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Hill et al.

[11] **3,889,744**
[45] **June 17, 1975**

[54] **RECUPERATOR STRUCTURES AND METHOD OF MAKING SAME**

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[73] Assignee: **Owens-Illinois, Inc.,** Toledo, Ohio

[22] Filed: **Apr. 20, 1972**

[21] Appl. No.: **245,933**

[52] **U.S. Cl.** **165/83;** 165/165
[51] **Int. Cl.** **F28f 21/04**
[58] **Field of Search** 165/165, 83, 82, 81, 166; 432/179

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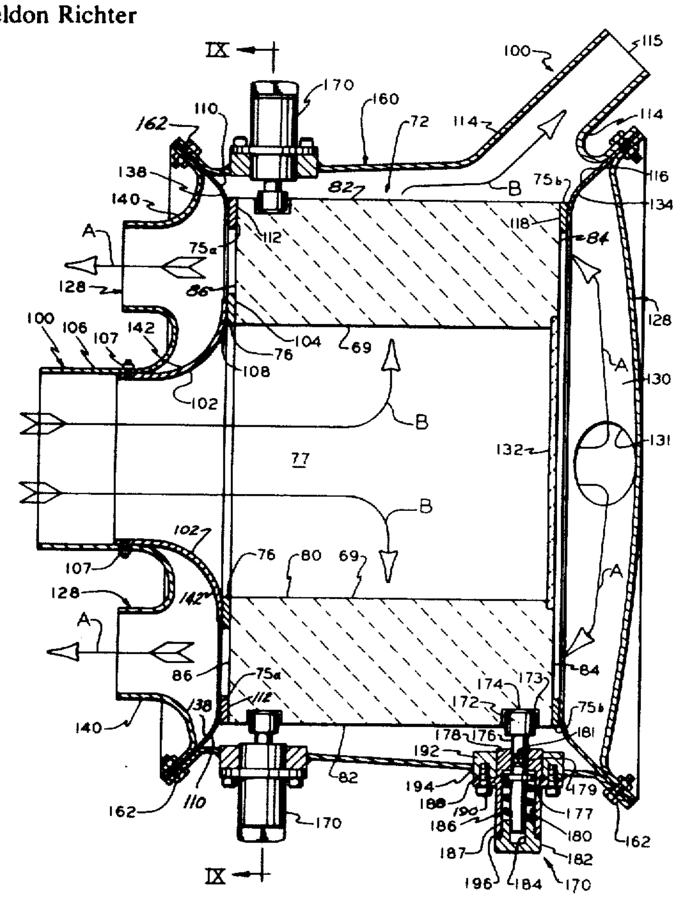
Primary Examiner—Albert W. Davis, Jr.
Assistant Examiner—Sheldon Richter

[57] **ABSTRACT**

In an embodiment disclosed herein there is illustrated a recuperator structure which includes housing apparatus for yieldingly supporting and protecting from mechanical shock a recuperator body constructed from glass-ceramic material, and for maintaining inlets and outlets of a first and second series of recuperator heat exchange passageways into the recuperator body in an alignment for connection with first and second ductwork means for delivering and collecting first and second fluids to the first and second series of passageways, respectively. The housing may include an outer shell and a plurality of support member means extending inwardly from the outer shell for yieldably contacting and supporting the recuperator body in a relatively stationary position within and with respect to the shell. The ductwork includes means for channeling a fluid to and collecting the fluid from one of the series of passageways, sealing means for disposition around the inlet and outlet openings of that series of passageways, and means for yeidlingly urging inlet and outlet wall portions of the ductwork means into sealing engagement with the sealing means. The entire structure thus enables an expansion and contraction of inlet and outlet wall portions of ductwork and other components while maintaining sealing contact with a glass-ceramic body utilized for effecting heat exchange between two fluids.

