US 20090000313A1

(19) **United States**

(12) **Patent Application Publication**

Bin-Nun

(10) **Pub. No.: US 2009/0000313 A1**

(43) **Pub. Date: Jan. 1, 2009**

(54) REGENERATOR MATRIX WITH MIXED SCREEN CONFIGURATION

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(21) Appl. No.: **12/156,642**

(22) Filed: **Jun. 3, 2008**

Related U.S. Application Data

(62) Division of application No. 10/444,194, filed on May 23, 2003.

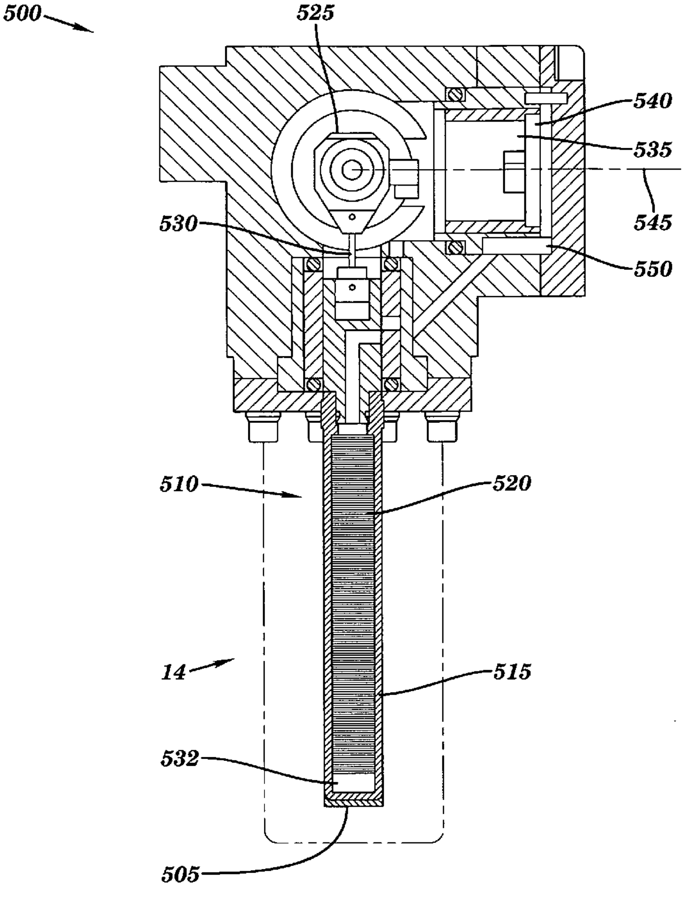
Publication Classification

(51) **Int. Cl.**
F25B 9/14 (2006.01)
F28D 17/02 (2006.01)

(52) **U.S. Cl.** **62/6**; 62/519; 165/9.4

(57) **ABSTRACT**

A regenerator matrix **215** disposed in a fluid conduit **152** for exchanging thermal energy with a fluid passing through the fluid conduit. The regenerator matrix **215** has a variable fluid flow resistance and a variable capacity for convective heat transfer with the fluid along it longitudinal length. Preferably, the flow resistance and the capacity for convective heat transfer between the fluid and the regenerator matrix each increase as the fluid flows from a hot end to a cold end of the fluid conduit **152**. The regenerator matrix **215** is formed from individual screen elements **50** or from stacks of screen elements sintered together as composite regenerator elements **110**. A first portion **235** of the regenerator matrix made from first individual screen elements is disposed at the hot end of the regulator matrix **215**. A second portion **210** of the regenerator matrix made from second individual screen elements is disposed at the cold end of the regulator matrix. A third portion **230** of the regenerator matrix made from third individual screen elements is disposed between the first portion **235** and the second portion **210**. The first portion **235** has the lowest flow resistance and convective thermal energy transfer capacity, the second portion has the highest flow resistance and convective thermal energy transfer capacity, and the third portion has an intermediate flow resistance and convective thermal energy transfer capacity.



