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(54) **HIGH-FREQUENCY, LOW-TEMPERATURE
REGENERATIVE HEAT EXCHANGER**

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(57) **ABSTRACT**

A high-frequency, low-temperature regenerator (12). The regenerator (12) includes a substrate (50) having rare earth material (52) disposed thereon. In a specific embodiment, the substrate (50) has channels or pores (54) therethrough or therein to facilitate gas flow through the regenerator (12). The substrate (50) is constructed from a material, such as polyimide, polyester, or stainless steel, which is sufficient to define the geometry of the regenerator (12). The rare earth material (52) is selected and deposited on the substrate (50) in a layer (52) having thermal penetration depth that is greater than the thickness of the layer (52). The thermal penetration depth is sufficiently high to enable all of the rare earth material (52) to contribute to thermal regeneration at an operating frequency of 30 Hz. In the illustrative embodiment, the thickness of the substrate (50) is less than or equal to approximately 0.001 inches. The layer of rare earth material (52) is approximately 0.0002 inches thick. The substrate (44, 50) includes a stack of plated substrates (44) that are stacked so that spaces (54) exist between the plated substrates (44), which result in a porosity of approximately 15 percent. Dimples, pleats, or other mechanisms in the plated substrates (44) preserve the spaces (54) between the plated substrates (44). In the specific embodiment, the spaces (54) are approximately 0.00025 inches wide, and the working gas is helium.

