



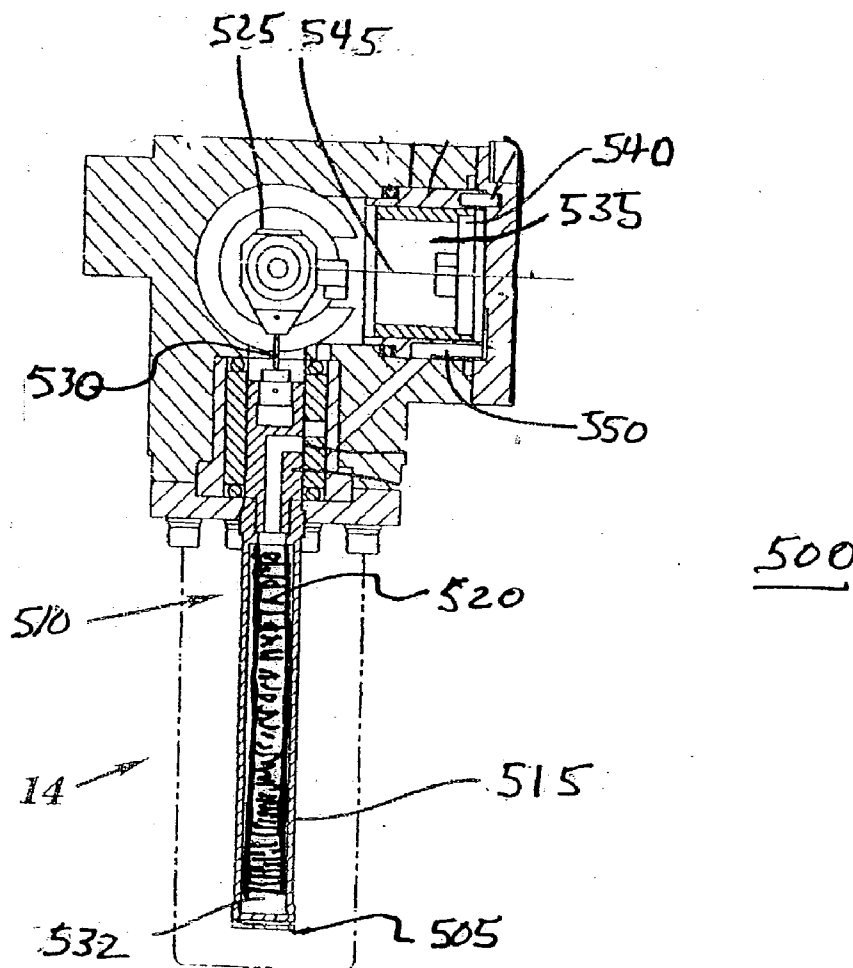
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(19) **United States**(12) **Patent Application Publication**  
Bin-Nun et al.(10) **Pub. No.: US 2004/0231340 A1**(43) **Pub. Date: Nov. 25, 2004**(54) **LOW COST HIGH PERFORMANCE  
LAMINATE MATRIX**(76) Inventors: **Uri Bin-Nun**, Keene, NH (US); **Daniel  
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F25B 9/00(52) **U.S. Cl.** ..... **62/6; 165/4**(57) **ABSTRACT**

A porous solid substrate suitable for forming heat exchange elements and method for fabricating the substrate are provided. The porous solid substrate is usable in a regenerator or heat exchanger for exchanging thermal energy with a fluid flowing through elements formed from the substrate. Elements formed from the substrate are especially suitable for use in a regenerator matrix used in deep refrigeration cryo-coolers based on the Stirling refrigeration cycle. The porous solid element substrate is formed from a plurality of thin screen sheets of interwoven stands of fine wire with each sheet having a thickness of substantially three times the diameter of the wire stands. Sheets are arranged one above another with surfaces of adjacent sheets in mechanical contact. The sheets sintered in a high temperature high-pressure environment to form a composite element having sintered contact points between adjacent sheets. The composite elements are more easily handled, less susceptible to damage during manufacturing and reduce the manufacturing cost of the heat exchanger.



# LOOSE MESH REGENERATOR

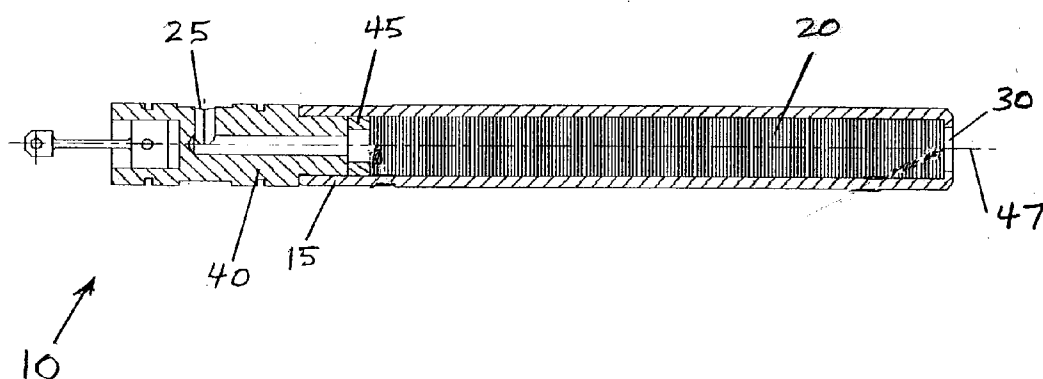


Figure 1

PRIOR ART

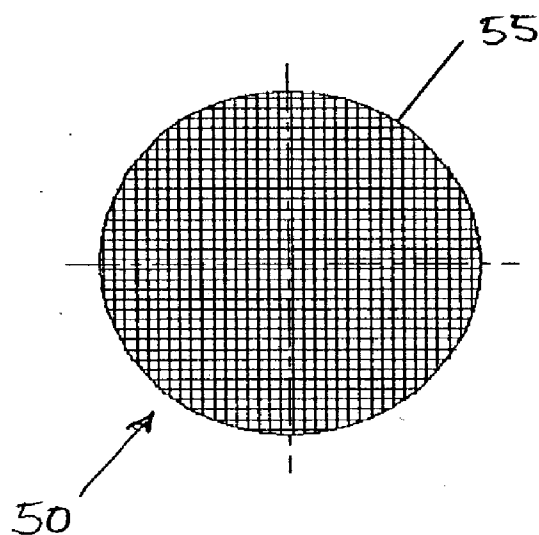
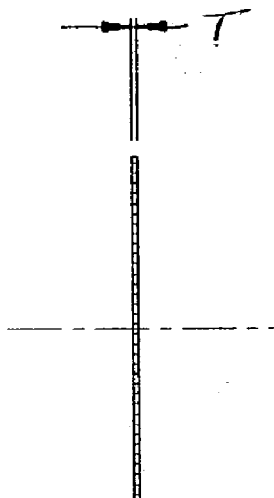