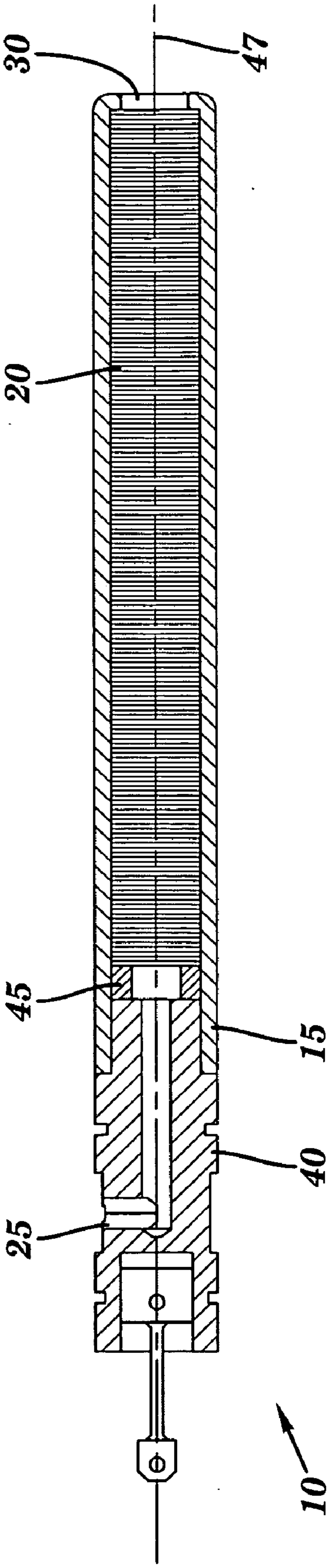


FIG. 1
PRIOR ART

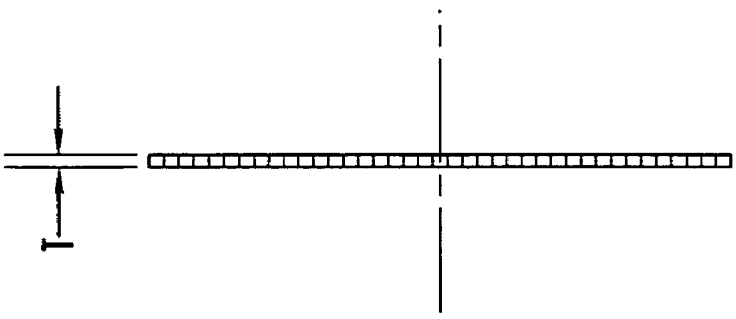


FIG. 2A
PRIOR ART

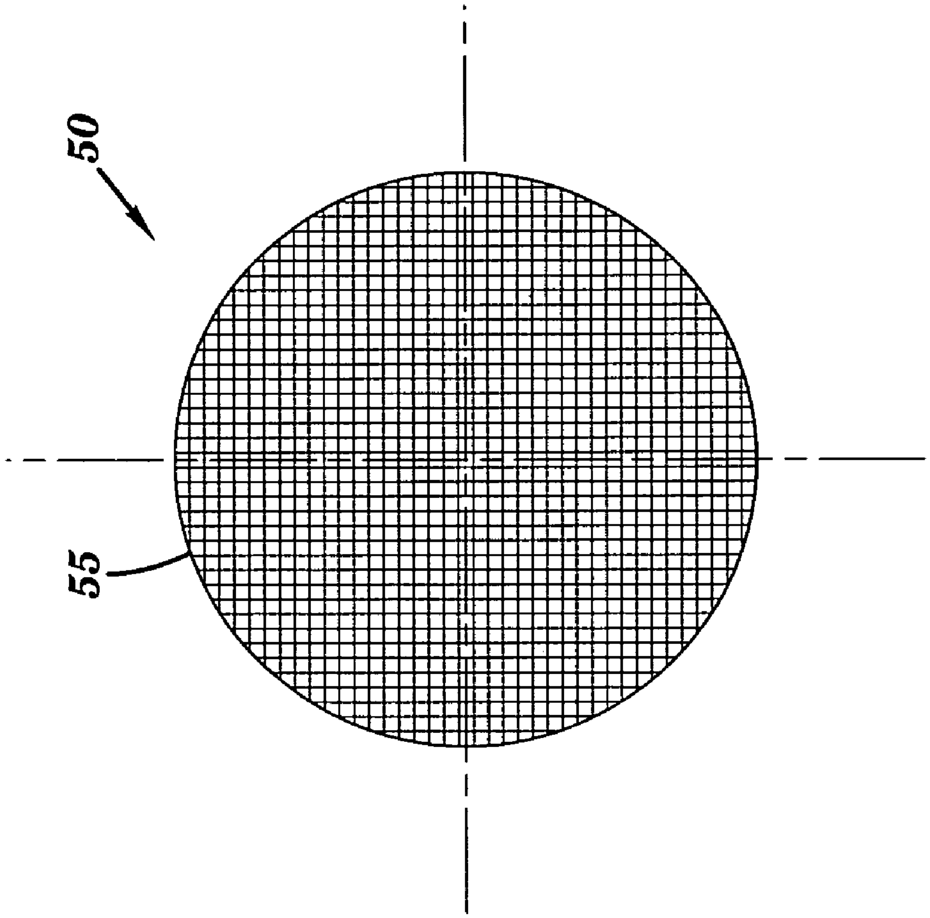


FIG. 2B
PRIOR ART

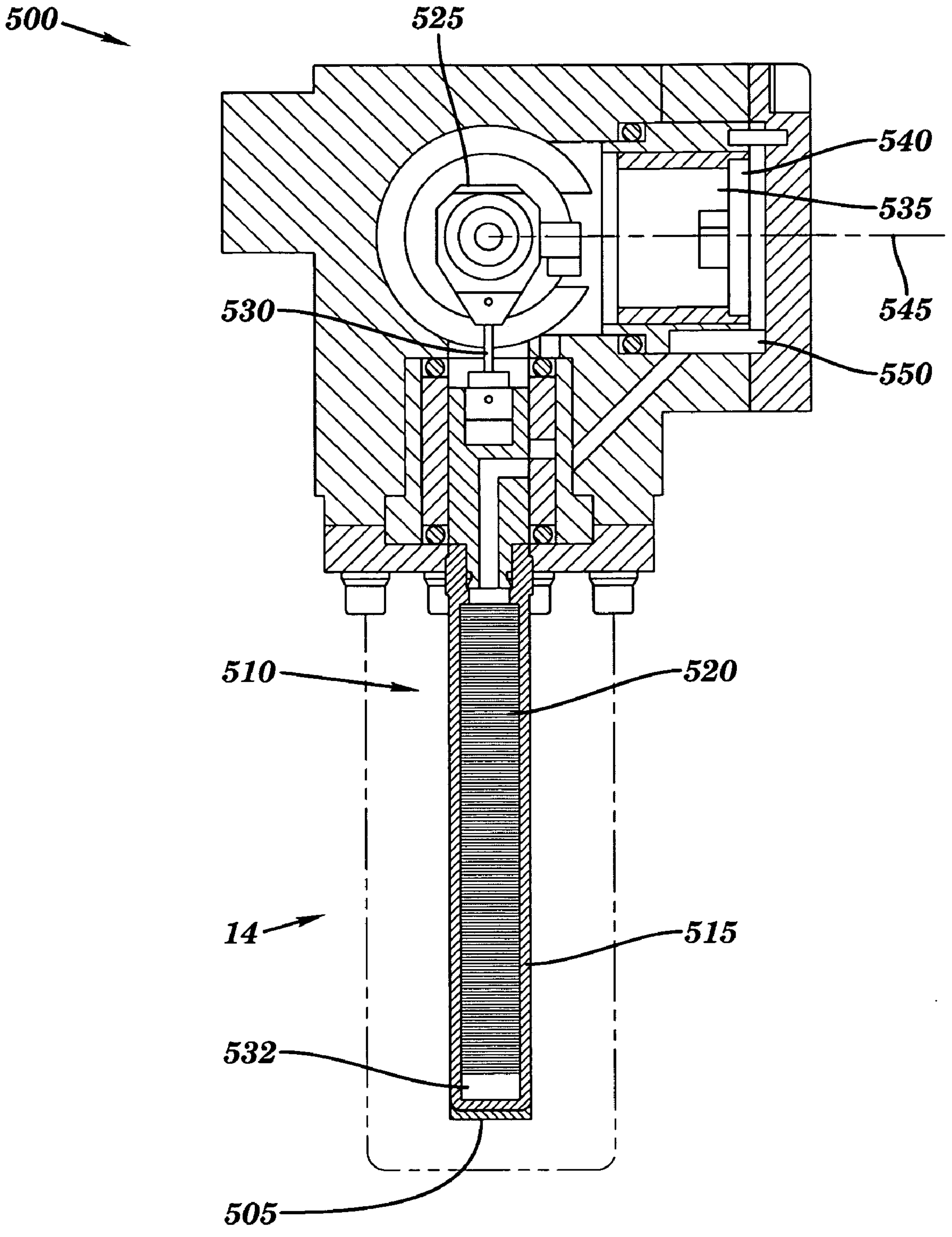


FIG. 3

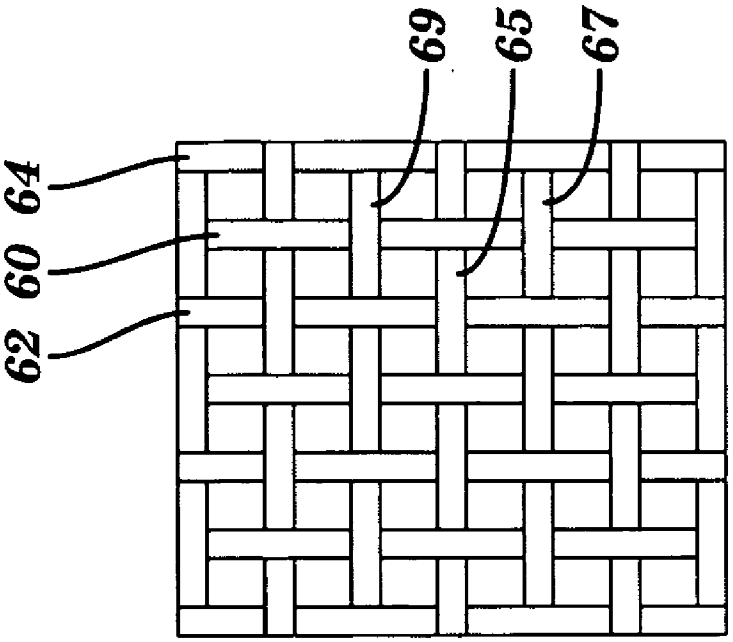


FIG. 4B

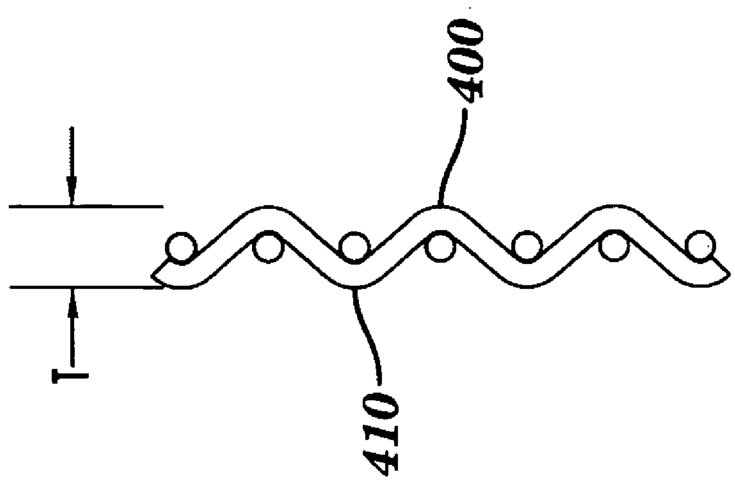


FIG. 4A

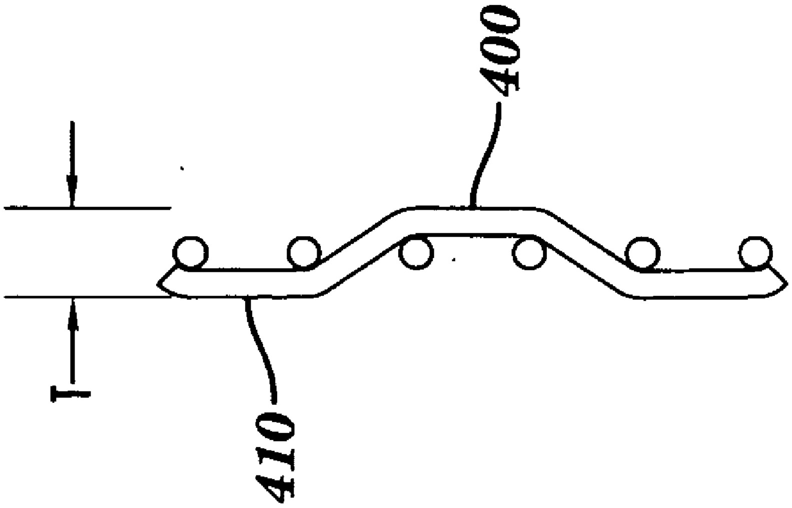


FIG. 5A

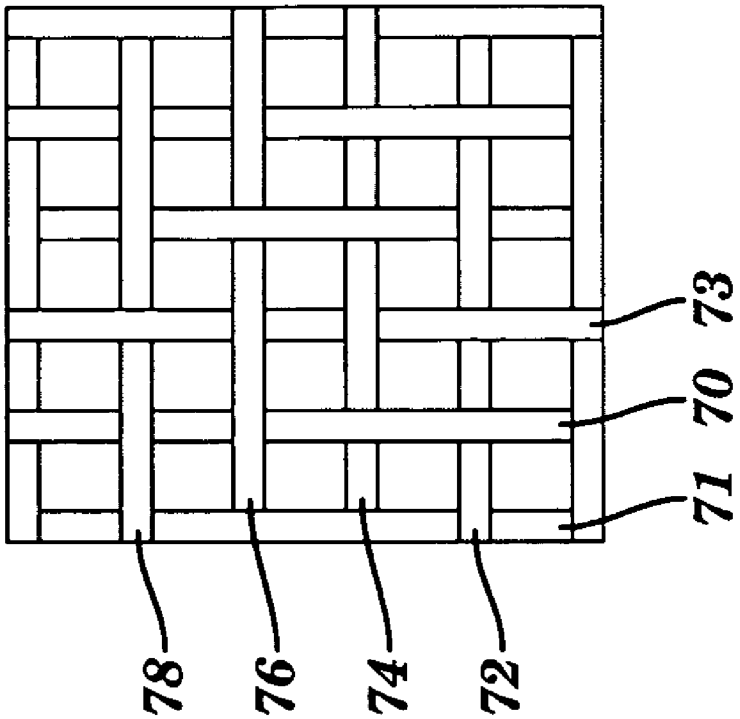


FIG. 5B

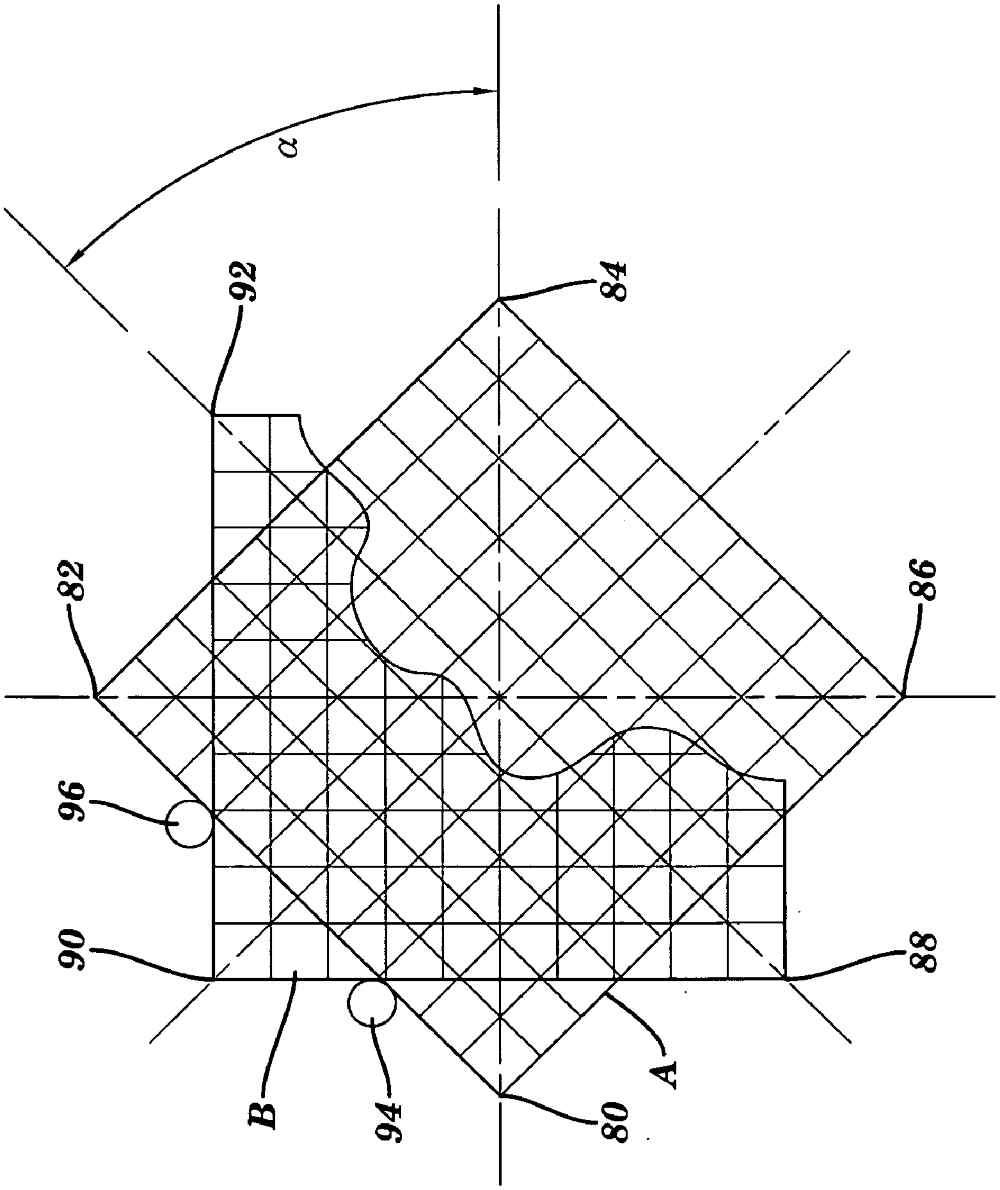


FIG. 6

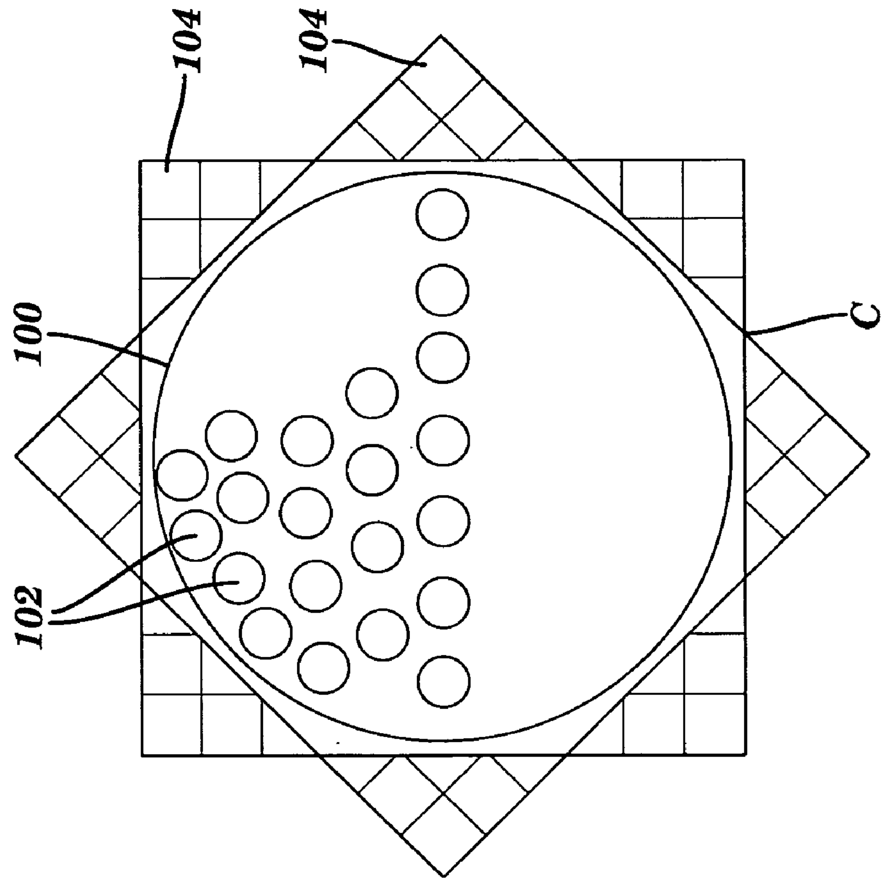


FIG. 7

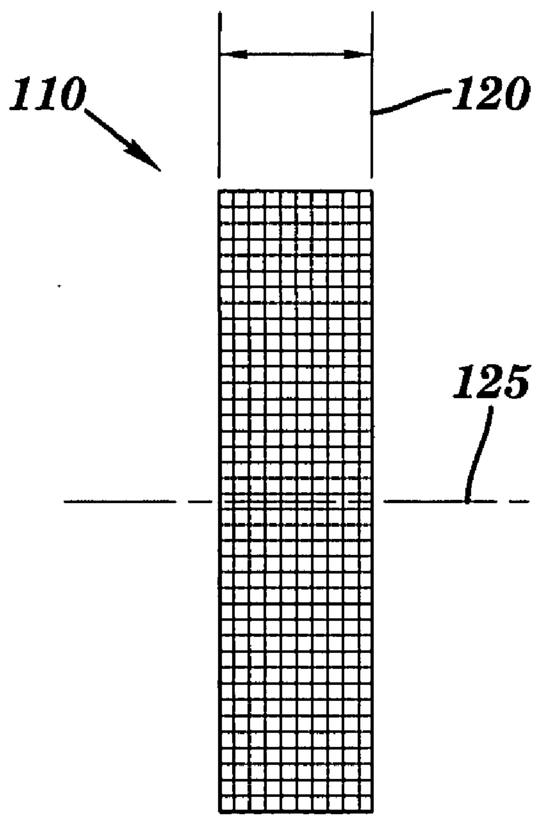


FIG. 8A

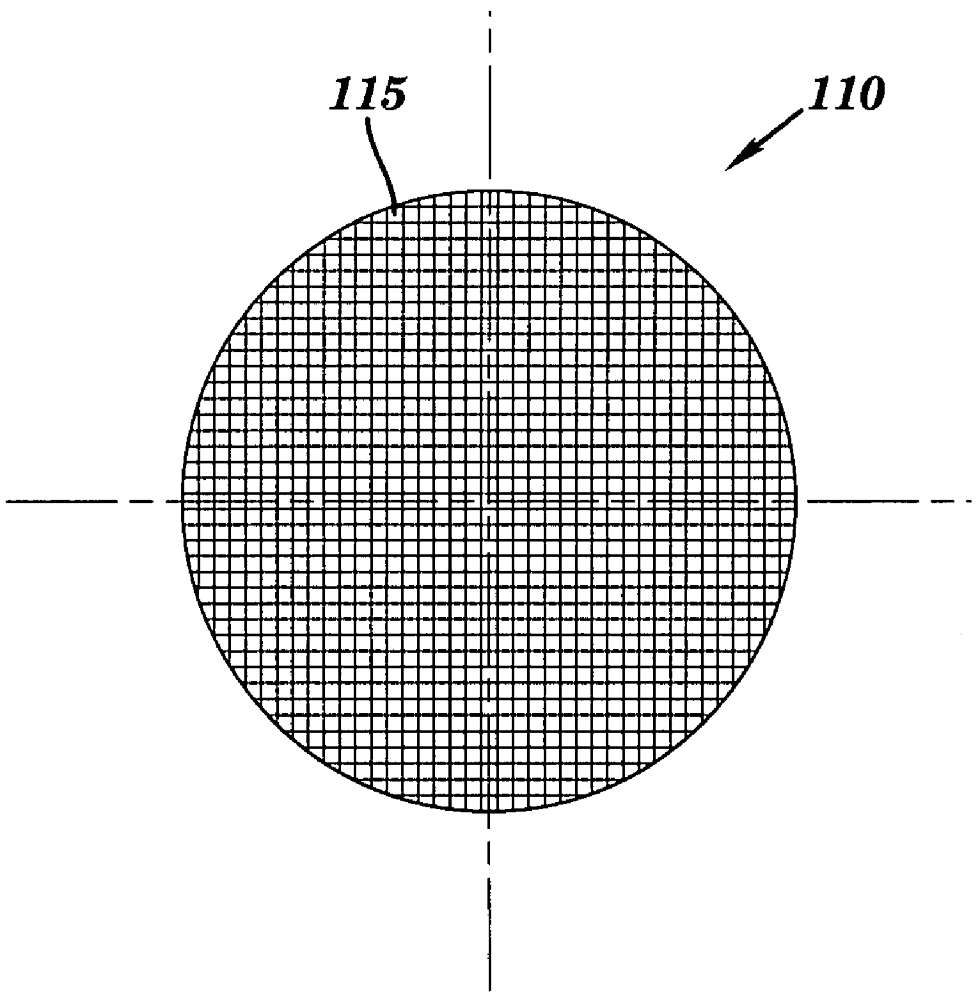


FIG. 8B

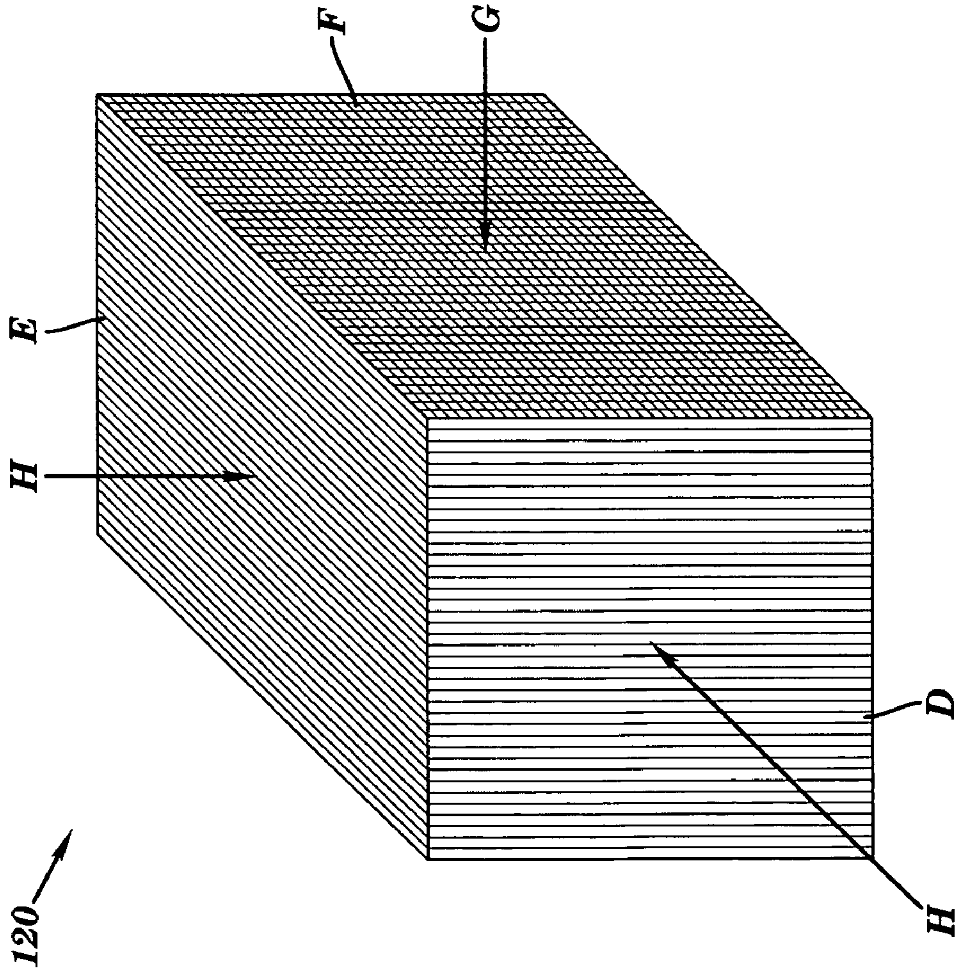


FIG. 9

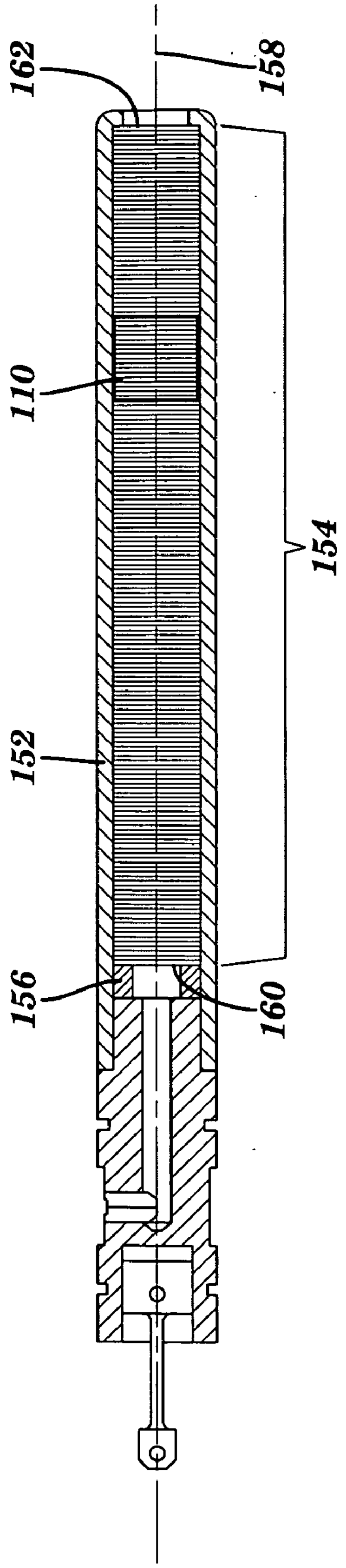


FIG. 10

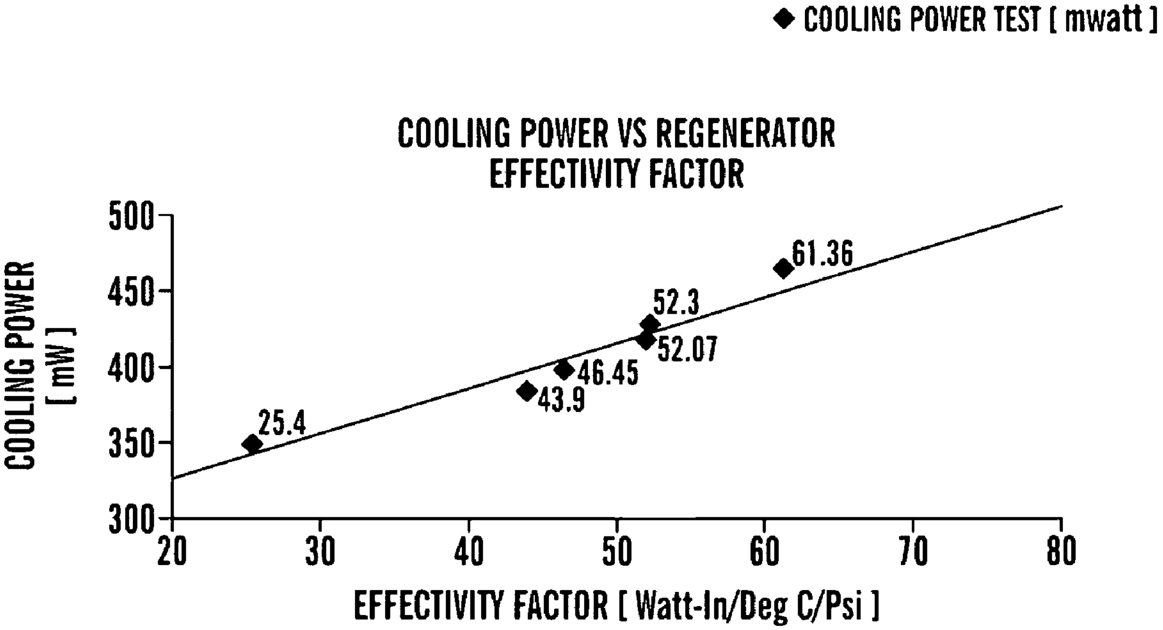

◆ COOLING POWER TEST [mwatt]
COOLING POWER VS REGENERATOR EFFECTIVITY FACTOR
COOLING POWER [mW]
500
450
400
350
300
20
30
40
50
60
70
80
EFFECTIVITY FACTOR [Watt-In/Deg C/Psi]
25.4
43.9
46.45
52.07
52.3
61.36

FIG. 11

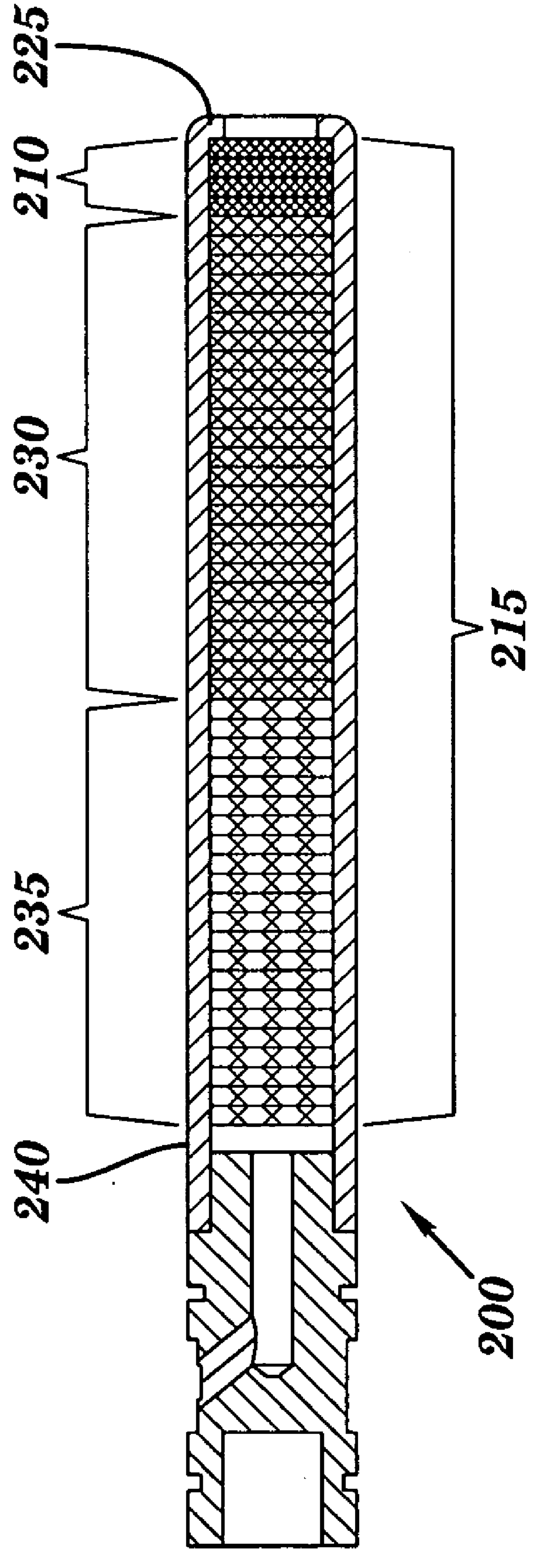


FIG. 12

REGENERATOR MATRIX WITH MIXED SCREEN CONFIGURATION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional application and claims priority under 35 U.S.C. 121 to U.S. application Ser. No. 10/444,194, filed May 23, 2003 entitled LOW COST HIGH PERFORMANCE LAMINATE MATRIX, which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] This invention relates generally to the field of cryogenic coolers and particularly to an improved regenerator type heat exchanger used in a miniature Stirling cycle cryocooler.

[0004] 2. Description of Related Art

[0005] Miniature refrigerators operating on the Stirling cycle provide cooling for infrared detectors and other electronic elements preferably operated at cryogenic temperatures. U.S. Pat. No. 4,858,442, by Stetson and commonly assigned with the instant invention describes a miniature Stirling cycle refrigerator and is hereby incorporated herein by reference. The Stirling cycle generates a refrigeration effect by alternating compressing and expanding a refrigeration gas. The cold refrigeration gas draws thermal energy away from an element to be cooled. The Stirling cycle includes 4 phases of which phase 1 is an isothermic or constant temperature compression of the working fluid by a compression piston reciprocating within a compression cylinder. Phase 2 comprises a cooling of the refrigeration gas at constant volume by transferring thermal energy from the gas to a regenerator matrix or heat exchange element medium. Phase 3 comprises an isothermic expansion of the gas, which causes the refrigeration gas to cool by a so-called refrigeration effect. Phase 3 occurs at a cold end of the cold well by providing an expansion space. An element attached to or proximate to the cold end cools when the cold gas absorbs its thermal energy. Phase 4 comprises a warming of the refrigeration gas at constant volume and occurs within the same regenerator or heat exchange element described above. In phase 4 the regenerator matrix or heat exchange medium transfers thermal energy stored therein, from phase 2, back to the cold refrigeration gas as it flows from the expansion space back to the working volume.