19 Claims, 18 Drawing Figures



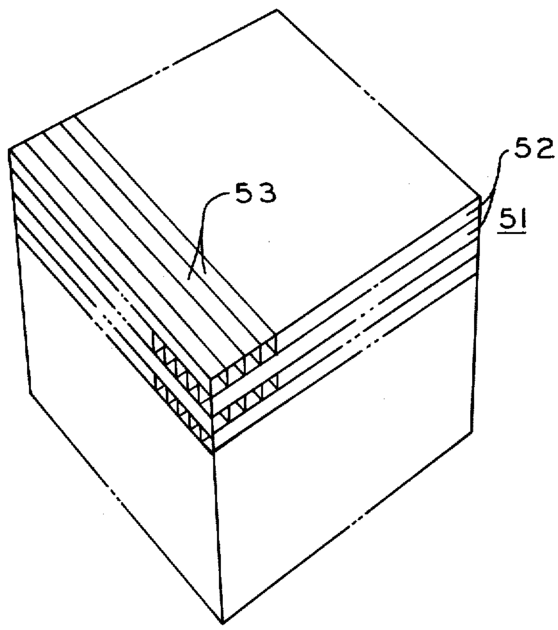


FIG. 1

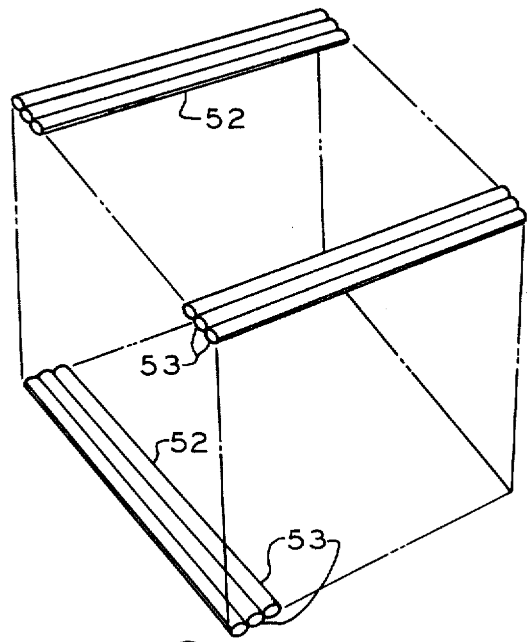


FIG. 2