Figure 2A

Figure 2B

PRIOR ART

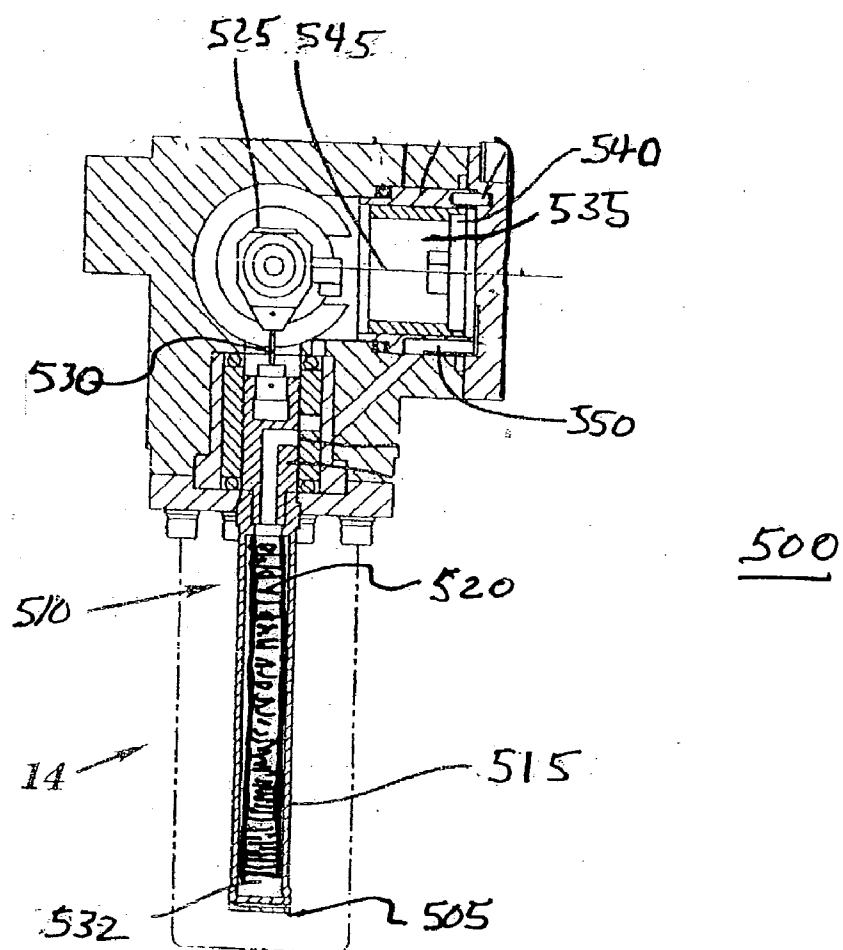


FIG. 3

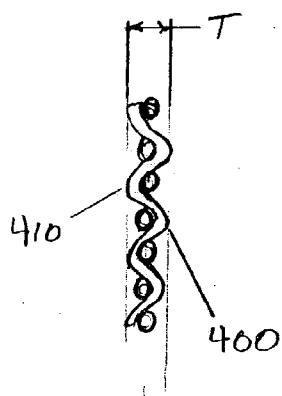


Figure 4A

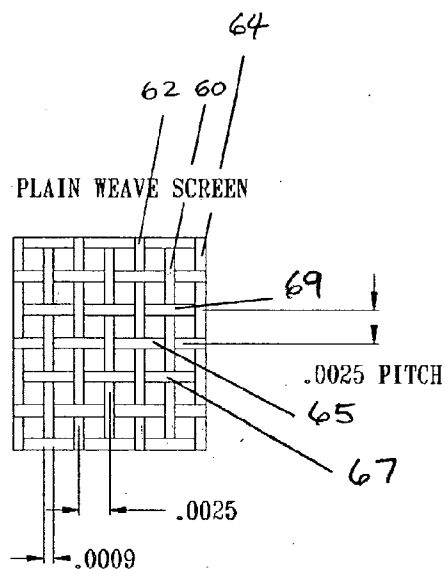


Figure 4B

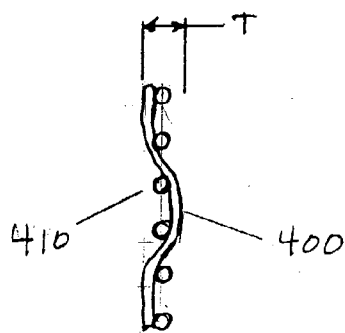


Figure 5A