[0006] As detailed in the '442 patent, a miniature Stirling cycle system employs a motor driven compressor to impart cyclic volume variations in a working volume filled with a pressurized refrigeration gas in phase 1. A passage from the working volume of the compressor leads to the cold well. A regenerator assembly resides in the cold well to exchange thermal energy with the refrigeration gas as it flows through the cold well during phases 2 and 4. In the example of the '442 patent the regenerator comprises a close fitting movable piston that is movable within the cylindrical cold well. As the regenerator piston withdraws from the cold well, the expansion space forms at the cold end thereof. The regenerator piston and the compression piston are driven at 90 degrees out of phase by a single drive element. The drive motion alternately creates the expansion space and compressed working volume at appropriate intervals of the cycle. The drive motion further forces the refrigeration gas to flow through the regenerator matrix in phases 2 and 4.

[0007] Accordingly, refrigeration gas is cycled between the compressor working volume and the expansion space and flows through the regenerator matrix in opposite directions during phases 2 and 4. In phase 2, the high temperature refrigeration gas is flowing from the compressor working volume toward the expansion space and transfers thermal energy to the regenerator matrix thereby cooling the gas at constant volume. In phase 4, the low temperature refrigeration gas flows from the expansion space toward the compressor working volume and receives thermal energy from the regenerator matrix thereby heating the gas at constant volume. A regenerator is 100% effective when the exiting or rejection temperature of the refrigeration gas, (at the end of phase 4), is equal to the entering temperature of the refrigeration gas, (at the beginning of Phase 2). If not, then further pre-cooling of the working fluid could be accomplished with a more efficient regenerator design.

[0008] A conventional regenerator assembly **10** is shown in FIG. **1**. The regenerator **10** comprises a generally hollow thin-walled cylindrical element or regenerator tube **15** for housing the regenerator matrix **20** and a solid sleeve portion **45** for supporting the regenerator tube **15**. The entire regenerator assembly **10** comprises a piston that closely fits inside and is movable with respect to a hollow cylindrical cold well having one closed end, not shown. The regenerator assembly or regenerator piston **10** connects to a drive element, not show, via a link **35**, which causes the regenerator piston to reciprocate within the cold well. An expansion space forms at the cold well, at the closed end, or cold end, each time the regenerator piston withdraws from the cold well. An entrance aperture **25** directs the working fluid through the regenerator at the hot end thereof and an exit aperture **30** directs the working fluid into the expansion space provided inside the cold well at the cold end.

