heat rejector fins **44**. From the heat rejector fins **44**, the heat is transferred to ambient air. As the displacer assembly **12** moves to the warm end P_{HOT} of the displacer housing **10**, the helium is displaced to the cold end P_{COLD} of the displacer housing **10**. As the helium passes through the displacer cylinder **12**, it deposits heat within the regenerator unit **14**, and exits into the cold end P_{COLD} of the displacer housing **10** at approximately 77° K. At this time, the compressor piston **50** preferably is at mid-stroke and moving in the direction of the spring assembly **56**. This causes the helium in the cold end P_{COLD} of the displacer housing **10** to expand further reducing the temperature of the helium and allowing the helium to absorb heat. In this fashion, the cold end P_{COLD} functions as a refrigeration unit and may act as a "cold" source.

By using the heat acceptor **20** with the radial component **22** and the annular component **24**, the lift of the Stirling cycle cryocooler **2** can be increased for any given input power. Generally, during operation of the Stirling cycle cryocooler **2**, helium gas expands at the cold end of the displacer unit **4**, which reduces the temperature of the helium gas, and thus reduces the temperature of the heat acceptor **20**. The temperature gradient in heat acceptor **20** and helium gas causes heat to flow from the device being refrigerated, such as a High Temperature Superconducting Filter (HTSF), to the heat acceptor **20** and helium gas. The heat transfer rate is a function of the temperature difference between the device being refrigerated and the temperature of the heat acceptor **20** and helium gas, the interface resistance between the device being refrigerated and the heat acceptor **20**, the conductive resistance of the heat acceptor **20**, and the convective resistance between the heat acceptor **20** and the helium gas inside the Stirling cycle cryocooler **2**.

In actual use, the greatest resistance to heat transfer occurs between the heat acceptor **20** and helium gas. The equation which defines this convective resistance is as follows:

(1) $Q=h*A*\Delta T$

where Q=heat transfer rate (watts)

h=convective heat transfer coefficient (watt/° C. m^2

A=heat transfer area (m^2), and

ΔT=temperature difference (°C.).

The Stirling cycle cryocooler **2** reduces the convective resistance by use of the heat acceptor **20**. The heat acceptor

20 accomplishes this by increasing the heat transfer area (A), and increasing the convective heat transfer coefficient (h). In addition, the radial holes 26 aid in increasing the convective heat transfer coefficient (h) between the helium gas and the annular portion 24 of the heat acceptor 20. By decreasing the overall convective heat resistance, the Stirling cycle cryocooler 2 requires less input power for the same amount of refrigeration.

FIG. 3 illustrates the improved performance of the Stirling cycle cryocooler 2 using the modified heat acceptor 20. As seen from FIG. 3, at 100 watts input power, the lift has increased from 4.25 watts to 5.7 watts, an improvement of about 34%. Consequently, a desired amount of lift can be achieved with reduced input power.

While embodiments of the present invention have been shown and described, various modifications may be made without departing from the scope of the present invention. The invention, therefore, should not be limited, except to the following claims, and their equivalents.

What is claimed is:

1. A displacer unit for use in a Stirling cycle cryocooler the displacer unit comprising:

a housing, the housing having a cold end and a hot end;

a displacer liner adjacent to the inside of the housing;

a displacer assembly located inside the displacer liner, the displacer assembly being axially slidable with respect to the housing, the displacer assembly containing a regenerator unit therein and a plurality of radial holes located in a cold end of the displacer assembly; and

a heat acceptor affixed to the cold end of the housing, the heat acceptor including a radial component and an annular component, the annular component extending perpendicular from the radial component, the annular component abutting against the cold end of the housing.

2. A displacer unit according to claim 1, wherein the plurality of radial holes in the displacer assembly are adjacent to the annular component of the heat acceptor.

3. A displacer unit according to claim 1, wherein the annular component of the heat acceptor and the radial component of the heat acceptor are formed of a single heat acceptor.

4. A displacer unit according to claim 1, the heat acceptor formed of a thermally conductive metal.

5. A displacer unit according to claim 4, wherein the heat acceptor is made from copper.

6. A displacer unit according to claim 5, wherein the heat acceptor is made from OFHC copper.

7. A displacer unit according to claim 1, the displacer unit coupled to a heat exchange unit and a compressor and linear motor assembly.

8. A displacer unit according to claim 1, wherein the heat acceptor is brazed to the housing to provide a hermetically sealed environment.

9. A Stirling cycle cryocooler comprising:

a pressure housing having a piston assembly mounted therein, said piston assembly including a piston adapted for reciprocating motion within a cylinder;

a displacer rod assembly being connected at a first end thereof to the piston; and

a displacer unit coupled to the Stirling cycle cryocooler, the displacer unit comprising:

a cold cylinder housing having a cold end and a hot end;

a displacer liner disposed inside the housing;

a reciprocating displacer assembly located inside the displacer liner, one end of the displacer assembly being connected to a second end of the displacer rod assembly, the displacer assembly being axially slidable within the cold cylinder housing, the displacer assembly further including a gas regenerator unit therein and a plurality of radial holes located in a cold end of the displacer assembly;

a heat acceptor affixed to the cold end of the cold cylinder housing, the heat acceptor having a radial component and an annular component, the annular component extending perpendicular from the radial component and abutting against the cold end of the cold cylinder housing.

10. An apparatus according to claim 9, wherein the annular component of the heat acceptor and the radial component of the heat acceptor are formed of a single heat acceptor.

11. An apparatus according to claim 9, the heat acceptor being formed of a thermally conductive metal.

12. An apparatus according to claim 11, wherein the heat acceptor is made from copper.

13. An apparatus according to claim 12, wherein the heat acceptor is made from OFHC copper.

14. An apparatus according to claim 9, wherein the plurality of radial holes in the reciprocating displacer assembly are located adjacent to an inner surface of the annular component of the heat acceptor during a portion of the reciprocating motion of the displacer assembly.

15. A displacer unit for use in a Stirling cycle cryocooler, the displacer unit comprising:

a housing, the housing having a cold end and a hot end;

a displacer liner adjacent to the inside of the housing;

a reciprocating displacer assembly having a cold end and a hot end located inside the displacer liner, the displacer assembly being axially slidable with respect to the housing, the displacer assembly further including a plurality of radial holes in the cold end thereof, the displacer assembly also containing a gas regenerator therein;

a heat acceptor affixed to the cold end of the housing, the heat acceptor including a radial component and an annular component; and

wherein the plurality of radial holes in the reciprocating displacer assembly are located adjacent to an inner surface of the annular component of the heat acceptor during a portion of the reciprocating motion of the displacer assembly.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,327,862 B1
DATED : December 11, 2001
INVENTOR(S) : Hanes

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 4,
Line 63, please change “(watt/° C. m^2” to -- (watt/° C m^2) --.
Line 66, please change “C.” to -- C --.

Signed and Sealed this

Twenty-ninth Day of October, 2002

Attest:

JAMES E. ROGAN

Attesting Officer

Director of the United States Patent and Trademark Office