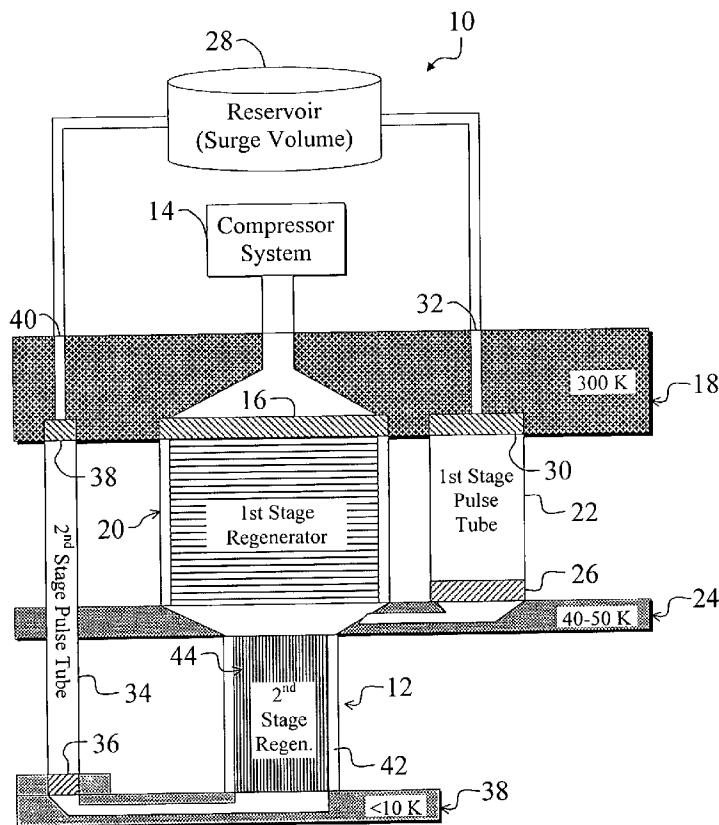


FIG. 1

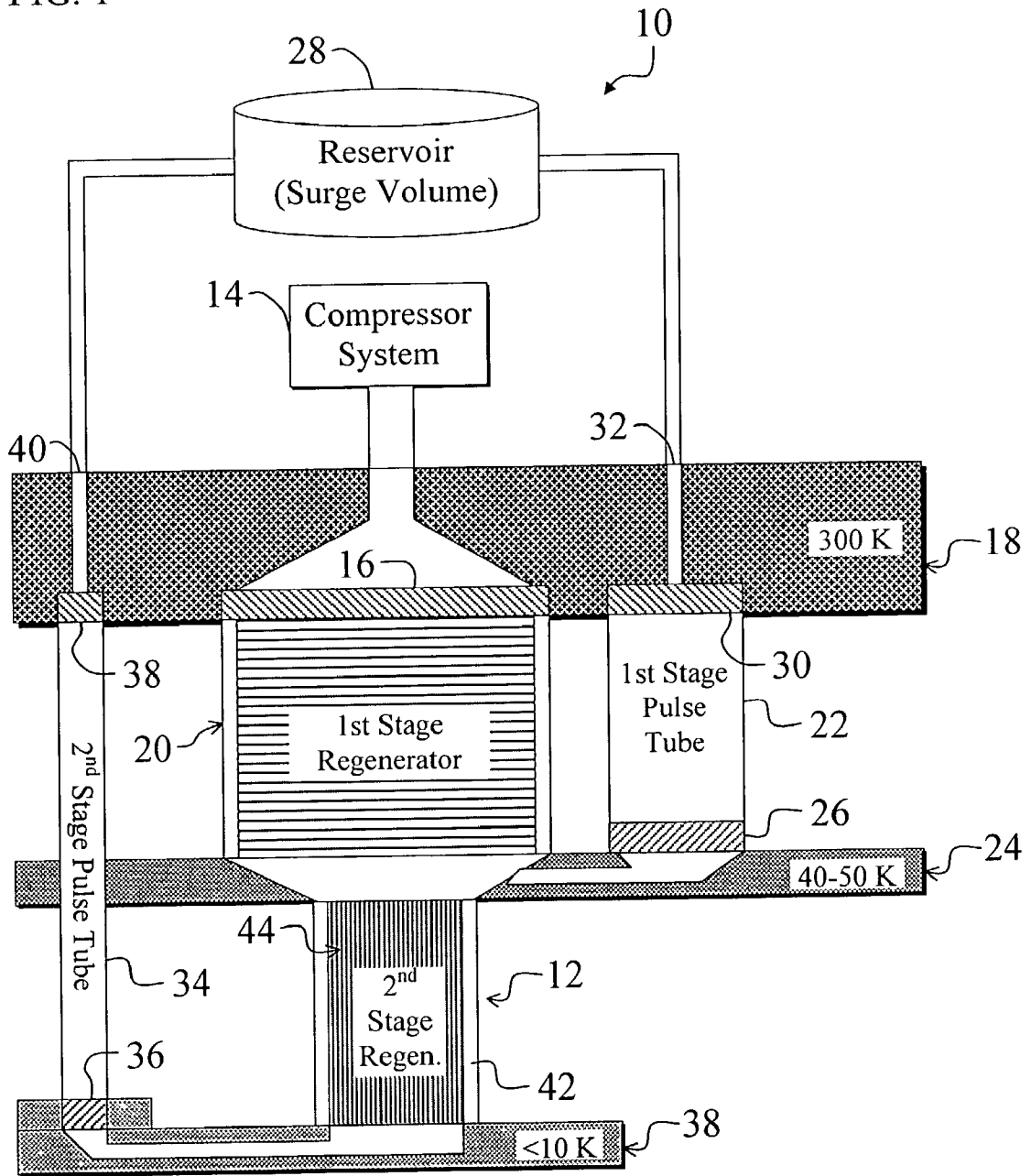


FIG. 2

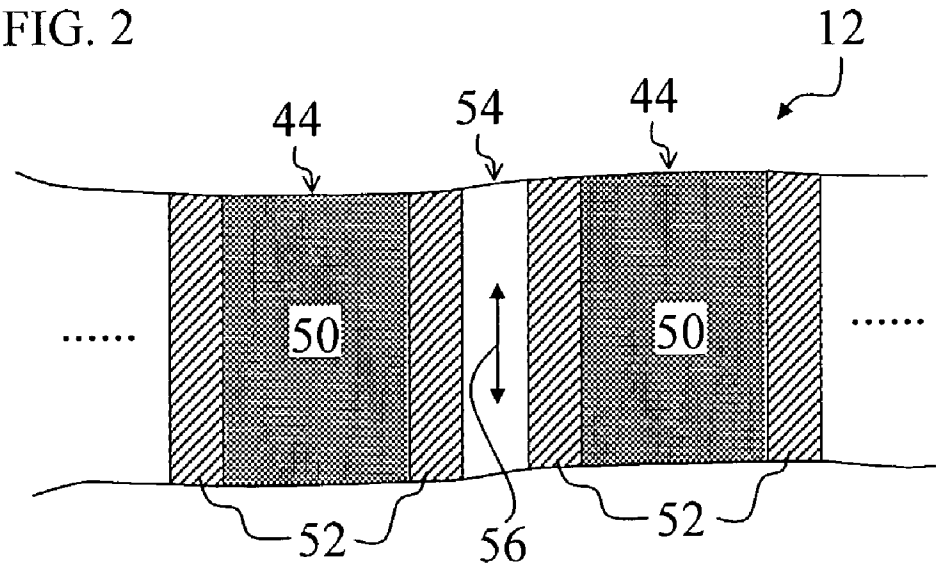


FIG. 3

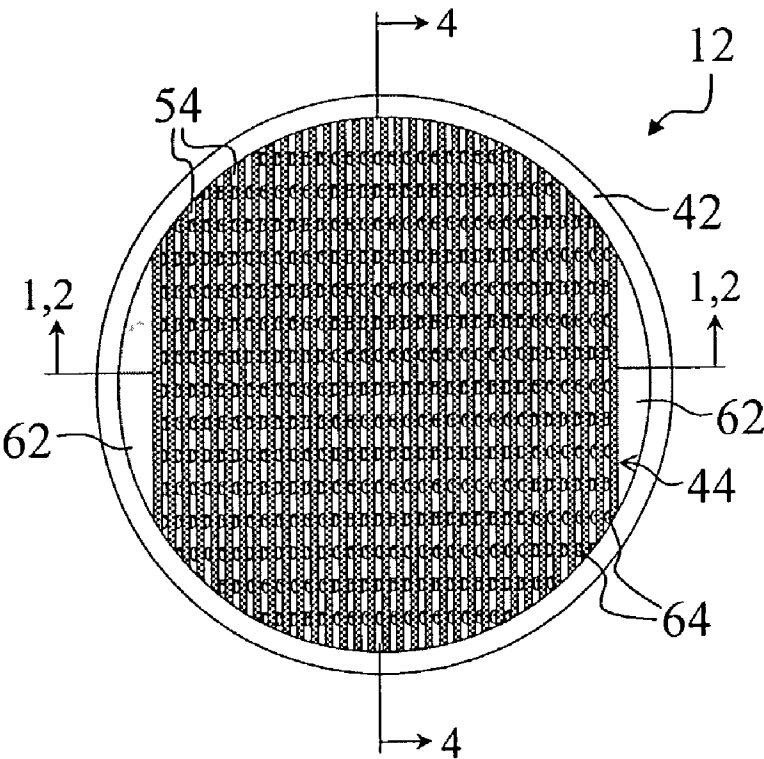


FIG. 4

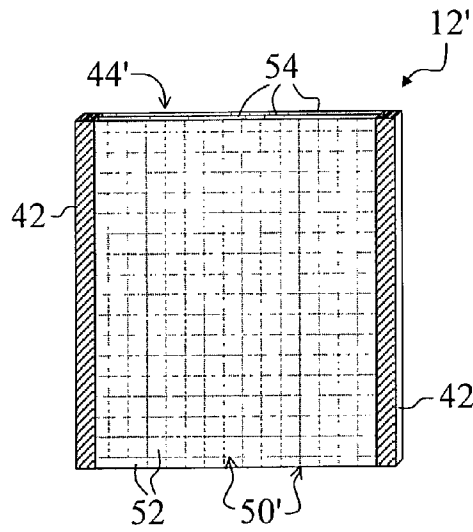


FIG. 5

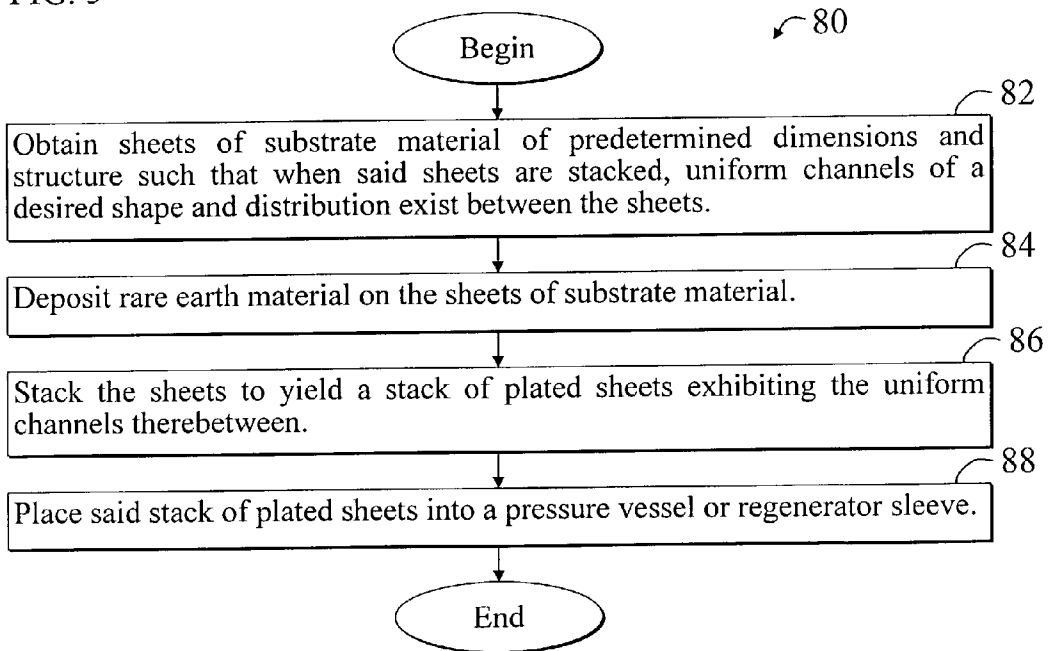


FIG. 6

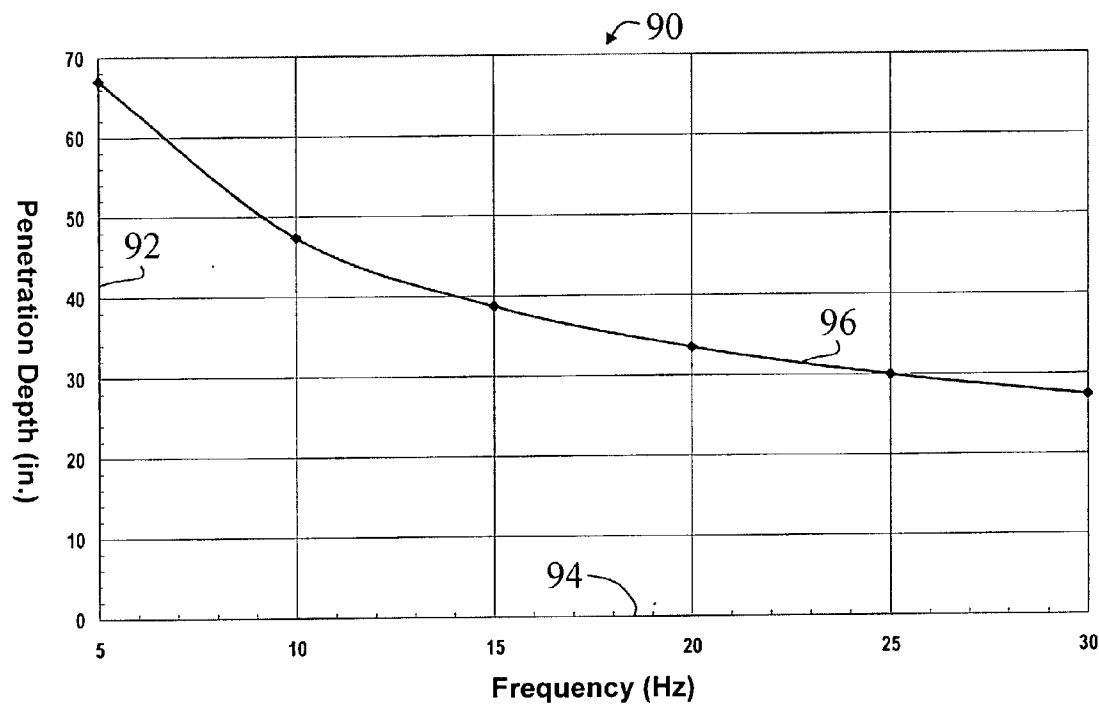


FIG. 7

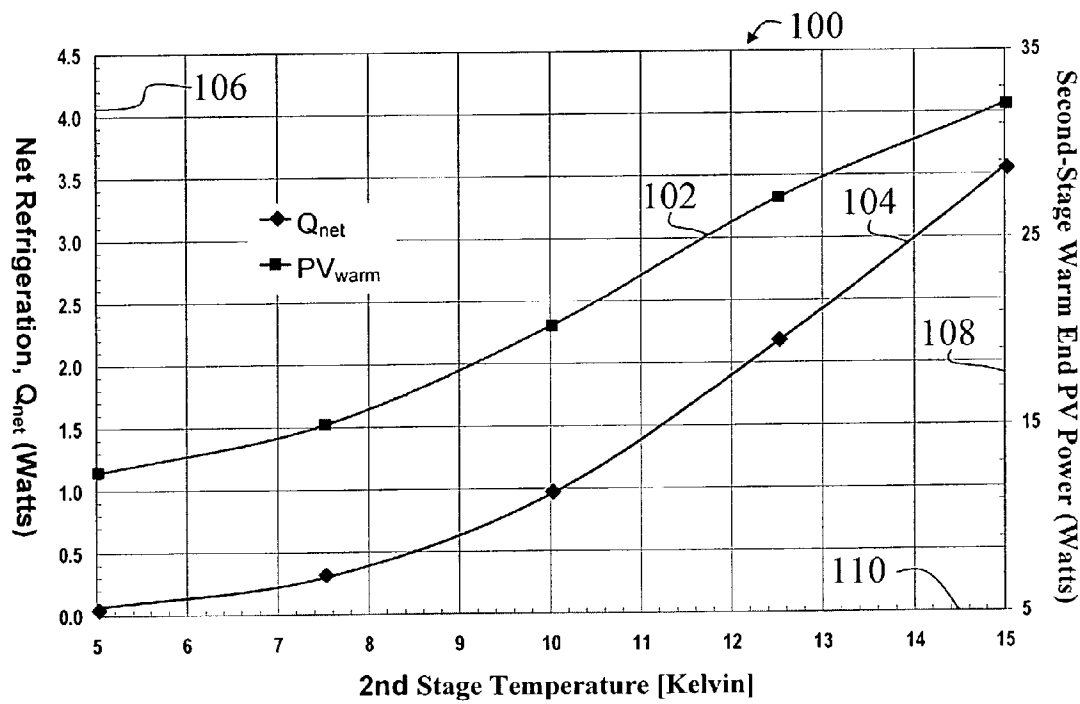
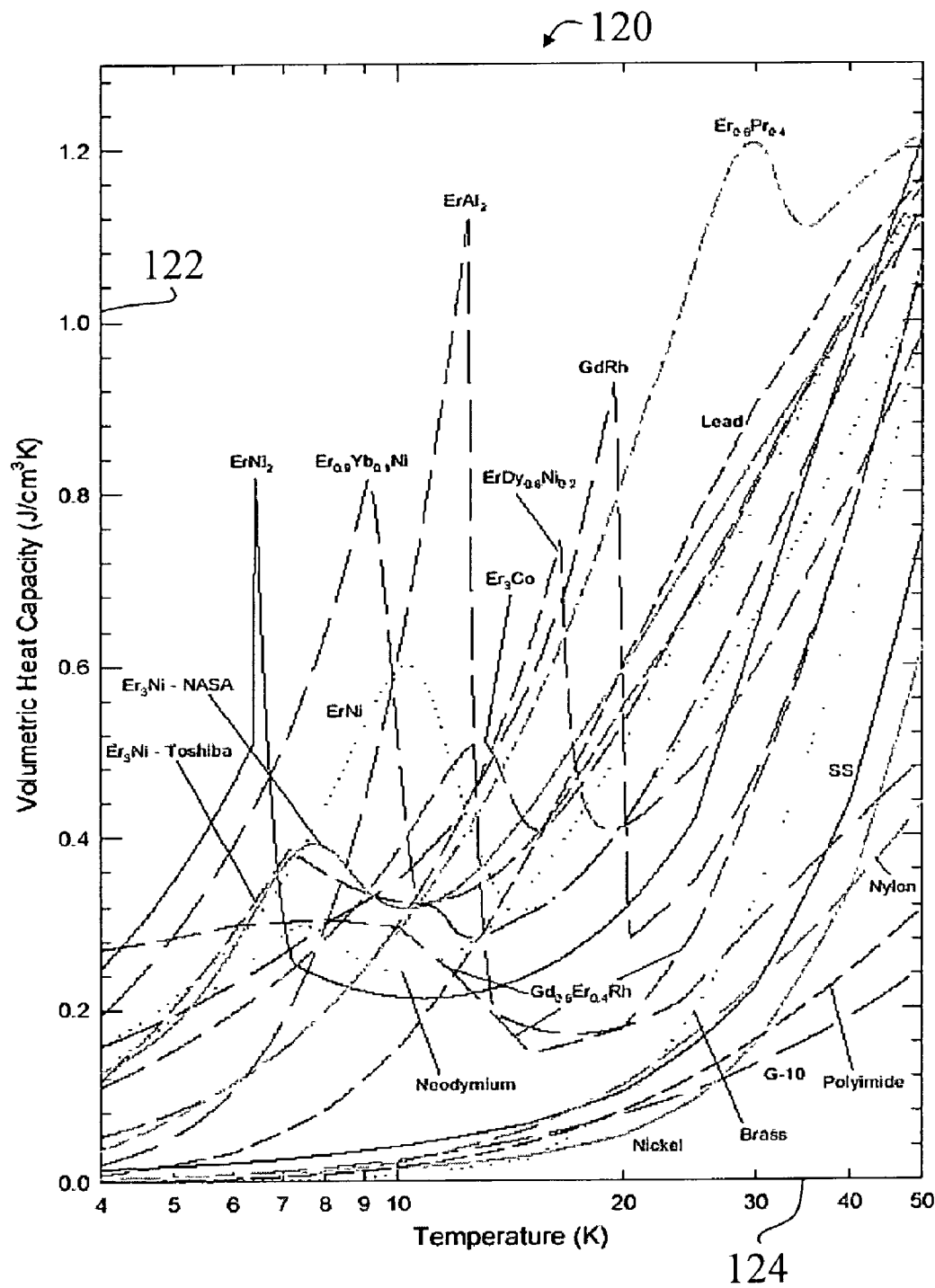


FIG. 8



HIGH-FREQUENCY, LOW-TEMPERATURE REGENERATIVE HEAT EXCHANGER

BACKGROUND OF THE INVENTION

[0001] 1. Field of Invention

[0002] This invention relates to regenerative thermodynamic systems and methods. Specifically, the present invention relates to regenerators used in systems employing regenerative thermodynamic cycles, such as pulse tube and Stirling cycle cryogenic coolers and engines.

[0003] 2. Description of the Related Art

[0004] Cryogenic cooling systems are employed in various demanding applications including space, cellular telephony, and high-speed computing. Such applications often demand efficient, compact, lightweight cryocoolers capable of establishing and maintaining the lowest possible cryogenic temperatures.

[0005] Efficient cryocoolers are particularly important in space-based applications, where size, weight, and cooling requirements are especially stringent. Space-based systems, such as satellites, space shuttles, and exo-atmospheric missiles, often employ sophisticated electronics and sensors that require cryogenic cooling for optimal operation.

[0006] Stored cryogen cooling systems are often used for this purpose. Typically, a stored cryogen cooling system employs a tank filled with pressurized cryogen, such as helium, hydrogen, nitrogen, neon, methane, or argon. The pressurized cryogen is often dispensed through a Joule-Thomson valve, which produces a pressure drop that causes the cryogen to cool in accordance with the Joule-Thomson effect. The cold cryogen is thermally coupled to a load, such as an instrument, a sensor, or a circuit requiring cooling.