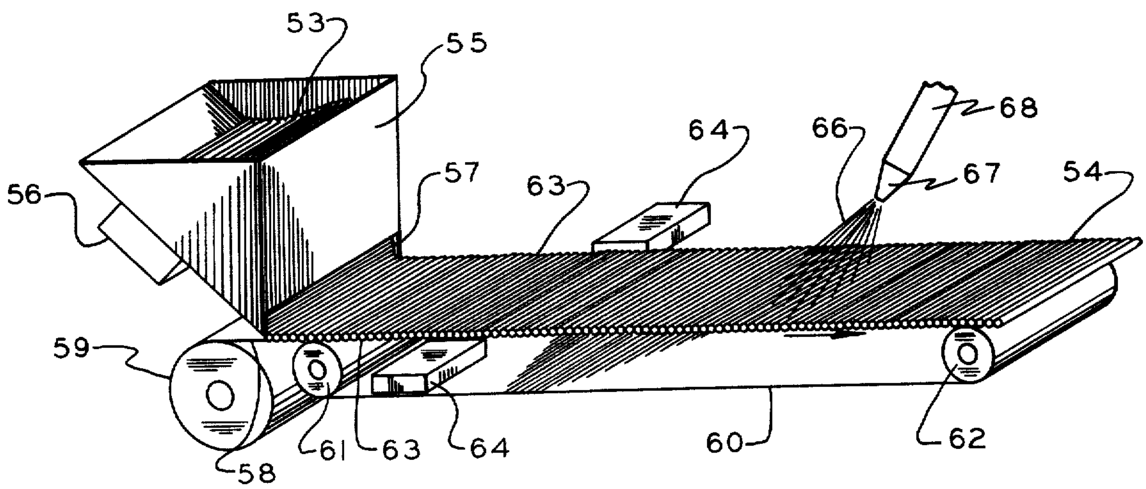


FIG. 3

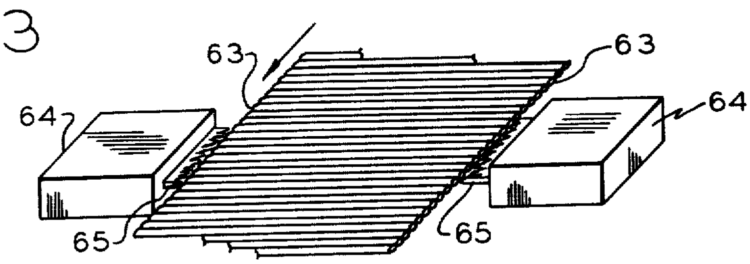


FIG. 4

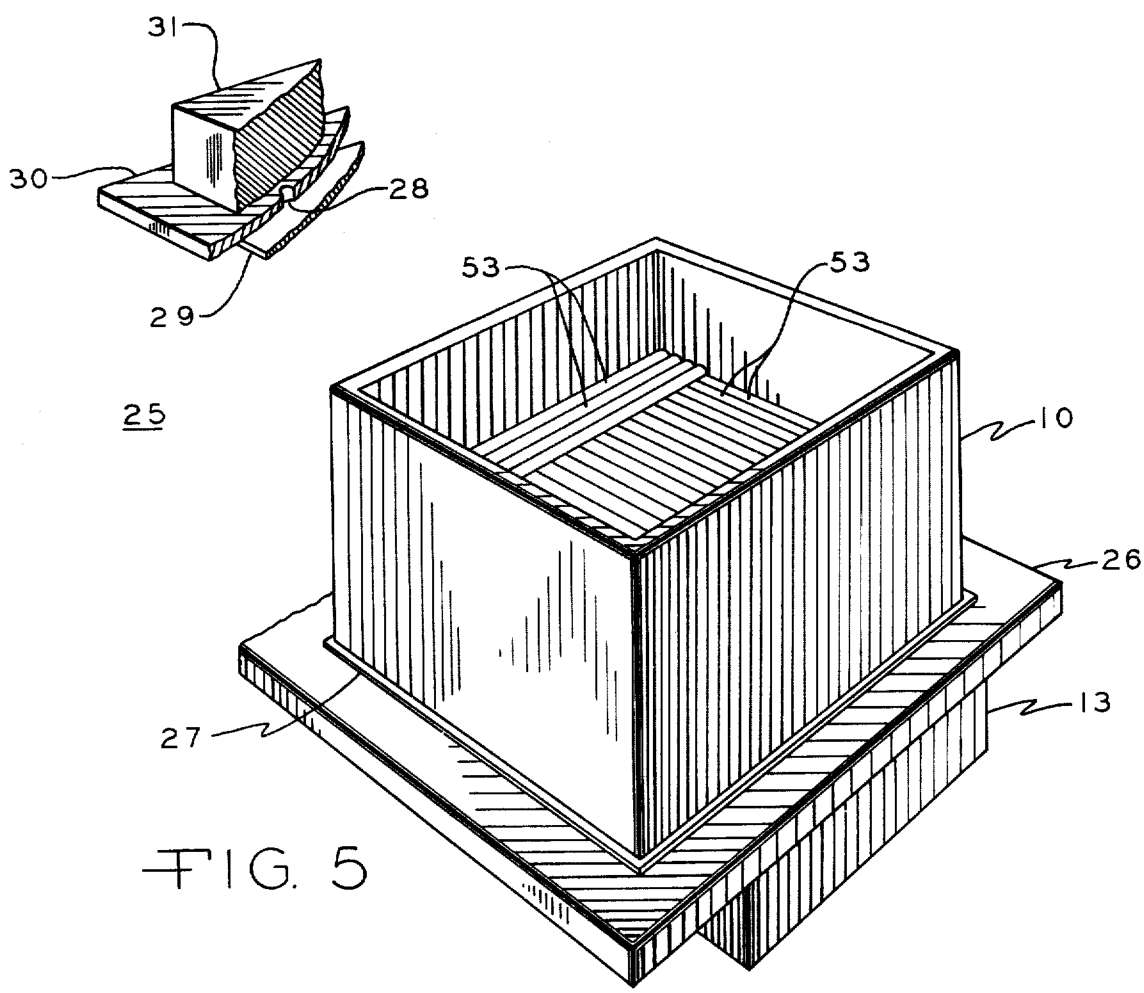