[0009] A conventional regulator heat-exchanging matrix **20** may comprises a porous material that the refrigeration gas can readily flow through and exchange thermal energy with, by convection heat transfer. Various porous metal configurations, e.g. closely pack spherical balls, or other compacted loose metal particles, as well as stacks of metal screens or mesh, are used as regenerator heat exchangers. Ideally, the porous solid substrate provides a low fluid flow resistance and high convective thermal energy exchange capacity. Examples of regenerator matrix materials include closely packed pulverized materials, e.g. spherical metal elements, as described in U.S. Pat. No. 6,042,657 spaced apart thin plate-shaped elements as described in U.S. Pat. No. 6,460,348, woven wire regenerator elements as described in U.S. Pat. No. 6,475,935 and laminated platelets as described in U.S. Pat. No. 6,153,326.

[0010] In another example, Fir Systems-Boston, Inc. utilizes a regenerator matrix comprising a stack of fine metal wire mesh or screen elements. The metal screens offer good convective thermal energy transfer between the working fluid and the matrix material, however, excessive thermal conductivity of the matrix configuration along an axis between the hot end and the cold end can create a thermal short circuit, which transfers thermal energy directly from the hot end to the cold end by conduction. This degrades the performance of the cooler. Convective heat exchange is improved by maximizing the amount of matrix material surface area in contact with the working fluid and by providing sufficient void volume local to the surface area to allow mixing or motion of the working fluid during convective thermal transfer. The amount of void volume also strongly governs flow resistance and pressure gradient in the matrix.

[0011] Applicants' have determined that the performance of a regenerator matrix behaves according to equation (1):

$$R_{pf} = \frac{A_s h}{\partial p / \partial x} \qquad \text{Equation (1)}$$

Where:

[0012]

$$R_{pf} = \text{Regenerator Performance Factor } \frac{\text{Watt}}{{}^{\circ}\text{C.}-\text{psi/in}}$$

$$A_s = \text{Regenerator Matrix Surface Area in}^2$$

$$h = \text{Matrix Convection Coefficient } \frac{\text{Watt}}{\text{in}^2 DegC}\text{; and,}$$

[0013] $\partial P/\partial X$=Pressure Drop per Matrix Unit Length psi/inch

[0014] The matrix R_{pf} value is calculated at a given volumetric flow rate and it provides the ratio between the capacity for the matrix to exchange energy with the working fluid and the local pressure gradient. As is clear from equation (1), the performance of a regenerator matrix can be optimized by increasing the surface area of the matrix material in direct contact with the working fluid, A_s by increasing the convection coefficient h or by reducing the pressure gradient $\delta P/\delta X$. As will be recognized by those skilled in the art, the surface area A_s is strongly dependent on the individual screen element configuration. For most matrix configurations, the surface area exposure to the working fluid is readily calculated. The convection coefficient and the pressure gradient are dependent upon the porosity of the matrix defined by a ratio of the matrix void or dead space volume to its total volume. In addition, characteristics of the working fluid itself, e.g. the fluid viscosity, density, thermal conductivity, and specific heat also affect the convection coefficient, and the pressure gradient. However, for a given refrigeration cycle and working fluid, the working fluid properties are consistent such that any improvement in the system cooling performance as described herein will be substantially attributable to changes in the regenerator matrix configuration.