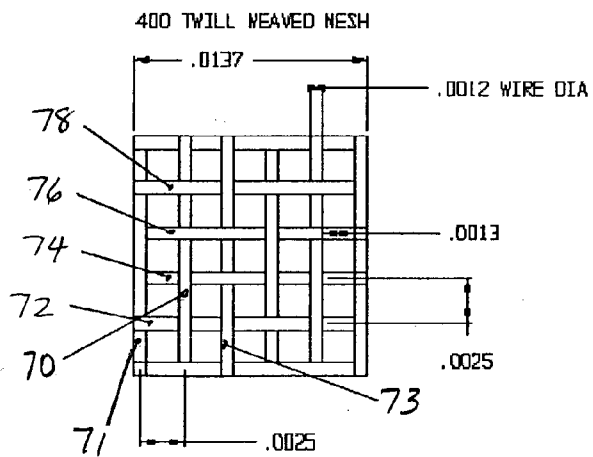


Figure 5B

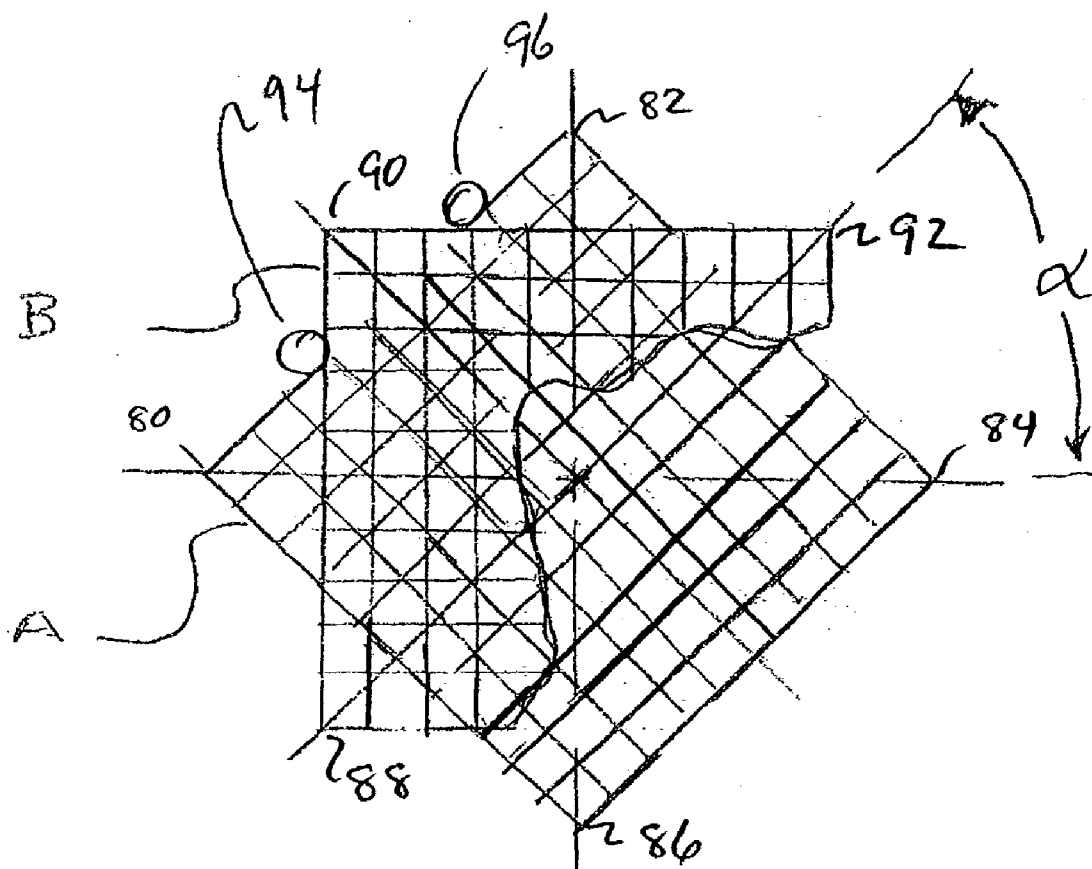


FIG 6

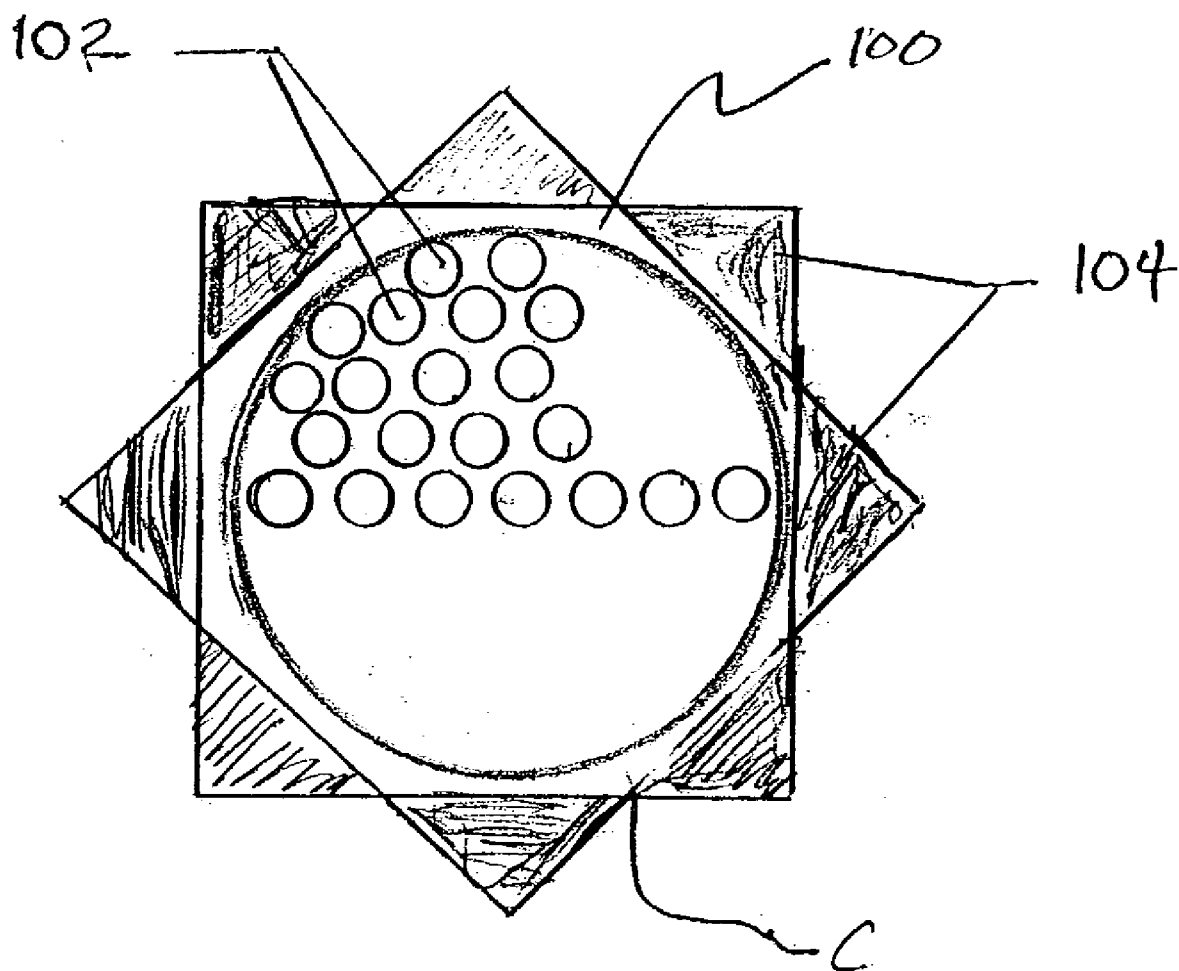


FIGURE 7

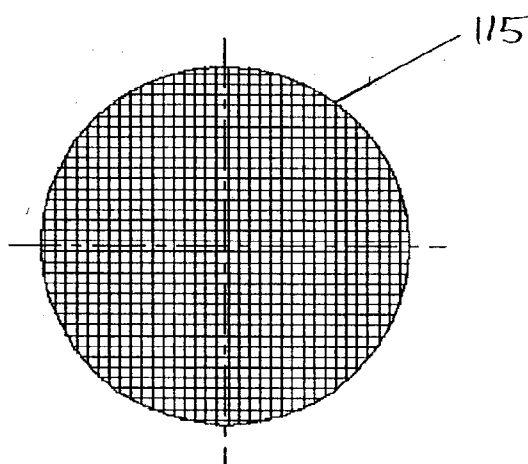
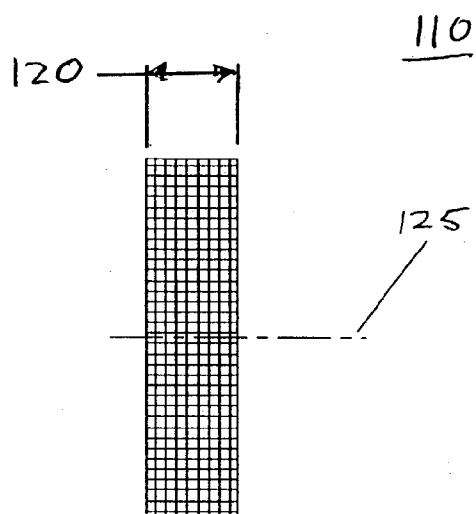