[0007] The stored cryogen tanks are often thermally insulated with multi-layer insulation blankets and thermal-structural isolators. Unfortunately, the cryogen storage tanks and accompanying insulation and thermal-structural isolators are often prohibitively bulky, especially for space-based applications involving lengthy operation and high heat loads.

[0008] Currently, stored cryogen technologies that provide cooling to liquid helium temperatures (4.2 Kelvin (K)) are impractical for long-life space-based applications. An undesirably large mass of helium is required to support even small heat loads at 4.2 K. An effective cryocooler capable of operating at liquid helium temperatures would greatly increase overall mission capability for various space-based applications.

[0009] Alternatively, flexure-bearing, closed-cycle cryocoolers are employed. These cryocoolers employ efficient flexures and seals that reduce parts degradation and cryogen contamination. Unfortunately, existing flexure-bearing closed-cycle cryocoolers exhibit significant performance degradation below 35 K, which is undesirably high for some applications. The operation of flexure-bearing cryocoolers below 35 K is limited by the lack of efficient regenerator designs for enabling requisite low-temperature and high-frequency operation.

[0010] Exemplary closed-cycle cryocoolers include Stirling cycle, pulse-tube, and Gifford-McMahon (G-M) cryocoolers. These cryocoolers, which are based on regen-

erative thermodynamic cycles, are often undesirably bulky and incapable of producing very cold cryogenic temperatures below 35 K. The lack of efficient regenerators with sufficient heat capacity to enable high frequency operation at low temperatures has limited reductions in cryocooler sizes and operating temperatures.