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FIG. 5

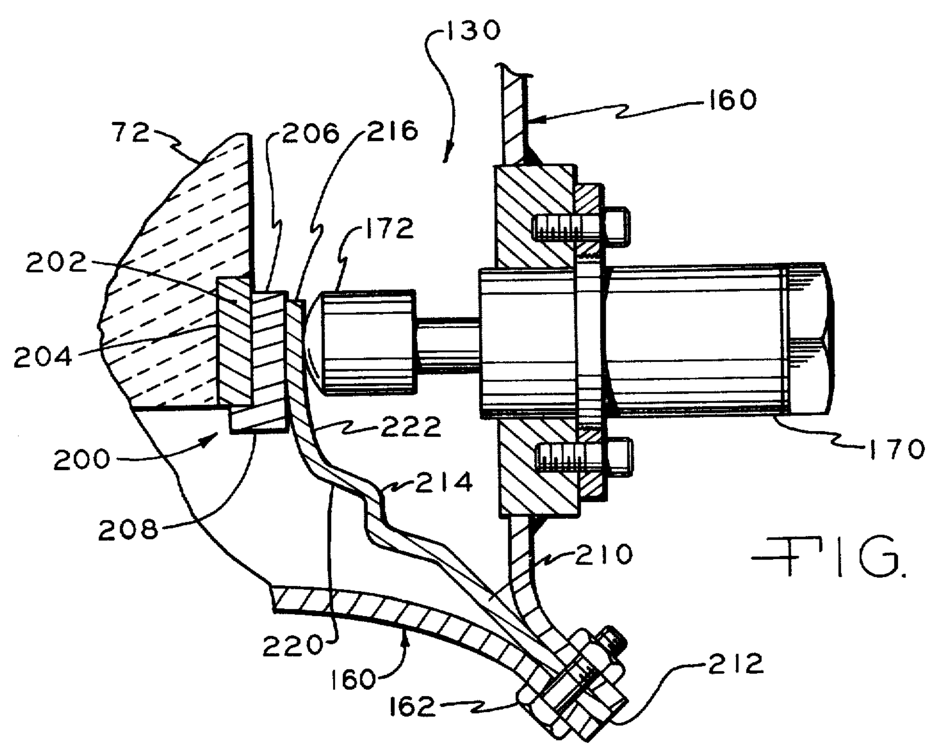
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FIG. 10