[0015] A specific matrix configuration used by Flir Systems-Boston, Inc. comprises a plurality of individual metal screen elements filling the regenerator tube **15**. In one particular embodiment, the regenerator tube contains 200-1000 650 individual metal screen elements such as the elements depicted in FIGS. **2**A and **2**B. A single screen element **50** comprises an outer diameter **55** that is sized to closely fit within the inside diameter of regenerator tube **15**. The screen material comprises a grid or mesh of fine woven stainless steel wire. The wire diameter is 0.0012 inches (0.031 mm) and is woven at a screen pitch of 400 wires per inch, i.e. with a center-to-center wire separation of 0.0025 inches, (0.064 mm). FIG. **2**B, depicts the element thickness T that is about three times the wire diameter. Each screen **50** provides a large wire surface area exposed to the working fluid for convective heat exchange therewith and provides a large void volume between the wires for the fluid to flow through and for the fluid to mix during convective heat exchange. Moreover, the screens **50** are stacked together in close mechanical contact by applying a compacting force to the stack for forcing adjacent screens into contact. The compacting force compacts the screen volume so that more screens can be used in the matrix. However, an excessive compacting force increases thermal conductivity between screens and a thermal short along the stack longitudinal axis allows thermal energy flow directly from the hot end to the cold end by conduction through the compressed screens.

[0016] The orientation of each screen in the stack influences the surface area exposure and void volume. For example, if every screen of the stack is oriented with the wire elements substantially co-aligned, the open spaces between the wires align along a longitudinal or axis of fluid flow of the stack and the working fluid will readily pass unobstructed through the aligned void volume. Screen wire element co-alignment also aligns the wires such that there are a large number of contact points between adjacent screens and less wire surface area exposed to the working fluid. In the conventional regenerator matrix of the present example, no attempt is make to align the screen elements in any specific orientation. This results in a substantially random alignment in the conventional regenerator matrix of the present example.

[0017] It is a general problem with conventional regenerator matrix configurations, such as the one described above, that the screen elements are extremely fragile. Applicants' observation is that a large number of elements become damaged during forming and or during the insertion of the elements into the regenerator tube **15**. Any screen element installed into the tube **15** in a non-flat condition can adversely affect the regenerator performance and because there are so many elements, it is difficult to assemble a regenerator matrix entirely of flat screen elements. As a result, the performance of a conventional regenerator varies in proportion to the number of damaged screens and this leads to an uncertainty about regenerator performance from unit to unit and can lead to a complete regenerator failure. Non-flat screens reduce screen-packing density; leave excess voids between screens and causes excess void space at the regenerator tube wall.

[0018] It is another problem that due to the nature of the regenerator operation, it has been very difficult to determine whether an assembled regenerator will meet its thermal exchange performance requirements. In order to quantify a regenerator performance, it is tested in a completed cryocooler device. If the generator fails to meet predetermined performance criteria, it must be replaced or reworked. As a result, an unacceptable yield of finished cryocoolers occurs. This adds cost to the manufacturing process.

[0019] It is a further problem in the art that assembling many hundreds of individual screens into a regenerator tube is tedious and labor intensive. A conventional regenerator as described above is tedious and painstaking to assemble and the assembly labor accounts for a significant percentage of the overall manufacturing cost.

[0020] It is another problem of the conventional regenerator matrix described above that the mechanical compacting force for compacting the screen elements in the tube is difficult to control. Excessive compacting causes a thermal short along a longitudinal axis of the stack while insufficient compacting leaves voids in the stack and reduces the number of screen elements in the matrix. Both conditions degrade performance. In FIG. **1**, a regenerator, clamp **45** applies a compacting force along a longitudinal axis **47** to compact the volume taken up by the stacked elements. However, non-flat screens or screens hung up by the regenerator tube inner wall result in excess voids that reduce the pressure pulse and decrease the matrix capacity. Similarly, fewer screens in the stack also decrease matrix capacity.

[0021] It is a still further problem with conventional regenerator elements that the size and shape of each element may vary due to unavoidable tolerances of the element forming process. Undersized screen diameters cause excess void volume between the regenerator tube inner wall diameter and the screen. Oversized screen diameters cause screens to hang up on the tube wall during insertion and this causes excess void volume. Excess void volume causes heat exchange and flow rate variations from unit to unit that can adversely affect the performance of a finished cryocooler.

[0022] The problems identified above cause a regenerator matrix to perform in an unpredictable manner and the acceptance of the matrix performance is not determined until it is tested in a finished cryocooler. As a result, the yield of finished cryocoolers in a production environment is adversely impacted. Non-performing finished cryocooler are disassembled and then reassembled with a new regenerator unit. The failed regenerator must be rebuilt or scraped. These shortcomings results in an undesirable manufacturing cost for the product.

BRIEF SUMMARY OF THE INVENTION

[0023] The problems of the prior art described above are addressed by the present invention which, provides a thermal energy exchange apparatus **500** for exchanging thermal energy with a fluid such as a refrigeration gas, e.g. helium. The thermal energy exchange apparatus **500** includes a hollow coldwell tube **515** disposed along a longitudinal axis **158** and extending between an open hot end and a sealed cold end. A regenerator piston **200** installs within the hollow coldwell tube **515** and is reciprocally movable with respect to the coldwell tube **515**. The regenerator piston **200** includes a hollow tube **152** forming a fluid conduit extending along the longitudinal axis **158**. The hollow tube **152** extends from an open hot end to an open cold end. Reciprocal movement of the regenerator piston **200** along the longitudinal axis **158** cyclically varies a volume of an expansion space **532** formed between the coldwell tube sealed cold end and the fluid conduit open cold end and further causes the fluid to flow through the fluid conduit formed by the hollow tube **152**.

[0024] A regenerator matrix **215** is disposed along the longitudinal axis **158** to substantially fill the hollow tube **152** and exchanges thermal energy with the fluid as the fluid passes through the fluid conduit from the hot end to the cold end and back from the cold end to the hot end. In particular, the regenerator matrix **215** is configured to vary a fluid flow resistance and a capacity for convective heat transfer with the fluid along the longitudinal axis **158**.

[0025] In particular, the regenerator matrix **215** includes three portions **235**, **210** and **230**. Each portion **235**, **210** and **230** is made from a plurality of individual screen elements **50** stacked together. Alternately, each portion is made from a plurality of composite regenerator elements **110** stacked together. In this case, each composite regenerator element **110** is made from a plurality of individual screen elements **50** sintered together in a stack. A first portion **235** of the regenerator matrix **215** is disposed proximate to the hot end of the regenerator piston **200**. A second portion **210** of the regenerator matrix **215** is disposed proximate to the cold end of the regenerator piston **200**. A third portion **230** of the regenerator matrix **215** is disposed between the first portion **235** and the second portion **210**. The first portion **235** is configured with the lowest flow resistance and convective thermal energy transfer capacity and includes individual screen elements having a large void volume and a small wire surface area. In particular, each individual screen element of the first portion **235** includes wires having a wire diameter of 0.0021 inches disposed at a pitch of 200 wires per inch. The third portion **230** is configured with an intermediate flow resistance and convective thermal energy transfer capacity and includes individual screen elements having an intermediate void volume and wire surface area. In particular, each individual screen element of the third portion **230** includes wires having a wire diameter of 0.0014 inches disposed at a pitch of 325 wires per inch. The second portion **210** is configured with the highest flow resistance and convective thermal energy transfer capacity and includes individual screen elements having a small void volume and small wire surface area. In particular, each individual screen element of the second portion **210** includes wires having a wire diameter of 0.0012 inches disposed at a pitch of 400 wires per inch.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The present invention is particularity described in the appended claims. The above and further advantages of the present invention may be better understood by referring to the following description in conjunction with the accompanying drawing in which:

[0027] FIG. **1** depicts a conventional regenerator assembly.

[0028] FIG. **2**A depicts a side view of a conventional individual regenerator screen element.

[0029] FIG. **2**B depicts a front view of a conventional individual regenerator screen element.

[0030] FIG. **3** depicts a miniature Stirling cycle cryocooler according to the present invention.

[0031] FIG. **4**A depicts a sectional view taken through the screen element of FIG. **4**B.

[0032] FIG. **4**B depicts details of an enlarged plan view of a thin screen element having a plain weave pattern of 400 MESH.

[0033] FIG. **5**A depicts a sectional view taken through the screen element of FIG. **5**B.

[0034] FIG. **5**B depicts details of an enlarged plan view of a thin screen element having a twill weave pattern of 400 MESH.

[0035] FIG. **6** depicts stacked screen elements rotated by 45 degrees.

[0036] FIG. **7** depicts the usable region of the lamented substrate.

[0037] FIG. **8**A depicts a side view of a laminated regenerator element according to the invention.

[0038] FIG. **8**B depicts a front view of a laminated regenerator element according to the invention.

[0039] FIG. **9** depicts another embodiment of a laminated regenerator element according to the invention.

[0040] FIG. **10** depicts one example of a regenerator assembly according to the invention.

[0041] FIG. **11** depicts a graphic relationship between calculated regenerator performance coefficients and measured cooling performance.

[0042] FIG. **12** depicts a second example of a regenerator assembly according to the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0043] The preferred embodiments of the present invention are illustrated in the accompanying detailed description and drawings. FIG. **3** depicts a cross-sectional view of a Stirling cycle cryocooler **500** used for cooling components to cryogenic temperatures, e.g. to less than about 135° K. or more particularly to less than about 80° K. FIG. **3** shows an element to be cooled **505** attached to the cold end of a cold well assembly **510**. The cold well **510** comprises a thin walled cylindrical cold well tube **515**, sealed at a cold end thereof and a cylindrical regenerator piston **520** movably supported within the cold well tube **510**. A drive coupling **525** reciprocates the regenerator piston **520** with respect to the cold well tube **515** through a link **530**. When the regenerator piston **520** is at the top of its motion cycle, a small volume at the sealed end of the cold well tube **515** provides the expansion space **532** in which an isothermic expansion of the refrigeration gas inside the cold well occurs.

[0044] A compression cylinder **535** and a compression piston **540** provide a variable working volume in which an isothermic compression of the refrigeration gas occurs. The compression piston **540** is movable supported within the compression cylinder **535** and is reciprocated within the compression cylinder by the drive coupling **525** through the link **545**. The motion of the compression piston **540** and the regenerator piston **520** are 90 degrees out of phase so that the volume of expansion space **530** increases as the working volume in the compression cylinder **535** is also increasing. A passage **550** allows the compressed refrigeration gas to pass from the working volume through the regenerator piston **520**. This occurs as the regenerator piston **520** withdraws from the cold well tube **515** and the volume of the expansion space **532** increases. When the regenerator piston **520** reverses directions, the volume of expansion space **532** decreases and the refrigeration gas is forced back through the regenerator piston **520** through the passage **550** and back into the compression cylinder **535**.

[0045] To illustrate the phases of the Stirling cycle in connection with the cryocooler hardware, Phase 1 occurs as the compression piston **540** decreases the working volume of the compression cylinder **535**. Phase 2 occurs as the refrigeration gas flows through the regenerator piston **520** toward the expansion space **530**. Phase 3 occurs inside the expansion space **532**, and Phase 4 occurs as the refrigeration gas flows through the regenerator piston **520** toward the compression cylinder **535**. A conventional regenerator piston **520** is illustrated FIG. **1** as item **10**.