[0011] The Stirling cycle is a regenerative cycle with the working fluid alternately absorbing and rejecting thermal energy at a predetermined operational frequency. To avoid undesirable heat transfer with the surroundings, a regenerator (regenerative heat exchanger) is employed. Heat transfer interactions with the surroundings should only occur during low temperature heat absorption (refrigeration) and high-temperature heat rejection, both occurring at a constant temperature. Existing regenerator designs prevent Stirling cycle cryocoolers from approximating ideal Stirling cycle efficiency for liquid helium temperatures and high frequencies at or above 30 Hz.

[0012] G-M cryocoolers operate on an Ericsson thermodynamic cycle, which includes two isothermal and two isobaric processes. These systems may operate at cryogenic temperatures below 35 K, but they are undesirably bulky for many applications. For operations between 15 K and 35 K, a regenerator packed with lead spheres is reasonably efficient at the cold end of the regenerator. The specific heat of lead does not decline with temperature as precipitously as steel or brass. Lead remains practical at temperatures down to approximately 15 K, which remains undesirably high for some applications.

[0013] Regenerators are often porous stainless steel and brass matrices designed for the optimal combination of low thermal conductivity, low pressure drop, and high thermal capacity. Wire mesh matrices have relatively large surface area-to-volume ratios with low pressure drops. Consequently, wire mesh matrices may enable accompanying cryocoolers to run at high frequencies, greater than 45 Hz. High frequency capabilities reduce requisite regenerator size and weight. Unfortunately, the specific heats of stainless steel and brass are prohibitive for regenerative heat exchange below 40 K.

[0014] Certain rare earth materials have relatively high specific heats at low temperatures. However, rare earth metals and intermetallic compounds are often brittle and nonmalleable. Rare earth materials are typically only available in certain geometries, such as spheres, which are sub-optimal for regenerator designs. Spheres have an undesirably low surface area-to-volume ratio and provide excessively high porosity for efficient operation at low temperatures. For example, the large surface area-to-volume ratio and high porosity of a packed-sphere rare earth regenerator limits operational frequencies in G-M systems to between 1 and 4 Hz. The brittle, nonmalleable properties of rare earth materials have inhibited the evolution of very low-temperature (<15 K), compact cryocoolers amenable to space-based applications.

[0015] Conventionally, the success of closed-cycle, reciprocating, flexure-bearing cryocoolers has been limited to systems operating at 35 K and above due to the lack of a regenerator capable of efficiently operating at very low temperatures and high frequencies. Cryocoolers, such as pulse tube and Stirling cycle cryocoolers typically operate on a Stirling thermodynamic cycle or variation thereof. Heat

transfer interactions, such as low temperature heat absorption (refrigeration) and high temperature heat rejection, occur at constant temperature. The regenerative heat exchanger (regenerator) fulfills the internally reversible high pressure-to-low-pressure heat transfer function.

[0016] A trade-off between cooling system size and cooling ability exists for current cryogenic cooling technologies. Very small cryogenic cooling systems may not provide extremely cold cryogenic temperatures below 35 K. Cooling systems that can produce very low temperatures are often undesirably bulky and are limited to low frequency operation. Shortcomings in conventional regenerator designs, including problems with materials selection and geometric structure, prevent current cooling technologies from achieving compact size, high-frequency operation, and extremely cold cryogenic temperatures simultaneously.

[0017] Hence, a need exists in the art for an efficient regenerator that enables lightweight and compact cryogenic cryocoolers capable of extremely cold operating temperatures (below 15 K) and a method for making same. There exists a further need for a lightweight and compact cryocooler that can operate at temperatures below 15 K that employs an efficient regenerator.

SUMMARY OF THE INVENTION

[0018] The need in the art is addressed by the high-frequency, low-temperature regenerator of the present invention. In the illustrative embodiment, the inventive regenerator is adapted for use with regenerative thermodynamic cycle cryocoolers. The regenerator includes a substrate and rare earth material disposed on a surface of the substrate.

[0019] In a more specific embodiment, the substrate has channels or pores therethrough or therein to facilitate gas flow through the regenerator. The substrate is constructed from a material sufficient to define the geometry of the regenerator, such as a flexible, thermally inert material like polyimide or polyester. The rare earth material is chosen and deposited on the substrate in a layer so that the thermal penetration depth of the layer is greater than the thickness of the layer.

[0020] In the specific embodiment, the thermal penetration depth is sufficiently high so that approximately all of the rare earth material contributes to thermal regeneration at an operating frequency of 30 Hz. The thermal penetration depth is approximately two orders of magnitude greater than the thickness of the layer of rare earth material. The thickness of the substrate is less than or equal to approximately 0.001 inches. The thickness of the layer of rare earth material is greater than or equal to approximately 0.0002 inches. The rare earth material may be any an element, compound, or alloy containing one or more lanthanide elements, such as erbium.

[0021] The regenerator includes a stack of plated substrates that are stacked so that spaces corresponding to the channels or pores occur between the plated substrates. The stack of plated substrates has a matrix porosity of approximately 15 percent, which is theoretically desirable. A plate-separation mechanism, such as dimples or pleats in the plated substrates, preserves the spaces between the plated substrates. In the specific embodiment, the spaces are

approximately 0.00025 inches, and the regenerator is adapted for use with helium gas. In an alternative embodiment, the plated substrates are screens or other woven wire meshes that are plated with sufficient rare earth material to fill spaces in the screens or other woven wire meshes.

[0022] The novel design of the present invention is facilitated by the use of rare earth materials with high specific heat in regenerator designs. Efficient use of the rare earth materials is facilitated by the use of a substrate that provides the desired form factor and is capable of sufficiently adhering to the rare earth material that is deposited on the substrate. Employing a substrate and depositing the rare earth materials onto the substrate in accordance with the teachings of the present invention, instead of attempting to extrude or otherwise work the rare earth material into a desired form, enables the construction of a high-frequency, compact, light-weight, and low-temperature (<15 K) regenerator. Furthermore, the use of parallel sheets of plated substrate results in low-pressure drop and high heat transfer efficiency between the working gas and the accompanying regenerator.

[0023] Due to shortcomings in conventional regenerator designs, the efficiency of the ideal Stirling cycle in conventional regenerative cycle cryocoolers is not adequately approximated at liquid helium temperatures and high frequency. Improvements in regenerator design afforded by the present invention enable the extension of the practical operating range of these proven long-life regenerative cycle cryocoolers to 10 K and below. By employing a regenerator matrix with the optimal combination of thermo-physical characteristics and geometric form, compact and light-weight cryocoolers and excellent cooling capacity are now readily achievable. The present invention achieves this efficient regenerator matrix via the deposition of rare earth material onto a substrate, such as polyimide, that provides the desired form factor.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] FIG. 1 is a block diagram of an exemplary two-stage pulse tube cryocooler employing an efficient regenerator constructed in accordance with the teachings of the present invention.

[0025] FIG. 2 is an enlarged cross-sectional view of a portion of the regenerator of FIG. 1.

[0026] FIG. 3 is a perpendicular cross-sectional view of a preferred embodiment the efficient regenerator of FIG. 1.

[0027] FIG. 4 is a cross-sectional view of an alternative embodiment of the regenerator of FIG. 1 employing sheets of rare earth materials plated over a stainless steel screen substrate.

[0028] FIG. 5 is a flow diagram of a method for building the regenerators of FIGS. 1-4.

[0029] FIG. 6 is a graph of penetration depth versus frequency for an exemplary erbium deposition on a polyimide substrate.

[0030] FIG. 7 is a graph of load and power curves for an exemplary regenerator constructed in accordance with the teachings of the present invention.

[0031] FIG. 8 is a graph of volumetric heat capacity versus temperature for various candidate regenerator materials including rare earth materials.

DESCRIPTION OF THE INVENTION

[0032] While the present invention is described herein with reference to illustrative embodiments for particular applications, it should be understood that the invention is not limited thereto. Those having ordinary skill in the art and access to the teachings provided herein will recognize additional modifications, applications, and embodiments within the scope thereof and additional fields in which the present invention would be of significant utility.

[0033] FIG. 1 is a block diagram of an exemplary two-stage pulse tube cryocooler 10 employing an efficient second stage regenerator 12 constructed in accordance with the teachings of the present invention. For clarity, various well-known components, such as power supplies, motors, compressor valves, acoustic phase shift networks, and so on, have been omitted from the figures, however those skilled in the art with access to the present teachings will know which components to implement and how to implement them to meet the needs of a given application.

[0034] The two-stage pulse tube cryocooler 10 includes a compressor system 14 that generates a pressure wave at a predetermined operational frequency in a cryogen fluid, such as helium gas, contained within the cryocooler 10. The compressor 14 is coupled to a first warm-end heat exchanger 16 at a warm end 18 of the cryocooler 10. The warm end 18 operates at approximately 300 K in the present specific embodiment.