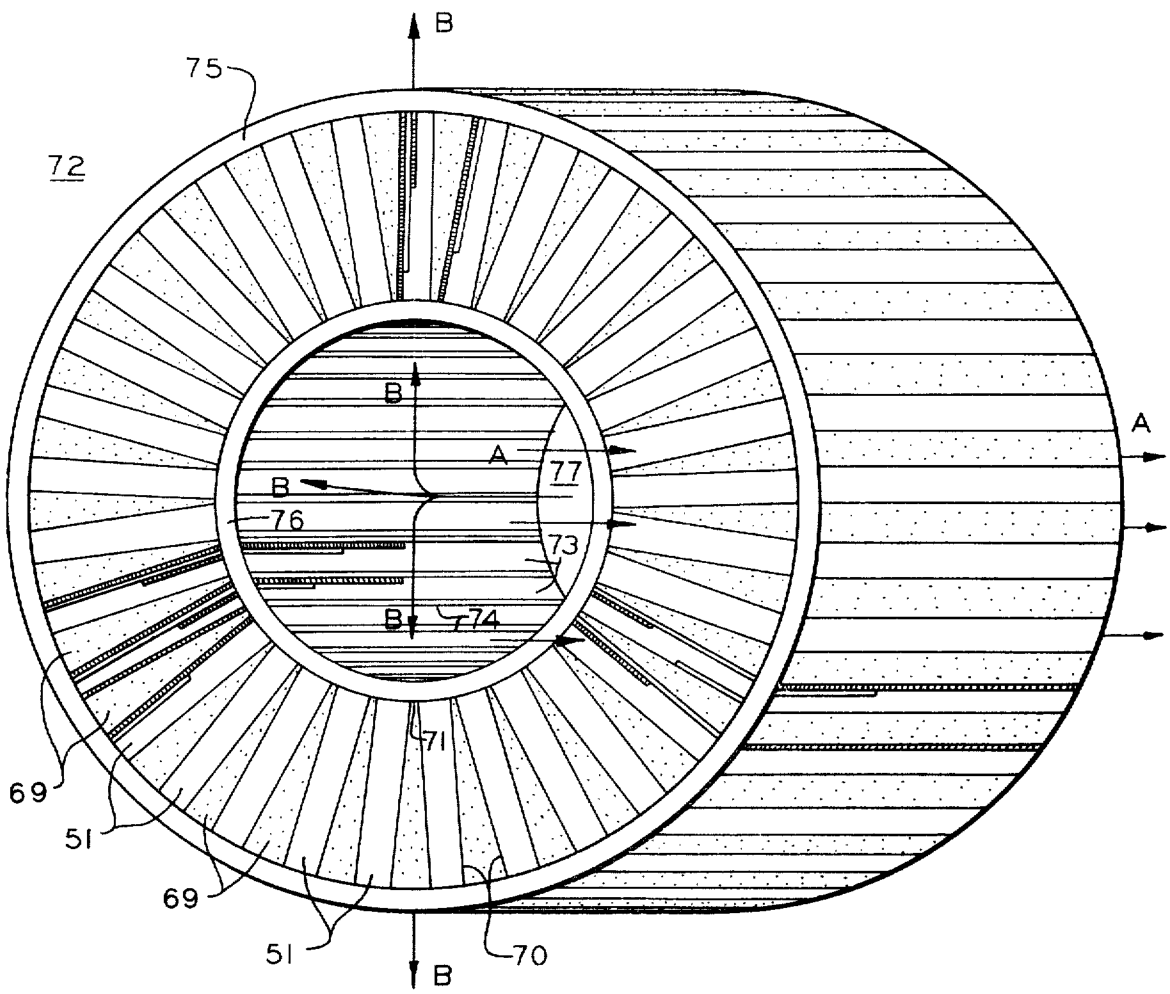

FIG. 6

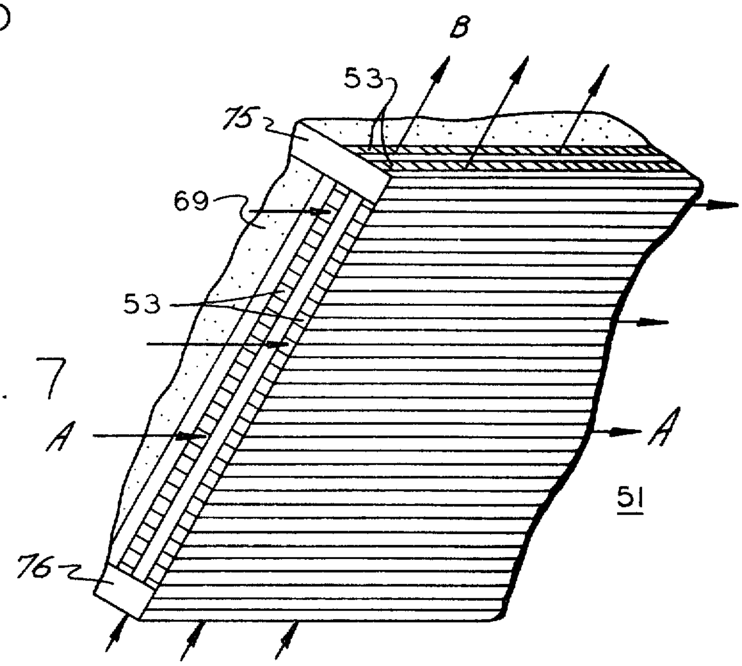

FIG. 7