Figure 8A

Figure 8B



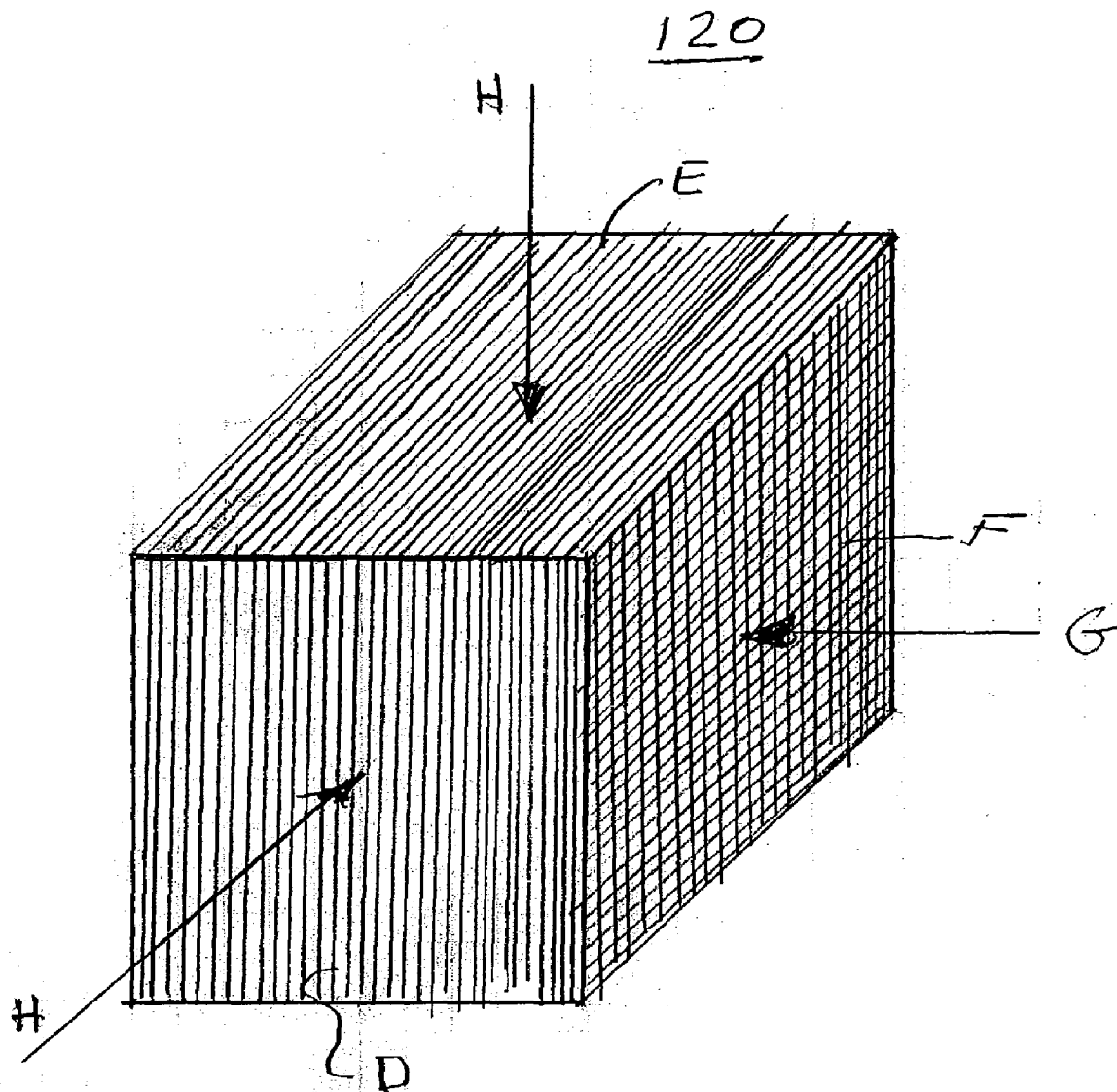


Figure 9

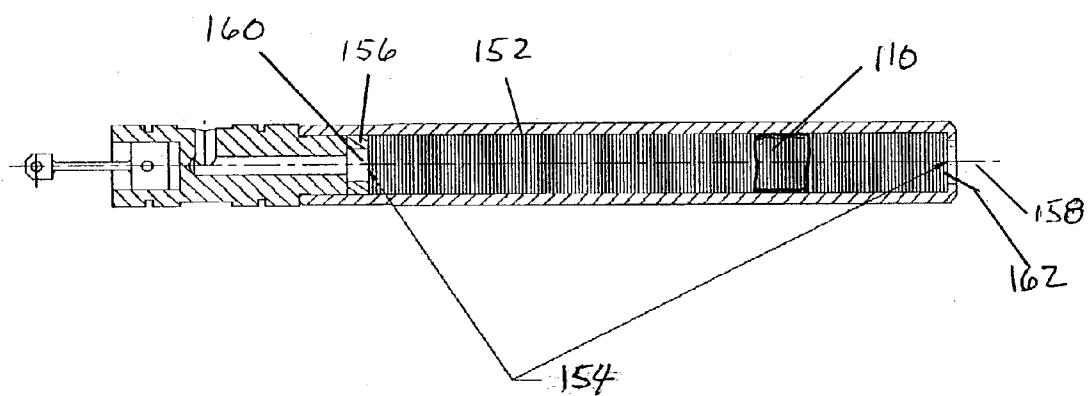


Figure 10

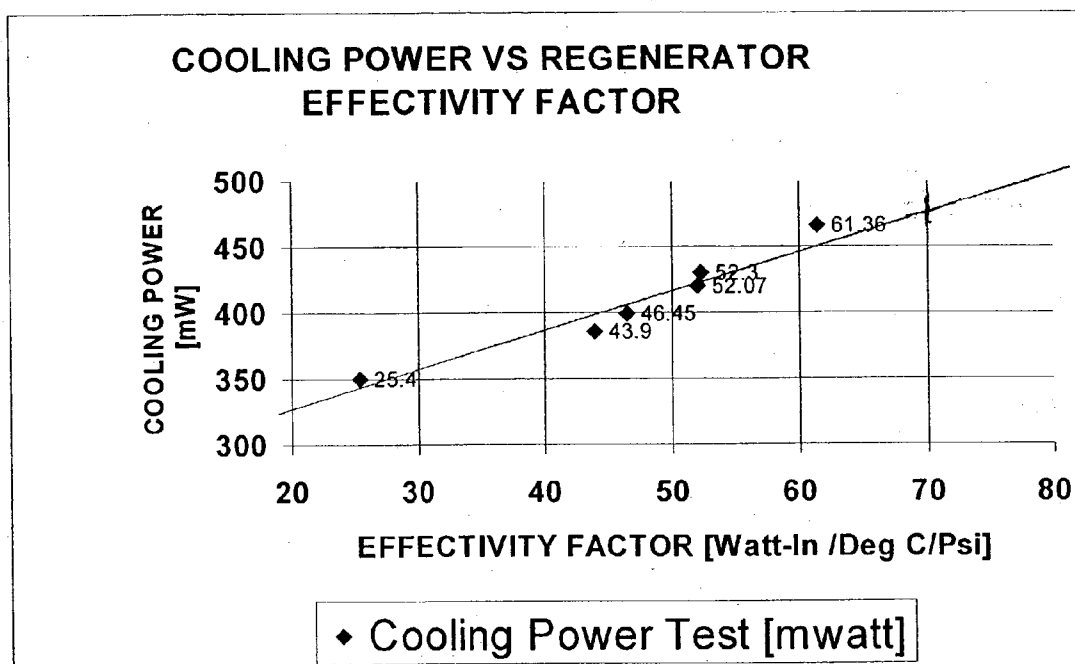


Figure 11

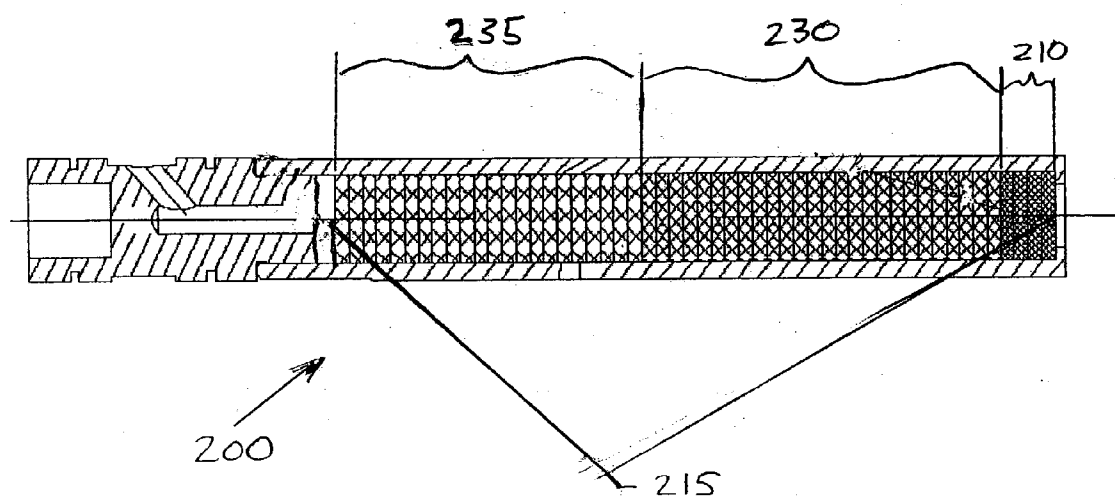


Figure 12

## LOW COST HIGH PERFORMANCE LAMINATE MATRIX

### BACKGROUND OF THE INVENTION

[0001] 1. Field of the invention

[0002] 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.

[0003] 2. 3.2 Description of Related Art

[0004] 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.

[0005] 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.

[0006] 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.

[0007] 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 shown, 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.

[0008] A conventional regulator heat-exchanging matrix 20 may comprise 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.

[0009] 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.

[0010] Applicants' have determined that the performance of a regenerator matrix behaves according to equation (1):

$$R_{pf} = \frac{A_s h}{\partial P / \partial X} \quad \text{Equation (1)}$$

Where:

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

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

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

$$\partial P / \partial X = \text{Pressure Drop per} \quad \text{psi/inch} \\ \text{Matrix Unit Length}$$

[0011] 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  $\partial P / \partial X$ . 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.

[0012] 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. 2A and 2B. 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. 2B, 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.

[0013] 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 made 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.

[0014] 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.

[0015] 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.

[0016] 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.

[0017] 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.

**[0018]** 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.

**[0019]** 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

**[0020]** The problems of the prior art described above are addressed by the present invention which, provides a porous heat exchange element for exchanging thermal energy with a fluid flowing through it. The heat exchange element is formed from a plurality of individual elements each having an external surface for exchanging thermal energy with the fluid. According to the invention, each of the plurality of individual elements joins at least one other of the plurality of individual elements by a sintered joint. The elements are arranged together in mechanical contact with one or more other elements such the external surfaces of the elements are in contact at a plurality of contacting points. With the elements held in the contacting arrangement, they are subjected to high pressure and temperature until a sintered joint is formed at the contact points, and the plurality of individual elements forms a single composite element. The form of the individual elements is selected to provide a composite element having sufficient exposed surface area for thermal energy exchange with the fluid and a void volume proximate to non-contacting points of the external surfaces. The void volume provides a path for the fluid to flow through and a mixing volume local to the surface area in which convective mixing occurs.