[0035] The first warm-end heat exchanger 16, is coupled to a first stage regenerator 20 at the warm end 18. An opposite end of the first stage regenerator 20 is coupled to the efficient second stage regenerator 12 and to a first stage pulse tube 22 at a cool section 24 of the cryocooler 10. The cool section 24 operates between approximately 40-50 K in the present specific embodiment.

[0036] The first stage pulse tube 22 is coupled to the first stage regenerator 20 via a cool-end heat exchanger 26 at the cool section 24 of the cryocooler 10. The first stage pulse tube 22 is coupled to a surge volume reservoir 28 via a second warm-end heat exchanger 30 and a first orifice 32 at the warm end 18 of the cryocooler 10.

[0037] The efficient second stage regenerator 12 is coupled to a second stage pulse tube 34 via a cold-end heat exchanger 36 at a cold end 38 of the cryocooler 10, which operates below 10 K in the present specific embodiment. The second stage pulse tube 34 is coupled to the surge volume 28 via a third warm-end heat exchanger 38 and a second orifice 40 at the warm end 18 of the cryocooler 10.

[0038] In operation, during the compression stroke, compressed gas, such as helium gas, flows from the compressor system 14 and into the first warm-end heat exchanger 16, where some heat resulting from gas compression is rejected. The working gas then flows through the first stage regenerator 20, which may be filled with metallic screens or other mechanisms designed to exchange heat with the working gas. During the compression stroke, the first stage regenerator 20 further cools the working gas.

[0039] The working gas is then partitioned, with a first portion of working gas flowing to the cool-end heat exchanger 26 connected to the first stage pulse tube 22 at the cool section 24 of the two-stage cryocooler 10. A second

portion of working gas flows through the second stage regenerator 12, which absorbs additional heat from the working gas during the compression stroke.

[0040] The second stage regenerator 12 includes stacked parallel plate substrates 44, which are coated with rare earth material and enclosed in a regenerator sleeve 42, as discussed more fully below. The novel use of rare earth materials in the second stage regenerator 12 enables high-frequency cryocooler operation beyond 30 Hz; reduces requisite size of the second stage regenerator 12; and facilitates cryogenic cooling to below 10 K at the cold end 38 of the cryocooler 10.

[0041] During the compression stroke, the working gas passes through the cool-end heat exchanger 26 and through the cold-end heat exchanger 36 at approximately the same temperature as the cool-end heat exchanger 26 and the cold-end heat exchanger 36, respectively. The first portion of working gas passes through the first stage pulse tube 22, while the second portion of colder gas passes through the second stage pulse tube 34. The pulse tubes 22 and 34, which are also called thermal buffer tubes, may include acoustic phase shift networks (not shown).

[0042] Cool gas enters the first stage pulse tube 22 from the first stage regenerator 20, while cold gas enters the second stage pulse tube 34 from the second stage regenerator 12. Warm gas flows from the first stage pulse tube 22 through the second warm-end heat exchanger 30 and the first orifice 32 into the surge volume reservoir 28. Similarly, warm gas flows from the second stage pulse tube 34 through the third warm-end heat exchanger 38 and the second orifice 40.

[0043] Adiabatic compression in the pulse tubes 22 and 34 heats the working gas. Some of this heat is rejected at the warm-end heat exchangers 30 and 38. As the compressed gas reaches the orifices 32 and 40, some gas flows through the orifices 32 and 40. However, additional time is required for compressed gas to flow through the narrow orifices 32 and 40. The expansion stroke occurs before most of the compressed gas passes into the surge volume reservoir 28. Consequently, compression and mass flow are out of phase.

[0044] During the expansion stroke, the gas is expanded adiabatically in the pulse tubes 22 and 34. Gas from the surge volume reservoir 28 enters the warm ends of the pulse tubes 22 and 34. Cool, expanded gas from the cool section 24 of the first stage pulse tube 22 passes through the cool-end heat exchanger 26, where heat may be absorbed from loads at the cool section 24. Similarly, cold, expanded gas from the cold end 38 of the second stage pulse tube 34 passes through the cold-end heat exchanger 36, where additional heat may be absorbed from loads at the cold end 38.

[0045] Convection currents from warm to cold, often called secondary flows, are largely suppressed in the pulse tubes 22 and 34. An oscillating slug of gas exists in each pulse tube 22 and 34. The oscillating gas slug in the first stage pulse tube 22 minimizes secondary flow between the cool end 24 and the warm end 18. The oscillating gas slug in the second stage pulse tube 34 minimizes secondary flow between the cold end 38 and the warm end 18 of the cryocooler 10.

[0046] The working gas shuttles back and forth between the warm end 18 and the cool and cold ends 24 and 38,

respectively, rather than circulating continuously around a loop, as in some refrigeration cycles. Heat is absorbed into the working gas at the cool and cold end heat exchangers **26** and **36**, respectively, and rejected at the warm-end heat exchangers **16**, **30**, and **38**.

[0047] Pulse tubes, such as the pulse tubes **22** and **34**, are analogous to expanders (displacers) in Stirling cycle cryocoolers. The oscillating slug of gas in a pulse tube is analogous to the oscillating displacer in a Stirling cycle machine. The cryocooler **10** may be modified by one skilled in the art to accommodate Stirling cycle expanders instead of pulse tubes without departing from the scope of the present invention.

[0048] Except for the efficient second stage regenerator **12**, the various components, such as pulse tubes, compressor systems, reservoirs, and heat exchangers required to implement the cryocooler **10** are readily commercially available. Additional details enabling one skilled in the art to build the second stage regenerator **12** are discussed more fully below.

[0049] The dimensions of the components of the cryocooler **10**, such as the pulse tubes **22** and **34**, may be determined by those skilled in the art to meet the needs of a given application. Those skilled in the art with access to the present teachings will know how to implement the invention without undue experimentation.

[0050] Advanced metal deposition techniques, such as highly energetic plasma deposition, are employed to apply rare earth metallic coatings and/or intermetallic compounds to substrate materials **44**. Candidate substrate materials include, but are not limited to polyimide, polyester, and stainless steel. The resulting plated substrate materials **44** are then formed and packed into the desired regenerator configuration **12**. The substrates **44** may be dimpled or pleated prior to coating so that the end product **12** is easily stacked into a matrix of parallel plates **44** with the desired porosity.

[0051] The parallel plate geometry of the regenerator **12** yields a lower pressure drop than packed sphere or packed screen matrices of comparable hydraulic radius. The use of a several-micrometer-thick coating of the participating regenerator medium facilitates an extremely large surface area-to-volume ratio. These characteristics facilitate the design and construction of a compact, high frequency cryocooler, such as the two-stage cryocooler **10**.

[0052] The second stage regenerator **12** employs an efficient, low-temperature, high-frequency regenerative heat exchanger matrix comprising the plated sheets **44** and having the following important characteristics.

[0053] 1. Low porosity. The mass of the plated sheets **44** is sufficient to absorb large amounts of thermal energy from the working gas (helium). The plated sheets have a very high volumetric heat capacity at high pressure and low temperature.

[0054] 2. High thermal capacitance. The thermal capacitance of the plated sheets **44** is sufficiently high to facilitate absorption of significant thermal energy from the working gas at high pressure and low temperature.

[0055] 3. Low pressure drop. The plated sheets **44** provide minimal resistance to gas flow, and exhibit a low pressure drop, especially at low cryogenic temperatures.

[0056] 4. Low convective thermal resistance. Effective thermal communication between the gas and the rare earth material on the plated sheets **44** is required to keep enthalpy flux losses low.

[0057] 5. Low axial conduction. The plated sheets **44** exhibit low axial conduction, which results in minimal conduction losses, especially at low temperatures below 35 K.

[0058] The regenerator **12** includes rare earth material deposited onto the plates **44**, which have a polyimide or polyester substrate in the present specific embodiment. The stacked plates **44** are sized, cut, and stacked into the parallel plate matrix **44**. A mechanism, such as dimples or pleats in the polyimide or polyester substrates, preserves space between the plates to facilitate gas flow.

[0059] FIG. 2 is an enlarged cross-sectional view of a portion of the regenerator **12** of FIG. 1 showing plated substrates **44**. The plated substrates **44** include polyimide substrates **50**, which are plated on each side with a layer of rare earth material **52**. The plated substrates **44** are stacked so that predetermined spacing **54** exists between the plated substrates **44** to enable vertical gas flow **56** between the plates. The spacing **54** between the plated substrates **44** is uniform to facilitate efficient heat exchange between gas flow **56** and the layer **52** of rare earth material.