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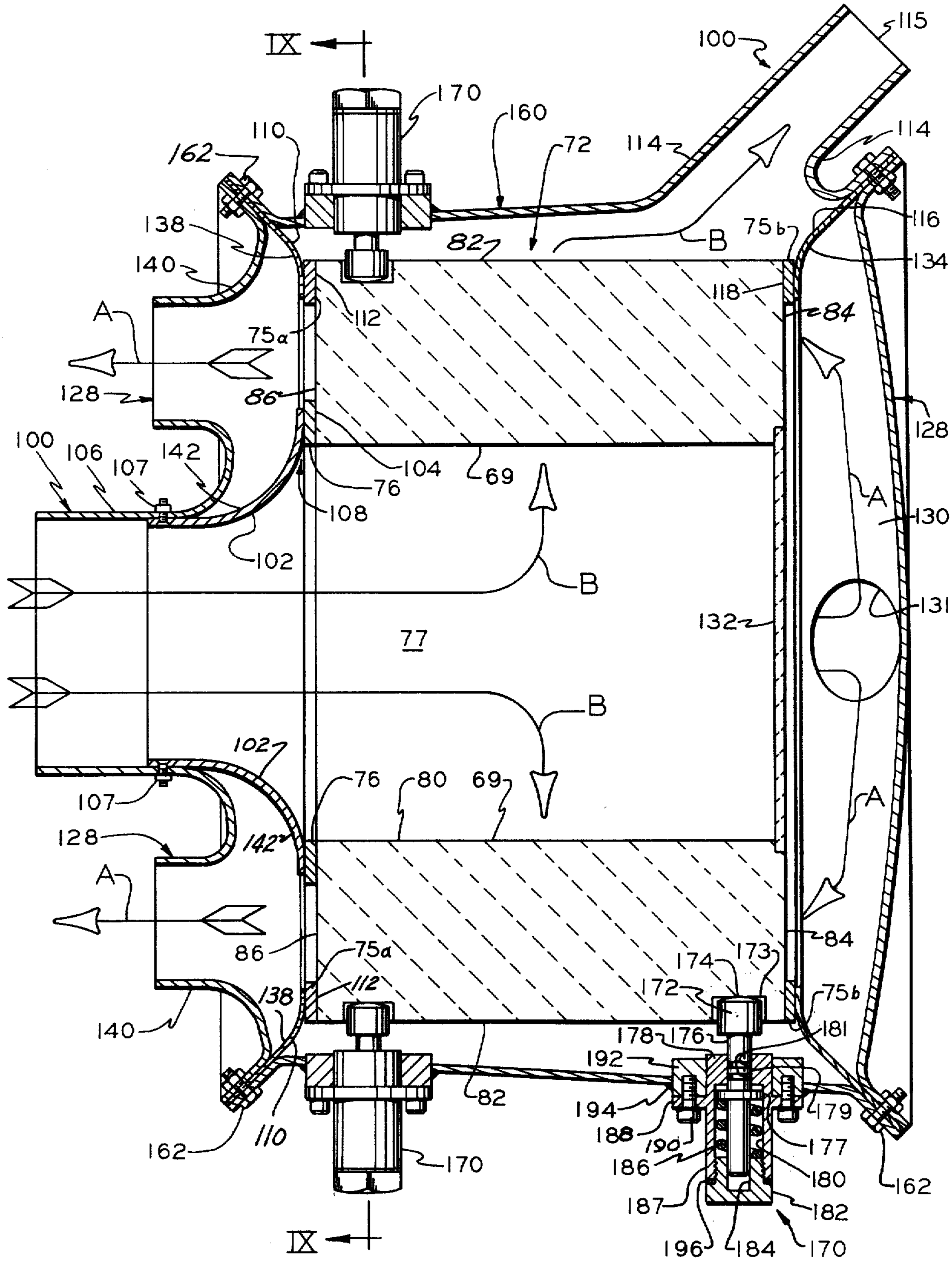