**[0021]** Individual elements in the form of a plurality of thin screen sheets of interwoven wire strands provide sufficient surface area and void volume for thermal energy exchange with a flow resistance consistent with the flow of a refrigeration gas, e.g. helium. The screen sheets have substantially opposing top and bottom external surfaces and a plurality of sheets are stacked together with the top and the bottom surfaces of alternating sheets in mating contact. The sheets are joined at contact points between the top and the bottom surfaces of alternating sheets by sintering to form a composite element. The composite element is sized and shaped for installation within a fluid conduit for exchanging

thermal energy with a fluid flowing through the conduit. Of course, other individual elements such loose material particles, loose wire strands or other individual element that can be arranged for providing a large surface area surrounded by void space may be used to form a porous element with sintered contact points.

**[0022]** Thin screen sheets may be woven with a plurality of substantially parallel first wire strands interwoven with a plurality of substantially parallel second wire strands with the first and second wire strands substantially perpendicular. Moreover, screens with a plain weave pattern and a twill weave pattern are suitable and other weave patterns are usable. In particular, screen sheets formed from round cross-section stainless steel wire strands with a diameter in the range of 0.0005-0.002 inches and interwoven with a mesh in the range of 10 to 2500 strands per inch are suitable for forming a composite element with good thermal exchange characteristics for refrigeration gases. In addition, various screen patterns and wire diameters are usable in a single composite element with more than one screen type be joined together to form a composite element.

**[0023]** The weave pattern of an individual element has an orientation and the thermal energy exchange and flow resistance of a composite element formed from a plurality of individual elements is dependent upon the orientation of the weave pattern of individual elements. Accordingly, the orientation of the weave pattern of individual elements is aligned along one or more axes before joining so that the composite element has a consistent flow and thermal energy exchange characteristic. In one example, alternating screens are oriented with the weave pattern orientation rotated by 45 degrees.

**[0024]** According to the invention, a heat exchange conduit is completely filled with a single composite element having a large number of individual screen sheets, e.g. 50 to 2000, or the conduit is completely filled with many composite elements formed from a small number of individual sheets, e.g. 2-100. In the latter case, thermal conduction along the direction of fluid flow is reduced and in a further embodiment is even further reduced by roughening the contacting surfaces of adjacent composite elements by sand-blasting the surfaces.

**[0025]** The invention further provides a method for exchanging thermal energy with a fluid flowing in a conduit by providing an energy exchange matrix with the conduit. The matrix is formed by providing individual elements with surface area for exchanging thermal energy with the fluid and a void volume proximate to the surface area, such as metal wire screens and arranging the individual elements to provide contacting points of the external surfaces of the elements and sintering the individual elements into contact to form a composite element. The composite element includes heat exchange surfaces proximate to void volume, which provides a path for the fluid to flow through, and a convective mixing volume. The composite element is then cut into on or more heat exchange elements sized and shaped to fill the conduit and the fluid is forced through the conduit and the void volume such that the fluid exchanges thermal energy with the composite element. The method may also include the steps of forming composite elements with a different fluid flow resistance characteristics and arranging composite elements in the tube in accordance with a local fluid viscosity in the tube.

[0026] The invention further includes a refrigeration unit for cyclically compressing and expanding a refrigeration gas in accordance with a Stirling cycle for cooling electronic devices and the like to cryogenic temperatures below about  $-130^{\circ}\text{C}$ . The refrigeration unit includes a compressor for compressing a refrigeration gas in a variable working volume and a hollow cylindrical cold well tube, which serves as a fluid conduit for the refrigeration gas. The cold well tube includes a sealed at a cold end to which is attached an element to be cooled. A heat exchanging regenerator piston is movably supported within the hollow portion of the cold well tube and provides an expansion space for expanding the refrigeration gas at the sealed cold end when the regenerator piston is partially withdrawn from the cold well tube. The regenerator piston includes a hollow regenerator tube filled with a regenerator matrix for exchanging thermal energy with the refrigeration gas as the gas flows through hollow portion of the regenerator piston at two times during the refrigeration cycle. According to the invention, at least a portion of the regenerator matrix comprises a plurality of individual screen elements sintered into physical contact and may further comprise composite elements having different flow resistance characteristics and that are placed in the regenerator tube in accordance with a local fluid viscosity within the regenerator tube.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0027] The present invention is particularly 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:

[0028] FIG. 1 depicts a conventional regenerator assembly.

[0029] FIG. 2A depicts a side view of a conventional individual regenerator screen element.

[0030] FIG. 2B depicts a front view of a conventional individual regenerator screen element.

[0031] FIG. 3 depicts a miniature Stirling cycle cryocooler according to the present invention.

[0032] FIG. 4A depicts a sectional view taken through the screen element of FIG. 4B.

[0033] FIG. 4B depicts details of an enlarged plan view of a thin screen element having a plain weave pattern of 400 MESH.

[0034] FIG. 5A depicts a sectional view taken through the screen element of FIG. 5B.

[0035] FIG. 5B depicts details of an enlarged plan view of a thin screen element having a twill weave pattern of 400 MESH.

[0036] FIG. 6 depicts stacked screen elements rotated by  $45$  degrees.

[0037] FIG. 7 depicts the usable region of the laminated substrate.

[0038] FIG. 8A depicts a side view of a laminated regenerator element according to the invention.

[0039] FIG. 8B depicts a front view of a laminated regenerator element according to the invention.

[0040] FIG. 9 depicts another embodiment of a laminated regenerator element according to the invention.

[0041] FIG. 10 depicts one example of a regenerator assembly according to the invention.

[0042] FIG. 11 depicts a graphic relationship between calculated regenerator performance coefficients and measured cooling performance.

[0043] FIG. 12 depicts a second example of a regenerator assembly according to the invention.

#### DETAILED DESCRIPTION OF THE INVENTION

[0044] 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  $135^{\circ}\text{K}$ . or more particularly to less than about  $80^{\circ}\text{K}$ . 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.

[0045] 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.

[0046] To illustrate the phases of the Stirling cycle is 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.

[0047] 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  $\epsilon$ .