[0060] Those skilled in the art will appreciate that the substrates **50** may be implemented via a material other than polyimide without departing from the scope of the present invention. The substrate material may be chosen by one skilled in the art to meet the needs of a given application and may be any material that can provide the desired form factor and sufficiently adhere to the rare earth material **52** disposed on the surface of the substrate **50**. If the selected rare earth material insufficiently adheres to the polyimide substrate at a desired operational temperature, a stainless steel substrate may suffice, as the thermal expansion properties of stainless steel more closely match those of rare earth materials than many other candidate materials, such as polyimide or polyester.

[0061] Generally, a polyimide material includes any of a class of polymers with an imido group. Polyimides are known for resistance to temperature, wear, radiation, and various chemicals. An imido group is the bivalent group (NH) linked to one or two acid groups.

[0062] The substrate **50** may be constructed from any material capable of defining the geometry of the plated composite structure **44**. This includes but is not limited to polyimide (non-reinforced and reinforced) sheet, polyester sheet, and woven wire mesh. Various substrate materials may serve as a flexible support for the rare earth thin films **52**.

[0063] The following Table 1 lists some physical and electrical properties of various non-reinforced polyimide materials that those skilled in the art may use to design substrates in accordance with the teachings of the present invention.

TABLE 1

Property	Film Thickness 0.001"			
	Kapton HN	Upilex-S	Api- cal AV	Method
<u>Mechanical</u>				
Tensile Strength, psi (Mpa)	24000	75400*	24000	ASTM D882
At 23 C. (73 F.) Machine Direction (M D) and Transverse Direction (TD), min.	(165)	(518)	(165)	*MD Only
Elongation, %, MD and TD, min.	40	42*	60	ASTM D882
Shrinkage, % MD and TD at 400 C., max.	2.5	—	—	*MD Only MIL-P-4611 2B
Shrinkage, % MD and TD at 150 C., max.	—	—	0.1	IPC TM-650 2.24
Shrinkage, % 200 C.	—	0.2	—	JIS C2318
Moisture Absorption, %, max	40	1.4	3.8+	ASTM D570 + IPC TM-650
<u>Electrical</u>				
Dielectric Strength, AC	6000	6800	6000	

TABLE 1-continued

Property	Film Thickness 0.001"			
	Kapton HN	Upilex-S	Api- cal AV	Method
V/mil (kV/mm), min	(236)	(267)	(236)	ASTM D149
Volume Resistivity, ohm-cm at 200 C., min	10 ¹²	10 ¹⁵	10 ¹²	ATSM D257
Dielectric Constant at 1 kHz, max.	3.9	3.5	3.9	ASTM D150
Dissipation Factor at 1 kHz, max.	0.0036	0.0013	0.0035	ASTM D150
<u>Thermal</u>				
Thermal Coefficient of Linear Expansion, ppm/C.	20	12	No Data	ASTM E794
Coefficient of Thermal Conductivity, cal/cm sec C.	2.87 × 10 ⁻⁴	69 × 10 ⁻⁴	No Data	ASTM F433 Laser Flash Method

[0064] Possible reinforced polyimide substrate materials and corresponding mechanical and electrical properties are shown in Table 2 below.

TABLE 2

Property	Laminate Material				Method
	Polyimide/Glass	Epoxy/Glass	BT Epoxy/Glass		
	Park Nelco N7000-1	Polyclad BC-2000	Park Nelco N5000	Polyclad GI-180	
<u>Mechanical</u>					
X/Y CTE, ppm/C (−40 C to + 125 C)	12–15		10–14	14	IPC-TM-650.2.4.4.1
Z CTE, ppm/C (50 C to 260 C)	86		181	55 ⁽⁴⁾	IPC-TM-650.2.4.4.1
Tg by TMA	250	175 ⁽³⁾	175	200 ⁽³⁾	IPC-TM-650.2.4.24c
Young's Modulus (X/Y × 10 ⁽⁶⁾ psi)	3.9/3.9		4.7/4.1		ASTM D3039
Poisson's Ratios (X/Y)	0.12/0.12		0.16/0.14		ASTM D3039
Thermal Conductivity (W/mK)				0.36	ASTM E1461
<u>Electrical</u>					
Electric Strength, V/mil	1350	1300	1200	1150	IPC-TM-650.2.5.6.2
Dielectric Constant @ 1 MHz			4.1		IPC-TM-650.2.5.5.3
Dissipation Factor @ 1 MHz			0.013		IPC-TM-650.2.5.5.3
<u>Volume Resistivity (megohm-cm)</u>					
Elevated Temperature		7.0 × 10 ⁷	1.0 × 10 ⁷	1.0 × 10 ⁵	IPC-TM-650.2.5.17.1
Temperature & Humidity		3.0 × 10 ⁷	1.0 × 10 ⁷	1.0 × 10 ⁶	IPC-TM-650.2.5.17.1
<u>Surface Resistivity (megohms)</u>					
Elevated Temperature		2.0 × 10 ⁹	1.0 × 10 ⁶	1.0 × 10 ⁵	IPC-TM-650.2.5.17.1
Temperature × Humidity		3.0 × 10 ⁶	1.0 × 10 ⁷	1.0 × 10 ⁶	IPC-TM-650.2.5.17.1
<u>Physical</u>					
Water Absorption, wt. %	0.35	0.3	<0.05%	0.3	

(1) Below 1800
(2) IPC-TM-650-
(3) By OSO

[0065] To minimize the size of the regenerator 12 of FIG. 1 and maintain volumetric efficiency, the plating layer 52 must be thick relative to the substrate 50. The cross section in FIG. 2 employs a 0.001-inch thick polyimide substrates 50 with a double-sided plating 52 of 0.0002 inches. The spacing 54 between the rare earth layers 52 is 0.00025 inches. These dimensions result in a regenerator 12 with a matrix porosity of approximately the theoretically desired value of 15 percent. The thermal penetration depth for the regenerator 12 is sufficiently high to operate at 30 Hz, and is consequently greater than the thickness of the rare earth layer 52 so that the entire plating layer 52 contributes thermally to the regeneration process.

[0066] The plated substrates 44 are arranged parallel to the gas flow 56. Those skilled in the art will appreciate that other geometric arrangements may be employed without departing from the scope of the present invention. The plated substrates 44 may be perforated with through-holes (not shown) to facilitate stacking perpendicular to the direction of flow.

[0067] FIG. 3 is a perpendicular cross-sectional view of a preferred embodiment the efficient regenerator 12 of FIG. 1. In the present specific embodiment, the stacked sheets 44, which are plated with rare earth material, are contained in a rigid cylindrical regenerator sleeve 42, which acts as a pressure vessel to house the stacked sheets 44. In FIG. 3, the working gas flow is in and out of the page as opposed to vertical as in FIGS. 1 and 2.

[0068] Alternatively, the stacked sheets 44 may be oriented perpendicular to the gas flow instead of parallel to the gas flow. In this case, the stacked sheets 44 would be perforated to allow gas to flow perpendicularly through the planes of the sheets 44.

[0069] To facilitate manufacturing, the stack of plated sheets 44 does not completely fill the cylindrical space in the regenerator sleeve 42. A stabilizing material 62, such as polyimide, fills remaining spaces at opposite ends of the stack of sheets 44. Those skilled in the art will appreciate that the stabilizing material 62 may be omitted and that the stack of sheets 44 may be extended to fill the cylindrical space within the regenerator sleeve 42 without departing from the scope of the present invention. Furthermore, the regenerator 12 is not required to be cylindrical. For example, a square or rectangular housing, pressure vessel, or regenerator sleeve may accommodate the stacked sheets 44 instead of the cylindrical regenerator sleeve 42. During manufacturing, the stack of sheets 44 may be cut to a desired shape using conventional Electrical Discharge Machining (EDM) cutting tools.

[0070] The predetermined uniform spacing 54 between the sheets 44 is maintained via dimples or ridges 64 formed in the polyimide substrates (see 50 of FIG. 2) and plated via the rare earth material (see 52 of FIG. 2). Other mechanisms, such as pleats in the substrates may be employed to maintain the spacing 54, without departing from the scope of the present invention. Furthermore, the inside of the regenerator sleeve 42 may be machined with slots (not shown) or steps designed to accommodate the edges of individual sheets 44, thereby holding the sheets in a desired configuration that maintains the predetermined spacing 54. In this case, dimples or ridges 64 may not be required. In this case, dimples or pleats may be included to accommodate certain

gas flow requirements, surface area requirements, and so on, which are application-specific and may be determined by one skilled in the art to meet the needs of a given application.

[0071] The spacing 54 between the plated sheets 44 of polyimide and the thickness of the sheets 44 are not shown to scale in FIG. 3. Furthermore, the number of sheets shown is illustrative. One skilled in the art with access to the present teachings will know how many sheets to include in the regenerator 12 to meet the needs of a given application.