[0046] Since the preferred embodiment of the present invention relates to improving regenerator, and ultimately cryocooler production yield and performance, Equation (2) describes the influence of regenerator performance on cryocooler performance in terms of refrigeration loss. Refrigeration loss is a function of the cryocooler compression ratio (V_4/V_3), the temperature ratio (T_2/T_3), the specific heat ratio, $\gamma = C_p/C_v$ and the regenerator effectiveness ϵ.

$$\frac{\Delta Q}{Q_{ideal}} = \left(\frac{1-\varepsilon}{\gamma-1}\right)\left(\frac{T_2/T_3-1}{\ln(V_4/V_3)}\right) \qquad \text{Equation (2)}$$

[0047] In equation 2: $\Delta Q/Q_{ideal}$ is the ratio of the energy left in the refrigeration gas after it exits from the regenerator cold end and the ideal cooling energy produced during expansion in the expansion space. It can also be described in terms of the Stirling cycle as the ratio of the energy remaining in the refrigeration gas at the end of the transition from phase 2-3 to the cooling energy produced during the transition from phase 3-4. T_2/T_3 is the ratio of the temperature of the refrigeration gas T_2 as it enters the regenerator from the compressor, at the beginning of the transition from phase 2-3, to the temperature of the refrigeration gas T_3 as it exist the regenerator to the expansion space, at the end of the transition from phase 2-3. V_4/V_3 is the expansion ratio in the expansion space or the ratio between the gas volume after expansion, V_4, to the gas volume before expansion, V_3. C_p/C_v is the ratio of the specific heat of the working fluid at constant pressure, (C_p) to the specific heat of the working fluid at constant volume, (C_v).

[0048] Using a numerical example, a cryocooler that uses helium as a refrigeration gas, has an expansion ratio $V_4/V_3=1.24$, a rejection temperature (T_2)=20 Deg C. and a cold end temperature, (T_3)=77 Deg K. In this example, the working fluid will lose 20% of its refrigeration power if the regenerator effectiveness, ϵ, is 99% instead of 100%. It is therefore desirable to maximize the regenerator effectiveness in a consistent and predictable manner. An ineffective regenerator requires additional input power to cool the element attached to the cold end to a desired cold temperature and the increase in power usage may become unacceptable, especially if the device is operating on battery power as many infrared camera systems do.

[0049] According to the present invention, a process similar to conventional sintering fuses a plurality of individual porous screen elements together to form a porous solid element. Sintering is widely used to join powdered metal particles confined in a mold or other container shaped to provide a solid element having a desired shape and size. The mold forms the shape and size as in other molding techniques. The mold containing the powder particles are heated to an elevated temperature in an elevated pressure environment. At a temperature just below the melting temperature of the powder particles, contacting particles bond or fuse together by a diffusion process. The diffusion process provides an intermingling of the powder particles at a molecular level. After the sintering process, no physical limits exist at the boundaries of the original powder particles and they become fused together at the contact points. Sintered metal parts can provide solid elements with characteristics that may not be achievable by other metal forming processes, e.g. porosity.

[0050] In one embodiment of the present invention, a plurality of sheets of wire screen mesh are joined by sintering to form a regenerator element substrate. FIGS. **4**A-**5**B depict examples of wire mesh structure typical of individual sheets of wire screen mesh. Individual sheets of wire screen mesh as well as sintered wire mesh elements are generally available, e.g. from Newark Wire in Newark N.J., USA.

[0051] FIGS. **4**A and **4**B depict a plain weave screen pattern. The plain weave pattern comprises first wire strands **60**, **62**, **64** arranged in parallel along a substantially vertical axis. Second wire strands **65**, **67**, **69** are arranged in parallel along a substantially horizontal axis such that the first and second wire strands are substantially perpendicular. First and second wire strands have a wire diameter of 0.0009 inches, (0.03 mm) and a center-to-center separation pitch of 0.0025 inches, (0.064 mm), or a 400 MESH, defined as 400 wires per inch.

The plain weave pattern has each wire interwoven with an adjacent wire. For example, a first (vertical) wire strand **60** passes over a second (horizontal) wire strand **65** and under each adjacent second (horizontal) wire strand **67** and **69**. The pattern is offset for the adjacent first (vertical) wires **62** and **64**, which pass over the second (horizontal) wires **67** and **69** and under the second horizontal wire **65**. FIG. **4**A depicts a sectional view taken through the plain weave pattern. The pattern thickness T is about three times the wire diameter but the screen sheet thickness may be compressed when a compression force is applied to a stack of sheets.

[0052] FIGS. **5**A and **5**B depict a twill weave screen pattern. The twill weave pattern comprises first wire strands **70**, **71**, **73** arranged in parallel along a substantially vertical axis. Second wire strands **72**, **74**, **76** are arranged in parallel along a substantially horizontal axis such that the first and second wire strands are substantially perpendicular. The first and second wire strands have a wire diameter of 0.0012 inches, (0.031 mm), a center-to-center separation pitch of 0.0025 inches, (0.064 mm), or a 400 MESH. The twill weave pattern has each wire interwoven with pairs of two adjacent wires. For example, a first (vertical) wire, **70** passes over two adjacent second (horizontal) wires, **72** and **74**, and passes under two adjacent second (horizontal) wires **76** and **78**. The pattern is offset for the adjacent first (vertical) wires **71** and **73**, which pass over the second (horizontal) wires **72** and **78** and under the second (horizontal) wires **74** and **76**. FIG. **5**A is a sectional view taken through the twill weave pattern. The twill pattern thickness T is about three times the wire diameter but can be compressed.

[0053] The plane and twill weave patterns shown are by way of example. Other weave patterns, wire diameters, meshes and or wire orientations are usable to form porous solid regenerator elements according to the present invention. In addition, square or other shaped wire strand shapes are usable. In addition, non-parallel wire stands and non-perpendicular wire strands are usable. Screen configurations that provide a balance between maximizing the wire surface area in contact with the refrigeration gas while also providing enough void volume or open space for a working fluid to flow through the matrix are the most desirable. However, a suitable screen configuration also depends upon physical characteristics of the working fluid, e.g. its viscosity, pressure, flow velocity, specific heat and temperature.

[0054] Regenerator screen elements formed with stainless steel wire, e.g. from 304 stainless steel wire, are preferred. Stainless steel is readily weaved into the fine mesh patterns, provides adequate thermal conductivity properties for conducting heat along a radial axis of the regenerator to distribute thermal energy in the screen and has sufficient thermal surface resistance between contacting screen elements to prevent a thermal short along the longitudinal axis of the regenerator matrix. Of course, other metal wire strands such as copper, bronze, aluminum, and titanium are usable.

[0055] Sintering screen sheets of interwoven wire strands into a stack involves cutting sheets of screen material to a desired size and shape and laying the sheets one above another in a stack. A mechanical clamping force forces the sheets into contact. The stack is sintered in a high temperature, high-pressure environment for a period consistent with completing the sintering process. Sintered screen substrates are available from (Newark Wire in Newark, N.J. USA). Referring to FIGS. **4**A and **5**A, individual sheets have a top surface **400** and an opposing bottom surface **410**. The surfaces are irregular with high and low points formed by the alternating interwoven first (vertical) and second (horizontal) wire strands. Accordingly, when a plurality of screen sheets are stacked together with top sides **400** in contact with bottom sides **410**, wire strands of each sheet contact at a limited number of contact points. In the sintering process, these contact points join at a molecular level and offer no physical boundary to conductive heat flow after sintering. As will be readily apparent, the orientation of the mesh pattern of each screen in the stack will influence the number of contact points, the void volume of the stack and the surface area of wire available for interaction with a refrigeration gas flowing through the stack.

[0056] FIG. **6** depicts a schematic example of a stack of screen sheets being prepared for sintering according to the present invention. In the example, alternating adjacent screen sheets are oriented with the mesh patterns rotated at a 45-degree angle. The stack of screen sheets is prepared for sintering as follows. A first substantially square screen sheet A, which includes corners **80**, **82**, **84**, **86**, is laid onto a support surface, not shown, at a first orientation as shown. Positioned on top of sheet, A, is a second substantially square screen sheet B, shown partially cut away, having the same size and weave pattern as sheet A. Sheet B includes corners **88**, **90**, **92**, with the fourth corner cut away. Sheet A is oriented with its mesh pattern aligned with a first axis. Sheet B is oriented with its mesh pattern aligned with a second axis that is rotated at an angle α with respect the first axis and the mesh pattern of sheet A. In the preferred embodiment, the angle α is substantially 45 degrees. A complete stack is assembled with alternating sheets being oriented with the mesh pattern along the first and the second axes, which are 45 degrees apart. As few as two sheets up to many thousands of sheets may be stacked together in the orientations shown. As shown, a pair of orientation pins **94**, **96** assure accurate alignment of each sheet to the desired orientation. Of course, numerous other alignment aids are usable. Moreover, more than two orientations are usable in a single stack, e.g. the mesh pattern of each successive sheet may be orientated 30 degrees rotated with respect to the mesh pattern of a previous sheet. In addition, the stack may comprise screen elements having different weave patterns and or wire diameters.

[0057] With a stack of screen sheets of the desired number assembled as shown, the entire stack is clamped together to keep the sheets flat and to ensuring good mechanical contact between mating screen sheets and sintered as described above. After sintering, individual regenerator, matrix elements are cut in the size and shape desired using a laser-cutting tool, by EDM, (Electro Discharge Machined), or by die cutting.

[0058] FIG. **7** depicts the stack of FIG. **6** after the sintering process is completed. The unshaded region C is usable to cut into individual regenerator elements of the size desired. One element **100**, or many elements **102**, may be cut from a single laminated stack.

[0059] FIGS. **8**A and **8**B depict a regenerator element **110** cut from the laminated substrate shown in FIG. **7**. The regenerator element **110** is cylindrical having an outside diameter **115** and a length or thickness **120**. The diameter **115** is sized to have a very small clearance fit with the inside diameter of a regenerator tube, which in the preferred embodiment is 0.1685 inches, (4.28 mm). The regenerator element thickness **120** depends on the number of individual screen sheets in the stack. A stack may comprise many hundreds of layers, e.g., enough to fill the full length of a regenerator tube, or a stack can have just two screens. In one example, a stack that fills a cryocooler regenerator tube may comprise many hundreds of screens. In this case, the stack thickness **120** may be about 2.0 inches, (50.8 mm). As will be explained below, a preferred regenerator element is comprised of a stack of 12-15 screens with a thickness **120** of about 0.03 inches, (0.762 mm).

[0060] The element **110** provides a composite porous solid element with similar properties to a stack of individual screen elements as used in the prior art, however, the element **110** is significantly more rigid and easier to handle than a single screen element. Moreover, because the orientation of each screen in the sintered element **110** is controlled, with alternating screens oriented with the mesh pattern at 45 degrees, each element **110** provides a consistent and predictable flow resistance, wire surface area and void volume. In addition, by cutting the element **110** using a laser or EDM cutting device, the element **110** can be cut to a more consistent outside diameter size and shape as compared to cutting individual screens. This provides a better diametrical fit with the regenerator tube and provides performance that is more consistent by reducing fluid flow variations near the regenerator tube wall and by providing more wire surface area and less dead volume per unit length of the regenerator.

[0061] One characteristic of the sintered element **110** is that it has a much higher thermal conductivity, along its longitudinal axis **125**, than a stack of an equivalent number of individual screen elements because the sintered screen elements have no physical boundaries or surface resistance at the contact points. Applicants' found that by forming a sintered element **110** with many screen sheets, e.g. enough to fill the regenerator tube, the increased thermal conductivity of an element **110** caused a thermal short to occur between the hot end of the regenerator tube and the cold end. A better solution is to form many laminated composite elements **110**, each comprising a small number of individual screen sheets, e.g. in a preferred embodiment, each element **110** comprises about 10-20 individual screens. This provides a plurality of thermal breaks along the regenerator matrix at the contacting interfaces between individual elements **110**. Although there is mechanical contact between adjacent elements **110**, a surface resistance at the contacting interfaces offers more resistance to conductive heat flow than the sintered interface between sintered screens. To further increase the surface resistance at the contacting interfaces, sand blasting is used to roughen the contacting surfaces of the elements **110**. Each element **110** is sand blasted either before being cut from the matrix substrate, shown in FIG. **7**, or after being cut into individual elements, e.g. **100** and **102** of FIG. **7**.