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

[0048] In equation 2:

[0049]  $\Delta Q/Q_{ideal}$  is the ratio of the energy left in the refrigeration gas after it exits from the regenerator cold 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 exits 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,  $V_3$ .  $C_{p/Cv}$  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, ( $C_v$ ).

[0050] 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,  $\epsilon$ , 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.

[0051] According to the present invention, a process similar to conventional sintering fuses a plurality of individual porous screen elements together to form 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 is 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 parts can provide solid elements with characteristics that may not be achievable by other metal forming processes, e.g. porosity.

[0052] In one embodiment of the present invention, a plurality of sheets of wire screen mesh is contacted by sintering to form a regenerator element substrate. FIGS. 4A-5B 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.

[0053] FIGS. 4A and 4B 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. 4A 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.

[0054] FIGS. 5A and 5B 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. 5A 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.

[0055] 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 strands 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.

[0056] Regenerator screen elements formed with stainless steel wire, e.g. from **304** stainless steel wire, are preferred. Stainless steel is readily woven 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.

[0057] 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. 4A and 5A, 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.

[0058] 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  $\alpha$  with respect to the first axis and the mesh pattern of sheet A. In the preferred embodiment, the angle  $\alpha$  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 a previous sheet. In addition, the stack may comprise screen elements having different weave patterns and or wire diameters.

[0059] 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.

[0060] 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.

[0061] FIGS. 8A and 8B 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).

[0062] 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.

[0063] 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**.

[0064] 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.

[0065] **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 filled 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. 8A and 8B**. 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**.

[0066] 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**.

[0067] The most significant impact of a regenerator matrix comprising 47 sintered elements **10** 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%.

[0068] 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.

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

[0069] Where:

[0070]  $f$ =Friction Factor

[0071]  $\rho$ =Local Fluid Density

[0072]  $d_h$ =Hydraulic Diameter

[0073]  $u$ =Fluid Velocity

[0074] 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  $\rho$ , the fluid velocity  $u$ , the fluid viscosity  $\mu$  and the hydraulic diameter  $d_h$ .

$$f = 129/R_e + 2.91R_e^{-0.103} \quad \text{Equation (4)}$$

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

[0075] Where:  $\rho$ =Local Fluid Density

[0076]  $u$ =Fluid Velocity

[0077]  $d_h$ =Hydraulic Diameter

[0078]  $\mu$ =Viscosity

[0079] The hydraulic diameter, given in equation (6) below, depends on the porosity of the regenerator matrix  $\beta$ , as defined by the void volume to total volume ratio, and the diameter of the regenerator matrix screen wire  $d_w$ .

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

[0080] 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  $\beta$  and these two variables are completely determined by the screen characteristics. Values of  $d_h$ ,  $\beta d_w$  and  $\delta p / \delta x$  and the surface area  $A_s$  for ten regenerator screen configurations are calculated using equations 3-6 and are listed in TABLE 1.

[0081] Using equations (7) and (8), to calculate the convection coefficient  $h$  for the different screen configurations these values are also listed in TABLE 1.

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

[0082] Where:

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

[0083]  $k$ =Fluid Conductivity

[0084]  $d_h$ =Hydraulic Diameter

[0085]  $\beta$ =Porosity

[0086]  $P_e$ =Peclet Number, which is a function of the Reynolds number, fluid viscosity and specific heat of the fluid.

[0087] 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.

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 woven 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.

[0089] Tests performed to determine if actual regenerator performance agrees with the results predicted in TABLE 1 confirm agreement. Testing was performed using a 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.

TABLE 1

Regenerator Performance Factor vs. regenerator matrix configuration							
Matrix Configuration	$d_h$ [inch]	$\beta$	$d_w$ [inch]	$\partial p / \partial x$ [psi/inch]	$h$ , [Watt/in <sup>2</sup> /Deg C]	$A_s$ [in <sup>2</sup> ]	$R_{pf}$ 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

[0088] All calculations assume Helium as the refrigeration gas, 20 Deg C. as the rejection temperature  $T_2$ , and a flow velocity  $\mu$  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

[0090] 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

[0091] 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.

[0092] 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. 8A and 8B 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.

[0093] 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.

[0094] 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.

[0095] 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.

[0096] 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 sand-blasting to reduce conductive thermal energy flow along the matrix.

What I claim:

1. A heat exchange element for exchanging thermal energy with a fluid flowing there through comprising:

a plurality of individual elements each having an external surface for exchanging thermal energy with the fluid and wherein each of the plurality of individual elements is joined together with another of the plurality of individual elements by a sintered joint between contacting points of the external surfaces thereof for forming a composite element; and,

wherein the plurality of individual elements are formed to provide a void volume proximate to non-contacting points of the external surfaces, said void volume providing a path for the fluid to flow through and a convective mixing volume.

2. The heat exchange element of claim 1 wherein the plurality of individual elements comprises a plurality of thin screen sheets of interwoven wire strands with each of the sheets having substantially opposing top and bottom external surfaces, and wherein the sheets are stacked together with the top and the bottom surfaces of alternating sheets in mating contact and wherein the sheets are joined together at contact points formed between the top and the bottom surfaces of alternating sheets.

3. The heat exchange element of claim 2 wherein each of the thin screen sheets of interwoven wire strands comprises a plurality of substantially parallel first wire strands interwoven with a plurality of substantially parallel second wire strands.

4. The heat exchange element of claim 3 wherein the first wire strands and the second wire strands are substantially perpendicular.

5. The heat exchange element of claim 4 wherein the first and the second wire strands are interwoven in a plain pattern.

6. The heat exchange element of claim 4 wherein the first and the second wire strands are interwoven in a twill pattern.

7. The heat exchange element of claim 3 wherein the wire strands comprise metal wire strands.

8. The heat exchange element of claim 3 wherein the wire strands have a round cross-section.

9. The heat exchange element of claim 3 wherein the wire strands comprise stainless steel wire having a round cross-section.

10. The heat exchange element of claim 8 wherein the wire strands have a diameter in the range of 0.0005-0.002 inches.

11. The heat exchange element of claim 10 wherein said first and second wire strands are interwoven with a mesh in the range of 10 to 250 strands per inch.

12. The heat exchange element of claim 11 wherein said first and second wire strands are interwoven with the same mesh.

13. The heat exchange element of claim 11 wherein said first and second wire strands are interwoven with a different mesh.