[0072] The regenerator 12 of the present invention employs a low-porosity matrix 44 with a high thermal capacitance and a high surface area-to-volume ratio. The only known materials that have a sufficiently high specific heat are rare earth materials. For the purposes of the present discussion, a rare earth material is any compound, element, or alloy that includes any of the lanthanide elements.

[0073] Current manufacturing techniques preclude manufactures from drawing or extruding rare earth materials into thin sheets or other forms required for regenerator construction. Techniques for creating sufficiently malleable rare earth alloys have been slow to develop. Consequently, techniques of the present invention, including rare earth deposition onto a thermally inert substrate are particularly useful for constructing workable regenerator matrix components. For the purposes of the present discussion, a thermally inert substrate is a substrate that has a very low or approximately zero volumetric heat capacity below 15 K. A thermally inert material has a volumetric heat capacity orders of magnitude lower than rare earth metals at temperatures below 15K.

[0074] FIG. 4 is a cross-sectional diagram of an alternative embodiment 12' of the regenerator 12 of FIG. 1 showing sheets 44' of rare earth material 52 plated over stainless steel screen substrates 50' and enclosed in the regenerator sleeve 42. The rare earth material 52 is sufficiently thick to completely cover the spaces between horizontal and vertical strands of the screen substrate 50' to a great extent, including the limiting case where the spaces are completely filled.

[0075] In some applications, the spaces in the screen substrates 50' are not completely filled, leaving perforations through the plated sheets 44'. In this case, the sheets 44' may be oriented parallel or perpendicular to the gas flow depending on application requirements.

[0076] After the spaces in the screen substrates 50' are covered with the rare earth material 52, the sheets 44' are stacked. Spaces 54 naturally form between the stacked sheets 44' due to the structure of the screens 50'. These spaces 54 facilitate uniform gas flow through the regenerator 12' and provide excellent surface area exposure to the high-heat-capacitance rare earth materials 52.

[0077] The screen substrates 50' comprise dense, commercially available, fine mesh wire. The matrix porosity of the plated screen sheets 44' is a function of the plating thickness, which effects the amount of void area between the sheets 44'. The sheets of completely plated screen mesh 44' are arranged within the regenerator 12' in a stack, which is analogous to the plated polyimide approach of FIGS. 2-3. Different operating temperatures may necessitate a different type of arrangement for the plated screens 44'. For example, the plated screen meshes 44' may be angled relative to each other so that the individual strands of the substrates 50' do

not line up with the other substrates, yielding different shaped spaces **54** between the sheets **44'**, which affects matrix porosity. Those skilled in the art with access to the present teachings may determine the ideal sheet orientation to meet the needs of a given application without undue experimentation.

[0078] FIG. 5 is a flow diagram of a method **80** for building the regenerator **12** of FIG. 1. With reference to FIGS. 2, 3 and 5, in an initial step **82**, sheets **44** of substrate material **50** of predetermined type and dimensions are obtained. In the present specific embodiment, the substrate **50** is polyimide, polyester, or stainless steel. The sheets **44** have a structure such that when stacked, channels **54** exist between sheets **44**. Alternatively, a structured regenerator sleeve **42** is employed to maintain the spacing between the sheets **44**.

[0079] In a subsequent deposition step **84**, rare earth material **52**, such as erbium, is deposited on the substrate sheets **50** to yield the plated sheets **44**. The rare earth material **52** may be deposited using highly-energetic plasma deposition techniques, which are commercially available through Materials and Electrochemical Research Corporation (MER).

[0080] Other deposition techniques, such as standard vapor deposition or ion sputtering, may be employed without departing from the scope of the present invention. Furthermore, rather than depositing rare earth material directly on the substrate **50**, rare earth materials may be diffused into the substrate **50**. If the rare earth material **52** is diffused into the substrate **50** to form the rare earth layer **52**, an appropriate substrate selection must be made. One skilled in the art may make the appropriate substrate selection to meet the needs of a given application without undue experimentation.

[0081] The rare earth material **52** is sufficiently thick and has sufficiently high specific heat at desired operating temperatures to accommodate a desired operational frequency. In the preferred embodiment, the rare earth material is chosen to have a sufficiently high specific heat and thickness to enable high frequency operation of an accompanying cryocooler **10** of FIG. 1 beyond 30 Hz at cryogenic temperatures below 35 K.

[0082] The sheets **44** are then stacked in a stacking step **86**. The stacked sheets **44** exhibit channels **54** or other desired spacing therebetween to enable gas flow **56** through the regenerator **12** and to enable effective heat transfer between the rare earth material **52** and the working gas flow **56**.

[0083] In a final containment step **88**, the stacked sheets **44** are cut to a desired shape via an EDM, Computer Numerical Controlled (CNC), or other tool so that they fit into the regenerator sleeve **42**. The stacked sheets **44** are then fitted into the regenerator sleeve **42**.

[0084] Those skilled in the art will appreciate that the sheets may be cut before they are stacked without departing from the scope of the present invention. Furthermore, the sheets may be individually placed into the regenerator sleeve **42** as they are stacked.

[0085] Previous attempts to incorporate rare earth materials into regenerators involved extruding, drawing, or oth-

erwise attempting to work the rare earth material into a desired shape. Unfortunately, rare earth materials are often not sufficiently malleable. Consequently, these previous attempts were largely unsuccessful.

[0086] Instead of attempting to work the rare earth material into a desired shape, manufacturing techniques of the present involve the unique steps **82-88** of depositing rare earth materials on a suitable substrate **50** that provides the desired form factor for components **44** of the regenerator **12**.

[0087] FIG. 6 is a graph **90** of penetration depth **92** versus frequency **94** for an exemplary erbium deposition on a polyimide substrate. With reference to FIGS. 2 and 6, the thermal penetration depth of the erbium rare earth layer **52** on the polyimide substrate **50** is chosen to be sufficiently high to enable operation of the regenerator **12** at 30 Hz. The thickness of the erbium layer **52** is chosen so that the thermal penetration depth is much greater than the thickness of the erbium layer **52**. This ensures that the entire plating layer **52** contributes thermally to regeneration.

[0088] The graph **90** of FIG. 6 shows a penetration depth-versus-frequency curve **96** of erbium at 8 K, which is described by the following equation:

$$\delta = \sqrt{\frac{D}{\pi f}}, \quad [12]$$

[0089] where δ is the thermal penetration depth; f is the operational frequency of the regenerator **12**; and D is the thermal diffusivity of the erbium layer **52** at 8 K.

[0090] The thermal penetration depth δ is two orders of magnitude larger than thickness of the erbium layer **52**, assuming that the thickness of the erbium layer **52** is approximately 0.0002 inches, and that the polyimide substrate **50** is approximately 0.001 inches thick. This is more than adequate for 30-Hz operation.

[0091] Those skilled in the art will appreciate that different thickness may be chosen for the layer **52** and the substrate **50** without departing from the scope of the present invention. Thinner substrates and thicker depositions may be more desirable for certain applications. This is particularly true at very low operating temperatures (<10 K), where the thermal capacity of the helium working gas **56** is relatively large.

[0092] FIG. 7 is a graph **100** of a load curve **104** superimposed over a power curve **102** for an exemplary regenerator (see **12** of FIG. 1) constructed in accordance with the teachings of the present invention. With reference to FIGS. 1 and 7, the graph **100** includes a left vertical axis **106** representing net refrigeration power in Watts (W) of heat transfer capability. The left vertical axis **106** corresponds to the load curve **104**. A right vertical axis **108** represents input power in Watts and corresponds to the power curve **102**. A horizontal axis **110** represents the operating temperature in Kelvin of the second stage cold end **38** of FIG. 1.

[0093] The graph **100** is based on an exemplary regenerator **12** modeled via publicly available REGEN 3.2 regenerator-modeling software. The REGEN 3.2 software was modified to accept numerical correction factors so that in the exemplary regenerator **12**, which includes a polyimide substrate that does not participate thermally in regeneration, can be better approximated.

[0094] The exemplary regenerator 12 was modeled as a rare-earth-plated polyimide regenerator 12 comprising parallel plates 44 that are incorporated into a second-stage of a cryocooler, such as the cryocooler 10 with a 40 K warm end corresponding to the cool end 24 of FIG. 1. The basic matrix inputs assume a matrix porosity of 15% for the stacked sheets 44. The hydraulic diameter was chosen to be twice the spacing, i.e., 1.27×10^{-5} meters. The regenerator geometry was varied to achieve a reasonable balance between gross refrigeration and regenerator loss. The values selected for length and diameter of the regenerator 12 to generate the graph 100 were 7.00 and 2.52 cm, respectively. The material properties for a staged layering of stainless steel, lead, ErNi, and Er₃Co were used to approximate what might be achieved in practice by optimally staging materials over the design point temperature gradient. The operating frequency was set at 30 Hz and the peak amplitude of the mass flux wave was held to 3.0 grams per second for all cases.