[0062] Heat exchange elements formed by sintering screen sheets according to the present invention are formable in any desired shape and size. For example, a cube element **120**, shown in FIG. **9**, comprises stack of screens elements sintered into contact and cut into the cube shape. Sides D and E comprise individual screen elements, shown end on, while side F comprises a single sheet of screen mesh. The element **120** may be oriented such that fluid flows along an axis normal to the weave or mesh pattern as depicted by the arrow G or the fluid may flow parallel to the weave plane as depicted by the arrow H.

[0063] FIG. **10** depicts one example of a regenerator assembly **150** according to the present invention. The assembly comprises a hollow thin-walled regenerator tube **152**, filled with a regenerator matrix **154**. The tube **152** comprises a substantially thermally insulating material e.g. a fiberglass filed resin having an outside diameter sized to provide a seal fit with the cold well tube, not shown, and an inside diameter sized to provide a close interference fit with the regenerator elements stacked therein. The insulating tube **152** keeps thermal energy from flowing out of the regenerator matrix **154** along a radial axis. The regenerator matrix comprises a plurality of substantially identical cylindrical regenerator elements **110**, e.g. as depicted in FIGS. **8**A and **8**B. Each regenerator element **110** comprises 17 identical individual screen elements alternately oriented with the mesh patterns rotated at 45 degrees and sintered together in accordance with the process described above. In the embodiment shown in FIG. **10**, the regenerator matrix **154** comprises 47 elements **110**. The contacting surfaces of each of the elements **110** are roughened by sandblasting to increase surface resistance between adjacent elements. A clamp **156** applies a force along the regenerator longitudinal axis **158** to hold the elements in place and to compact the elements within the tube **152**. As stated above, the regenerator has a hot end **160** and a cold end **162**. The use of 47 elements each comprising 17 sintered screen elements was determined empirically to adequately reduce thermal conductivity of the regenerator matrix along the axis **158**.

[0064] As stated above, a conventional regenerator matrix comprising many hundreds of individual screen elements is tedious to assemble and has an excessive assembly time and cost associated with that assembly time. The regenerator matrix example depicted in FIG. **10**, takes 90% less time to assemble, is less tedious to assemble, is less prone to assembly error and is less prone to element damage during installation and removal, if required. In addition, the regenerator **150**, assembled as described above, provides consistent heat exchange performance with the working fluid because the screen mesh orientations are aligned and because the diameter of each element more closely matches the inside diameter of the regenerator tube **154**.

[0065] The most significant impact of a regenerator matrix comprising 47 sintered elements **110** is that 90% of the assembly labor is eliminated when compared with a single screen conventional regenerator. In addition to a minor reduction in material costs, the example regenerator of FIG. **10** reduces the regenerator manufacturing cost by more than 60%.

[0066] Having realized the benefits of the cost reduction made available by utilization of sintered screen elements, a numerical analysis conducted by the Applicants quantifies regenerator performance vs. screen characteristics, e.g. mesh, wire diameter and weave patterns. Referring back to equation 1 above, the regenerator performance factor R_{pf} depends of the pressure gradient. Specifically, regenerator performance improves with decreasing pressure gradient. Equation (3) provides the gradient pressure or pressure drop per unit length of the regenerator.

$$\frac{\partial p}{\partial x} = \frac{f}{d_h}\frac{\rho u^2}{2} \qquad \text{Equation (3)}$$

Where:

[0067] f=Friction Factor

[0068] ρ=Local Fluid Density

[0069] d_h=Hydraulic Diameter

[0070] u=Fluid Velocity

[0071] Equation (4) below defines the friction factor f. It is completely dependent on the Reynolds Number R_e of the fluid flow in the matrix. The Reynolds Number R_e is shown in equation (5) and depends on the fluid density ρ, the fluid velocity u, the fluid viscosity μ and the hydraulic diameter d_h.

$$f=129/R_e+2.9R_e^{-0.103} \qquad \text{Equation (4)}$$

$$R_e=\rho u d_h/\mu \qquad \text{Equation (5)}$$

Where:

[0072] ρ=Local Fluid Density

[0073] u=Fluid Velocity

[0074] d_h=Hydraulic Diameter

[0075] μ=Viscosity

[0076] The hydraulic diameter, given in equation (6) below, depends on the porosity of the regenerator matrix β, as defined by the void volume to total volume ratio, and the diameter of the regenerator matrix screen wire d_w.

$$d_h = \frac{\beta}{1-\beta} d_w \qquad \text{Equation (6)}$$

[0077] Using the equations above, it is clear that the pressure gradient although influenced strongly by fluid velocity, viscosity and density is also dependent upon the effective hydraulic diameter d_h and the matrix porosity β and these two variables are completely determined by the screen characteristics. Values of d_h, β d_w and δp/δx and the surface area A_s for ten regenerator screen configurations are calculated using equations 3-6 and are listed in TABLE 1.

[0078] Using equations (7) and (8), to calculate the convection coefficient h for the different screen configurations these values are also listed in TABLE 1.

$$h = \frac{N_u k}{d_h} \qquad \text{Equation (7)}$$

Where:

[0079]

$$N_u=(1+0.99P_e^{0.66})\beta^{1.79} \qquad \text{Equation (8)}$$

[0080] k=Fluid Conductivity

[0081] d_h=Hydraulic Diameter

[0082] β=Porosity

[0083] P_e=Peclet Number, which is a function of the Reynolds number, fluid viscosity and specific heat of the fluid.

[0084] As can be seen from equations (7) and (8), the screen characteristics also influence the convection coefficient h. Finally, the regenerator Performance Factor R_{pf} as determined by equation (1) is calculated and listed in TABLE 1 as a function of screen characteristics.

TABLE 1

Regenerator Performance Factor vs. regenerator matrix configuration

Matrix Configuration	d_h [inch]	β	d_w [inch]	∂p/∂x [psi/inch]	h, [Watt/in^2/Deg C.]	A_S [in^2]	R_{pf}, Performance Factor
Single Screen Element 400 mesh .0012 Twill (1)	.0017	.59	.0012	2.25	3.27	35.83	52.1
Single Screen Element 400 mesh .0009 Plain (2)	.0015	.63	.0009	2.83	3.92	44.24	61.4
Laminate 400 mesh .0012 Twill (3)	.0014	.54	.0012	3.30	3.12	27.0	25.4
Laminate 325 mesh .0014 Twill (4)	.00177	.56	.0014	2.15	2.92	32.3	43.9
Laminate 325 mesh .0011 Plain Sandblasted (5)	.00158	.59	.0011	2.66	3.42	40.59	52.3
Mixed Laminates (4) 400 mesh .0012 (26) 325 mesh .0014 (17) 200 mesh .0021 (6)	n/a	n/a	n/a	1.75 Length weighted average	2.82 Surface Area Weighted Average	28.9 Total Surface Area	46.5

[0085] All calculations assume Helium as the refrigeration gas, 20 Deg C. as the rejection temperature T_2, and a flow velocity u of 2.58 Ft/Sec. The six screen characteristics or regenerator matrix configurations are numbered 1-6 in column 1. For example, configuration (3) lists, "Laminate 400 mesh 0.0012 twill" It refers to a complete regenerator matrix formed of sintered or laminated screen elements with each screen elements having 400 wires per inch, 0.0012 inch

(0.031 mm), wire diameter and woven in a twill weave pattern. Configurations (1) and (2) are single screen matrix configurations each having 400 wires per inch but different wire diameters and weave patterns. As can be seen, the smaller diameter wire weaved in the twill pattern of configuration (2) provides the higher regenerator performance factor R_{pf}. TABLE 1 include calculated values for screen elements having 200 to 400 wires per inch and wire diameters ranging between 0.0009 and 0.0021 inches, (0.023-0.053 mm), and with plane and twill weave patterns. Configuration (2) provides the highest regenerator performance factor R_{pf}. As will be clear from Equation (1)-(8), whether the regenerator matrix comprises laminated or individual screens has no influence on calculated values listed in TABLE 1. Accordingly, TABLE 1 applies to single screen regenerators and sintered screen regenerators.

[0086] Tests performed to determine if actual regenerator performance agrees with the results predicted in TABLE 1 confirm agreement. Testing was performed using complete regenerators assembled using the characteristics listed in TABLE 1. Completed regenerators were installed into finished cryocoolers and the cryocooler performance was evaluated under conventional test conditions and procedures. TABLE 2 lists the cooling power generated by the finished cryocoolers.

[0087] FIG. **11** is a plot of calculated regenerator performance coefficient vs. actual cooling test results. The plot demonstrates a linear correlation between calculated regenerator performance coefficients and cooling power measurements. These results suggest that the calculated values are reliable for predicting regenerator matrix performance and specifically that regenerators with high R_{pf} values always performed better.

TABLE 2

Cooling Power Test Results Summary

REGENERATOR TYPE DESCRIPTION	Regenerator Performance coe. [Watt-in/Deg C./Psi]	Cooling Power Test [mwatt]
400 MESH TWILL .0012, SINGLE SCREEN DISKS (PRIOR ART) (1)	52.07	420 (Production Average)
400 MESH PLAIN .0009, SINGLE SCREEN DISKS (2)	61.36	410-466
400 MESH TWILL .0012, LAMINATES (3)	25.4	350-410
325 MESH TWILL .0014 LAMINATES (4)	43.9	386-410
325 MESH PLAIN .0011 LAMINATES SAND BLASTED (5)	52.3	430-460
MIXED LAMINATE MATRIX REGEN (4 elements) 400 MESH .0012 WIRE DIA TWILL LAMINATE (26 elements) 325 MESH .0014 WIRE DIA TWILL LAMINATE (17 elements) 200 MESH .0021 WIRE DIA TWILL LAMINATE (6)	46.45	400-410

[0088] The regenerator configuration labeled (1) in TABLES 1 and 2 is the conventional regenerator matrix used by Flir System in production regenerators. Large amounts of test data for this configuration confirm that a cryocooler utilizing regenerator configuration (1) generates an average cooling power of 420 mwatt. Referring to configuration (2), a cooling power of 410-466 mwatts shows that improvement over the standard average is attainable using configuration (2). It is noted that a matrix comprising the screens of configuration (2) has more screens per unit length because of the wire diameter reduction. However, the wire diameter reduction renders the screens even more fragile than the screens of configuration (1), and an increased number of screens per unit length increases the assembly labor cost. Fortunately, the sintering techniques of the present invention make the use of more a fragile screen practical and reduce the labor cost associated with increasing the number of screens.

[0089] Referring now to configuration (6), a further embodiment of a regenerator matrix of the present invention is described below. This regenerator matrix comprises a plurality composite or laminated regenerator elements having different screen mesh configurations used in combination within the regenerator tube. FIG. **12** depicts a regenerator assembly **200** including a regenerator tube **210** filled with a plurality of laminated regenerator elements, each having the characteristics of the laminated element **110** depicted in FIGS. **8**A and **8**B and described above. The regenerator matrix **215** comprises (4) laminated elements **210**, formed by individual screens having 400 wires per inch of 0.0012 inch (0.31 mm) wire diameter, woven a twill pattern, stacked at the cold end **225** of the regenerator **200**. Stacked above the elements **210** are (26) laminated elements **230** formed by individual screens having 325 wires per inch of 0.0014 inch wire diameter, and woven in a twill pattern. Stacked above the elements **230** are (17) laminated elements **235** formed by individual screens having 200 wires per inch of 0.0021 inch, (0.053 mm), wire diameter, and woven with a twill pattern. Theoretical performance factors for configuration (6), listed in TABLE 1, were made using averages and weighting factors to approximate the regenerator performance factor R_{pf} and other values listed therein. For configuration (6), the estimated regenerator performance value, R_{pf} is 46.5. Of significance about the test results performed on configuration (6) is that the cooling power range in configuration (6) was 400-410 mwatts while the range of cooling power for all of the other configurations is larger. Accordingly, the mixed screen matrix of FIG. **12** and configuration (6) nearly meets the standard cooling power of the prior art but is significantly less expensive to manufacture and offers a more consistent cooling power result in a finished cryocooler.