14. The heat exchange element of claim 1 wherein each of plurality of individual elements is substantially identical.

15. The heat exchange element of claim 1 wherein each of the plurality of individual elements has a characteristic orientation that relates to the performance of the element for one of exchanging thermal energy with the fluid and providing flow resistance to the fluid and wherein the characteristic orientation of each of the plurality of elements is aligned along a desired axis.

16. The heat exchange element of claim 2 wherein the plurality of individual thin screen sheets comprises less than 25 substantially identical screen sheets formed from stainless steel wire having a round cross-section with a diameter in the range of 0.0005-0.002 inches and interwoven with a mesh in the range of 200-400 wire strands per inch.

17. The heat exchange element of claim 2 wherein each of the plurality of screen sheets has a characteristic orientation defined by a weave pattern and wherein the characteristic orientation affects the performance of the element for one of exchanging thermal energy with the fluid and providing flow resistance to the fluid and wherein the characteristic orientation of each of the plurality of elements is aligned along a first desired axis.

18. The heat exchange element of claim 2 wherein each of the plurality of screen sheets has a characteristic orientation defined by a weave pattern and wherein alternating sheets are stacked together with the characteristic orientation aligned along a first desired axis and a second desired axis separated from the first desired axis by an angle  $\alpha$ .

19. The heat exchange element of claim 18 wherein the angle  $\alpha$  is 45 degrees.

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

a hollow conduit for confining fluid flow therein;

a thermal energy exchange matrix contained within the hollow conduit for exchanging thermal energy with the fluid, said thermal energy exchange matrix comprising;

a plurality of individual elements each having an external surface for exchanging thermal energy with the fluid and wherein each of the plurality of individual elements is joined together with another of the plurality of individual elements by a sintered joint between contacting points of the external surfaces thereof for forming a composite element; and,

wherein the plurality of individual elements are formed to provide a void volume proximate to non-contacting points of the external surfaces, said void volume providing a path for the fluid to flow through and a convective mixing volume.

21. The thermal energy exchange apparatus of claim 20 wherein the number of individual elements is selected to provide one composite element filling the hollow conduit.

22. The thermal energy exchange apparatus of claim 20 wherein the number of individual elements is selected to provide a plurality of separate composite elements stacked together to substantially fill the hollow conduit.

23. The thermal energy exchange apparatus of claim 22 wherein each of the plurality of separate composite elements is substantially identical.

24. The thermal energy exchange apparatus of claim 20 wherein each of the plurality of individual elements has a characteristic surface area and a characteristic void volume that affect the thermal energy exchange characteristic and the flow resistance of the composite element formed thereby and wherein the thermal energy exchange matrix comprises a plurality of composite elements and wherein at least a portion of the composite elements comprises individual elements having a different characteristic surface area and a different characteristic void volume.

25. The thermal energy exchange apparatus of claim 24 wherein the flow resistance of each composite element is selected in accordance with a local viscosity of the fluid within the conduit.

26. The thermal energy exchange apparatus of claim 22 wherein:

each of the plurality of composite elements is formed with less than 20 substantially identical individual screen elements; and,

each of the individual screens comprises interwoven round stainless steel wire strands having a diameter in the range of 0.0005-0.002 inches and a mesh in the range of 200-400 wire strands per inch.

27. The thermal energy exchange apparatus of claim 22 wherein:

the hollow conduit comprises a cylindrical element with an inside tube diameter of less than 0.25 inches; and,

wherein each of the plurality of composite elements are cylindrical with an outside diameter sized to provide a slight clearance fit with the inside diameter of the tube and wherein each of the plurality of individual elements joined together to form each composite element comprises a screen formed from interwoven stainless steel wire strands having a round cross-section with a diameter of less than 0.002 inches, said screens each having a substantially identical weave pattern of parallel first wire strands interwoven with parallel second wire strands, with said first and said second wire strands being substantially perpendicular, and with said first and said second wire strands having a mesh of more than 100 wires per inch.

28. A method for exchanging thermal energy with a fluid flowing in a conduit comprising:

forming a plurality of individual elements with surface area for exchanging thermal energy with the fluid and void volume proximate to the surface area;

arranging each of the plurality of individual elements in a position for contacting at least one other of the plurality of individual elements at contacting points of the surface area thereof;

sintering the individual elements into contact thereby forming a composite element comprising all of the plurality of individual elements, said composite element comprising a void volume proximate to non-

contacting points of the surface area, said void volume providing a path for the fluid to flow through and a convective mixing volume;

forming the composite element to a shape and size for installation within the conduit; and,

forcing the fluid through the conduit and the void volume such that the fluid exchanges thermal energy with the composite element.

29. The method of claim 28 wherein the composite element size and shape are selected to substantially fill the conduit with one composite element.

30. The method of claim 28 wherein the composite element size and shape are selected to substantially fill the conduit with a stack of a plurality of composite elements.

31. The method of claim 30 further comprising the steps of:

forming a plurality of types of composite elements each with a different fluid flow resistance; and,

arranging the types of composite elements in the tube in accordance with a local fluid viscosity in the tube.

32. The method of claim 30 further comprising the step of roughening contacting surfaces of each of the plurality of composite elements in the stack to increase conductive thermal resistance between adjacent elements in the stack.

33. A refrigeration unit for cyclically compressing and expanding a refrigeration gas in accordance with a Stirling cycle comprising:

a compressor for providing a variable working volume within a compression cylinder thereof for compressing the refrigeration gas therein;

a hollow cylindrical cold well tube in fluid communication with the compression cylinder, said cold well tube being sealed at a cold end thereof;

a regenerator piston movably supported within the hollow portion of the cold well tube for providing an expansion space for expanding the refrigeration gas at said sealed cold end in response to partially withdrawing the regenerator piston from the cold well tube, said regenerator piston comprising a hollow regenerator tube filled with a regenerator matrix for exchanging thermal energy with the refrigeration gas as the gas flows through hollow portion of the regenerator piston; and,

wherein at least a portion of the regenerator matrix comprises a plurality of individual screen elements sintered into physical contact to form a composite element.

34. The refrigeration unit of claim 33 wherein the composite element comprises less than 25 substantially identical individual screen elements comprising stainless steel wire having a round cross-section with a diameter in the range of 0.0005-0.002 inches and interwoven with a mesh in the range of 200-400 wire strands per inch.

35. The refrigeration unit of claim 33 wherein composite element types having different flow resistance characteristics are formed using different individual screen elements and further wherein the flow resistance of a portion of the plurality of composite elements is selected in accordance with a local fluid viscosity within the regenerator tube.