[0095] The constant mass flux approach yields a performance curve that is unlike the traditional load curve in which the compressor stroke is held constant, or the power curve in which compressor power is held constant. The net refrigeration result 104 obtained by this approach produces a tailing capacity at the low end of the temperature range because of the commensurate drop-off in input power 102.

[0096] The curves 102 and 104 illustrate that the regenerator 12 can yield reasonable performance at high frequency and low temperature. The roughly 1 W of refrigeration power 104 produced at 10 K for only 20 W input power 102 at the warm end of the regenerator 12 indicates that the present invention is highly effective.

[0097] FIG. 8 is a graph 120 of volumetric heat capacity 122 versus temperature 124 for various candidate regenerator materials, including rare earth materials shown for comparison purposes. One skilled in the art, with reference to FIG. 8 can readily select the right combination of rare earth materials to achieve a desired specific heat capacity for the regenerator 12 of FIG. 1 to achieve a desired high operating frequency, compactness, and low-temperature cooling capability for a given application.

[0098] Candidate rare earth materials for operation below 10 K are numerous, as illustrated in the graph 120 of FIG. 8. For various specific embodiments of FIGS. 1-4, erbium was chosen for its availability high specific heat down to 10 K.

[0099] Thus, the present invention has been described herein with reference to a particular embodiment for a particular application. Those having ordinary skill in the art and access to the present teachings will recognize additional modifications, applications, and embodiments within the scope thereof.

[0100] It is therefore intended by the appended claims to cover any and all such applications, modifications and embodiments within the scope of the present invention.

[0101] Accordingly,

What is claimed is:

1. A regenerator comprising:
 - a substrate and
 - rare earth material disposed on a surface of said substrate.
2. The regenerator of claim 1 wherein said substrate has channels or pores therethrough or therein.

3. The regenerator of claim 2 wherein said substrate is constructed from a material sufficient to define the geometry of said regenerator.

4. The regenerator of claim 3 wherein said substrate is constructed from a flexible material that is thermally inert below temperatures of 15 K, whereby the volumetric heat capacity of said flexible material is very low below 15 K.

5. The regenerator of claim 3 wherein said substrate includes polyimide or polyester.

6. The regenerator of claim 3 wherein said rare earth material is chosen and deposited on said substrate in a layer so that the thermal penetration depth of said layer of rare earth material is greater than the thickness of said layer.

7. The regenerator of claim 6 wherein said thermal penetration depth is sufficiently high so that approximately all of said rare earth material contributes to thermal regeneration at an operating frequency of 30 Hz.

8. The regenerator of claim 7 wherein said thermal penetration depth is approximately two orders of magnitude greater than the thickness of said layer of rare earth material.

9. The regenerator of claim 7 wherein said rare earth material includes an element, compound, or alloy containing one or more lanthanide elements.

10. The regenerator of claim 9 wherein said rare earth material is erbium.

11. The regenerator of claim 9 wherein the thickness of said substrate is less than or equal to approximately 0.001 inches.

12. The regenerator of claim 11 wherein said layer of rare earth material that is approximately greater than or equal to 0.0002 inches thick.

13. The regenerator of claim 13 wherein each of said plated substrate includes plural substrates having perforations therethrough, said substrates being stacked perpendicular to a flow of working gas in said regenerator.

14. The regenerator of claim 3 wherein said substrate includes a stack of plated substrates that are stacked so that spaces corresponding to said channels or pores occur between said plated substrates.

15. The regenerator of claim 14 wherein said stack of plated substrates is a matrix having a matrix porosity of approximately 15 percent.

16. The regenerator of claim 14 further including means for preserving said spaces between said plated substrates.

17. The regenerator of claim 16 wherein said means for preserving spaces includes dimples in said plated substrates.

18. The regenerator of claim 17 wherein said spaces are approximately 0.00025 inches wide.

19. The regenerator of claim 18 wherein said regenerator is adapted for use with helium gas.

20. The regenerator of claim 14 wherein said plated substrates are screens or other woven wire meshes, said screens or other woven wire meshes plated with sufficient rare earth material to fill spaces in said screens or other woven wire meshes

21. A method for constructing an efficient regenerator comprising:

- obtaining sheets of substrate material;
- dimpling or pleating said substrate material;
- employing deposition techniques to deposit a layer of rare earth materials on said sheets of substrate to yield plated sheets; and

stacking said plated sheets in a shape desired for said regenerator.

22. The method of claim 21 wherein said step of employing vapor deposition includes using highly-energetic plasma deposition techniques.

23. The method of claim 21 wherein said substrate includes a polyimide sheet, a polyester sheet, and/or a woven wire mesh.

24. The method of claim 21 wherein said plated sheets are stacked parallel to the direction of flow of cryogen through said regenerator.

25. A method for constructing an efficient regenerator comprising the steps of:

obtaining sheets of substrate material of predetermined dimensions, said sheets having a structure such that when said sheets are stacked, uniform channels exist between said sheets;

depositing a high specific heat material of a predetermined thickness on said sheets to yield plated sheets in response thereto, said high specific heat material not thick enough to completely fill said uniform channels;

stacking said sheets to yield a stack of plated sheets; and

placing said stack of plated sheets into a pressure vessel or regenerator sleeve.

26. The method of claim 25 wherein said sheets are polyimide sheets.

27. The method of claim 25 wherein said sheets are screens.

28. The method of claim 25 wherein said substrate material is polyimide or stainless steel.

29. The method of claim 28 wherein in said step of depositing, enough high specific heat material is deposited on said screens to fill in spaces in said screens to yield solid plated sheets.

30. The method of claim 28 wherein in said step of depositing, sufficient high specific heat material is deposited on said screens to partially in spaces in said screens to yield plated sheets having perforations therethrough.

31. The regenerator of claim 25 further including the step of cutting said stack of plated sheets to accommodate said pressure vessel.

32. The method of claim 25 wherein said step of depositing includes using plasma deposition techniques.

33. The method of claim 25 wherein said channels are uniform channels.

34. The method of claim 25 wherein said thickness of said high specific heat material is sufficient to accommodate a desired operational frequency of said regenerator.

35. The method of claim 34 wherein said high specific heat material has a sufficiently high specific heat to enable high frequency operation of an accompanying cryocooler beyond 30 Hz at cryogenic temperatures below 35 K.

36. The method of claim 35 wherein said high specific heat material includes one or more rare earth materials.

37. A pulse tube cryocooler comprising:

first means for generating a pressure wave through a cryogenic fluid;

second means coupled to said first means for implementing regenerative heat exchange with said cryogenic fluid, said second means including a heat exchange structure having rare earth materials disposed thereon or therein; and

third means coupled to said second means for harnessing a temperature differential resulting from said pressure wave and facilitated by said second means.

38. The pulse tube cryocooler of claim 37 wherein said first means includes a compressor or pressure wave generator.

39. The pulse tube cryocooler of claim 38 wherein said second means includes a first stage regenerator in gaseous communication with said compressor.

40. The pulse tube cryocooler of claim 39 wherein a first warm-end heat exchanger is connected between said first stage regenerator and said compressor, said first heat exchanger positioned at a warm end of said cryocooler.

41. The pulse tube cryocooler of claim 40 wherein said first stage regenerator is coupled to a cold end of a first stage pulse tube at a cool portion of said cryocooler and is coupled to a second stage regenerator at said cool portion.

42. The pulse tube cryocooler of claim 41 wherein a cool-end heat exchanger is connected between said first stage pulse tube and said first stage regenerator at said cool portion of said cryocooler.

43. The pulse tube cryocooler of claim 42 wherein said first stage pulse tube is coupled to a surge volume at said warm end of said cryocooler, and wherein a second warm-end heat exchanger is positioned between said second stage pulse tube and said surge volume at said warm end of said cryocooler.

44. The pulse tube cryocooler of claim 43 wherein said second stage regenerator includes sheets of rare earth material stacked so that predetermined spacing exists between said sheets.

45. The pulse tube cryocooler of claim 44 wherein said rare earth material and said predetermined spacing are sufficient to enable high-frequency operation of said cryocooler at or beyond 30 Hz and cooling to below 35 K.

46. The pulse tube cryocooler of claim 45 wherein said second stage regenerator is coupled to a second stage pulse tube at a cold end of said cryocooler.

47. The regenerator of claim 46 further including a cold end heat exchanger connected between said second stage regenerator and said second stage pulse tube at said cold end of said cryocooler, said cold end producing temperatures below 10 K.

48. The pulse tube cryocooler of claim 47 wherein said second stage pulse tube is coupled to said surge reservoir at said warm end of said cryocooler, and wherein a third warm-end heat exchanger is connected between said second stage pulse tube and said surge volume.

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