[0090] As will be recognized by those skilled in the art, the properties of the refrigeration gas change quickly along the flow path between the compression cylinder and the expansion space. In particular, the refrigeration gas at the hot end **240** of the regenerator matrix has a temperature of 20° C. while the refrigeration gas at the cold end **225** has a temperature of −200° C. In addition, the gas pressure is lower at the cold end than at the hot end. Of particular note is that the gas viscosity at the cold end **225** is lower than the gas viscosity at the hot end **240**. The regenerator matrix of FIG. **12** and configuration (6) is designed to take advantage of the lower viscosity at the cold end but positioning a finer screen mesh having more wire surface area and less void volume, elements **210**, at cold end. Since the gas temperature and pressure increase with distance from the cold end, a more course screen mesh with less wire surface area but more void volume is placed in the middle portion of the regenerator matrix as represented by the elements **230**. Finally, an even more course, larger void volume element **235**, is installed near the hot end of the regenerator piston **200**.

[0091] In accordance with the mixed screen type configuration, flow resistance of the regenerator matrix increases from the hot end **240** to the cold end **225** as the gas viscosity decreases inversely. At the same time, the surface area of screen wire available for convective heat transfer from the gas to the matrix increases as the fluid approaches the cold end **225**. The increased wire surface area provides increased convective thermal transfer capacity while the lower fluid viscosity requires less void volume for effective fluid mixing during convective thermal transfer. It is also noted that the regenerator matrix **215** can be fabricated from single screen elements but such a matrix will not benefit from the cost reduction offered by laminated or sintered screen regenerator elements.

[0092] Finally, tests conducted to evaluate a regenerator matrix according to configuration (5), which specifically includes sandblasted contacting surfaces as described above, show that configuration (5) outperforms the convention regenerator matrix of configuration (1). Configuration (5) comprises a complete matrix of substantially identical laminated elements, e.g. element **110** shown in FIG. **10**, formed from individual screens having a 325 MESH, plain weave and 0.0011 inch diameter, (0.028 mm), wire configuration with each element sandblasted to roughen mating surfaces for reducing conductive heat exchange between elements of the matrix.

[0093] Thus, according to the invention individual screen elements are laminated into regenerator elements for forming a regenerator matrix having similar performance characteristics as compared to conventional non-laminated screen regenerator matrix configurations but with a manufacturing cost reduced by 60% or more. In a further embodiment of the invention, a regenerator matrix comprising a plurality of regenerator elements formed from laminated individual screen elements utilizes multiple regenerator element types each type having a different flow resistance and a different thermal energy transfer characteristic. In particular, multiple regenerator element types are used to take advantage of a refrigeration gas viscosity decrease during flow through the regenerator. In yet another embodiment of the invention a regenerator matrix comprising a plurality of regenerator elements formed from laminated individual screen elements is stacked together with contacting surfaces and the contacting surfaces are roughened, e.g. by sandblasting to reduce conductive thermal energy flow along the matrix.

What I claim:

1. A thermal energy exchange apparatus for exchanging thermal energy with a fluid comprising:

a hollow coldwell tube disposed along a longitudinal axis between an open hot end and a sealed cold end;

a regenerator piston installed within the hollow coldwell tube and reciprocally movable with respect thereto comprising a hollow tube forming a fluid conduit extending along the longitudinal axis from an open hot end thereof to an open cold end thereof and wherein reciprocal movement of the regenerator piston along the longitudinal axis cyclically varies a volume of an expansion space formed between the coldwell tube sealed cold end and the fluid conduit open cold end and further causes the fluid to flow through the fluid conduit;

a regenerator matrix disposed to substantially fill the fluid conduit wherein the regenerator matrix comprises;

one more first composite regenerator elements loaded into the fluid conduit to form a first portion of the regenerator matrix proximate to the hot end wherein the first composite regenerator elements are formed from first individual wire screen elements sintered together in a stack with each first individual wire screen element having a substantially identical first wire surface area and first void volume;

one or more second composite regenerator elements loaded into the fluid conduit to form a second portion of the regenerator matrix proximate to the cold end wherein the second composite regenerator elements are formed from second individual wire screen elements sintered together in a stack with each second individual wire screen element having a substantially identical second wire surface area and second void volume;

wherein the second wire surface area is greater than the first wire surface area and the second void volume is less than the first void volume.

2. The thermal energy exchange apparatus of claim **1** further comprising:

one or more third composite regenerator elements loaded into the fluid conduit to form a third portion of the regenerator matrix disposed between the first portion and the second portion wherein the third composite regenerator elements are formed from third individual wire screen elements sintered together in a stack with each third individual wire screen element having a substantially identical third wire surface area and third void volume wherein the third wire surface area is less than the second wire surface area and greater than the first wire surface area and further wherein the third void volume is greater than the second void volume and less than the first void volume.

3. The thermal energy exchange apparatus of claim **2** wherein:

the first individual screen elements comprise wires having a diameter of 0.0021 inches and a screen pitch of 200 wires per inch;

the second individual screen elements comprise wires having a diameter of 0.0012 inches and a screen pitch of 400 wires per inch; and,

the third individual screen elements comprise wires having a diameter of 0.0014 inches and a screen pitch of 325 wires per inch.

4. The thermal energy exchange apparatus of claim **1** wherein each of the first and second composite regenerator elements comprises a stack of 2 to 25 individual screen elements.

5. The thermal energy exchange apparatus of claim **3** wherein each of the first, second and third composite regenerator elements comprises a stack of 2 to 25 individual screen elements.

6. The thermal energy exchange apparatus of claim **3** wherein each of the first, second and third individual screen elements is formed with a weave pattern axis and further wherein each of the first second and third composite regenerator elements is assembled in the stack with alternating adjacent individual screen elements rotated to align the weave pattern axes thereof with one of two different alignment axes.

7. The thermal energy exchange apparatus of claim **6** wherein the two different alignment axes are separated by an angle of 45 degrees.

8. A thermal energy exchange apparatus for exchanging thermal energy with a fluid comprising:

a hollow coldwell tube disposed along a longitudinal axis between an open hot end and a sealed cold end;

a regenerator piston installed within the hollow coldwell tube and reciprocally movable with respect thereto comprising a hollow tube forming a fluid conduit extending along the longitudinal axis from an open hot end thereof to an open cold end thereof and wherein reciprocal movement of the regenerator piston along the longitudinal axis cyclically varies a volume of an expansion space formed between the coldwell tube sealed cold end and the fluid conduit open cold end and further causes the fluid to flow through the fluid conduit; and,

a regenerator matrix disposed along the longitudinal axis to substantially fill the fluid conduit for exchanging thermal energy with the fluid as the fluid passes through the fluid conduit from the hot end to the cold end and from the cold end to the hot end, wherein the regenerator matrix is configured with a fluid flow resistance and with a capacity for convective heat transfer with the fluid that each vary along the longitudinal axis.

9. The regenerator device of claim **8** the regenerator matrix has minimum fluid flow resistance and minimum convective heat transfer capacity proximate to the hot end, and maximum fluid flow resistance and maximum convective heat transfer capacity proximate to the cold end.

10. The regenerator device of claim **9** wherein the regenerator matrix includes three portions disposed along the longitudinal axis with a first portion disposed proximate to open hot end, a second portion disposed proximate to the open cold end and a third portion disposed between the first portion and the second portion and wherein the first portion is formed with a first fluid flow resistance and capacity for convective heat transfer with the fluid, the second portion is formed with a second fluid flow resistance and capacity for convective heat transfer with the fluid and the third portion is formed with a third fluid flow resistance and capacity for convective heat transfer with the fluid.

11. The regenerator device of claim **10** wherein the regenerator matrix comprises individual screen elements with each individual screen element comprising wires woven together in a weave pattern wherein each wire screen element has a wire surface area, a void volume and a weave pattern axis.

12. The regenerator of device of claim **11** wherein:

the first portion comprises a plurality of substantially identical wire screen elements formed from first individual wire screen elements having a first wire surface area and a first void volume;

the second portion comprises a plurality of substantially identical wire screen elements formed from second individual wire screen elements having a second wire surface area and a second void volume; and,

the third portion comprises a plurality of substantially identical wire screen elements formed from third individual wire screen elements having a third wire surface area and a third void volume.

13. The regenerator device of claim **11** wherein the regenerator matrix comprises stacks of two or more substantially identical wire screen elements sintered together.

14. The regenerator device of claim **13** wherein each stack is assembled with the weave pattern axis of alternating adjacent individual screen elements in the stack aligned with one of two different alignment axes.

15. The thermal energy exchange apparatus of claim **14** wherein the two different alignment axes are separated by an angle of 45 degrees.

16. A method for exchanging thermal energy between a fluid and a regenerator matrix comprising the steps of:

disposing a fluid conduit along a longitudinal axis with an open hot end for receiving hot fluid for therein and with an open cold end for delivering cold fluid out therefrom;

forming the regenerator matrix by filling the fluid conduit with individual screen elements each comprising wires woven together in a weave pattern wherein each individual screen element has a wire surface area, a void volume and a weave pattern axis; and,

varying the wire surface area and void volume of individual screen elements along the longitudinal axis to thereby vary a flow resistance of the regenerator matrix along the longitudinal axis and to further vary a capacity for convective heat transfer between the regenerator matrix and the fluid along the longitudinal axis.

17. The method of claim **16** further comprising the step of forming the regenerator matrix with minimum flow resistance and maximum capacity for convective heat transfer between the regenerator matrix and the fluid at the hot end and a maximum flow resistance and minimum capacity for convective heat transfer between the regenerator matrix and the fluid at the at the cold end.

18. The method of claim **18** further comprising the steps of:

forming a first regenerator portion from a plurality of first individual screen elements each having a first wire surface area and a first void volume, wherein the first regenerator portion is disposed proximate to the hot end;

forming a second regenerator portion from a plurality of second individual screen elements each having a second wire surface area and a second void volume, wherein the second regenerator portion is disposed proximate to the cold end; and,

forming a third regenerator portion from a plurality of third individual screen elements each having a third wire surface area and a third void volume, wherein the third regenerator portion is disposed between the first regenerator portion and the second regenerator portion.

19. The method of claim **16** wherein each of the individual screen elements has a weave pattern axis, further comprising the step of; assembling the regenerator matrix by aligning the weave pattern axis of alternating adjacent individual screen elements with one of two different alignment axes.

20. The method of claim **19** wherein the step of aligning the weave pattern axis of alternating adjacent individual screen elements with one of two different alignment axes comprises rotating the weave pattern axis of alternating adjacent individual screen element by 45 degrees.

21. The method of claim **18** further comprising the steps of:

forming the first regenerator portion from a plurality of stacks each comprising a plurality of the first individual screen elements sintered together in a stack with the weave pattern axis of alternating adjacent individual screen elements in the stack aligned with one of two different alignment axes;

forming the second regenerator portion from a plurality of stacks each comprising a plurality of the second individual screen elements sintered together in a stack with the weave pattern axis of alternating adjacent individual screen elements in the stack aligned with one of two different alignment axes; and,

forming the third regenerator portion from a plurality of stacks each comprising a plurality of the third individual screen elements sintered together in a stack with the weave pattern axis of alternating adjacent individual screen elements in the stack aligned with one of two different alignment axes.

22. The thermal energy exchange apparatus of claim **21** wherein the two different alignment axes are separated by an angle of 45 degrees.

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