FIG. 8

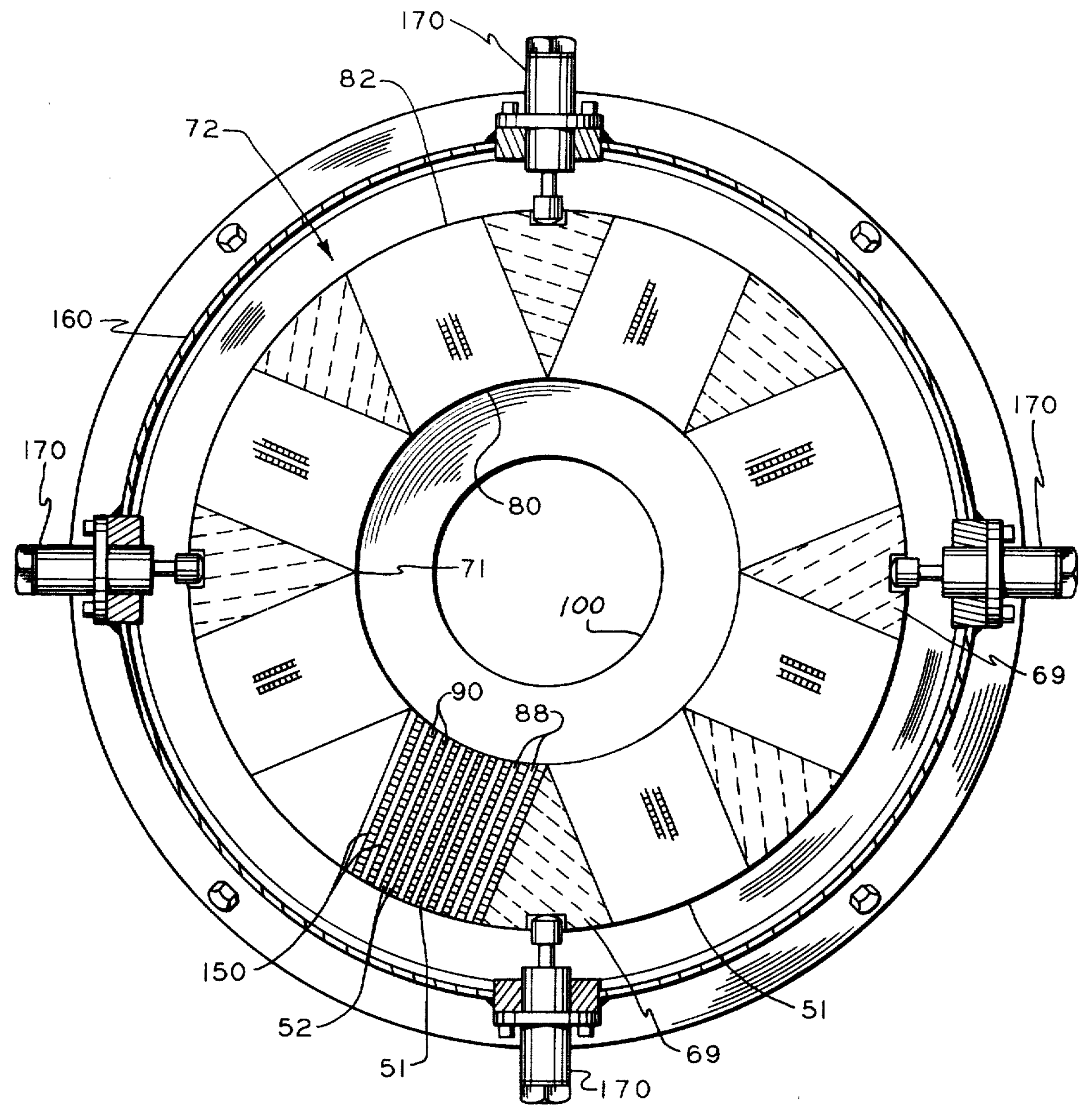


FIG. 9

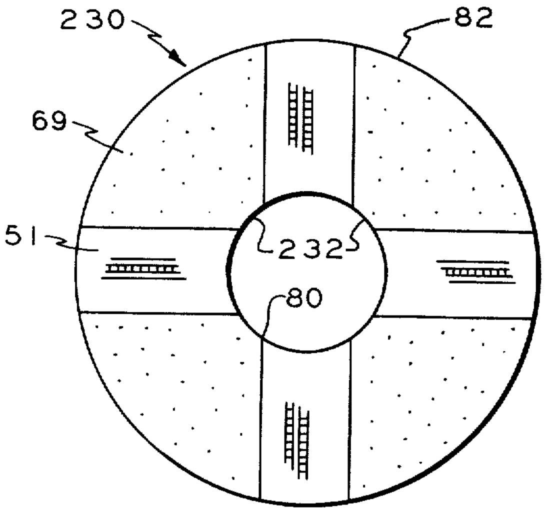


FIG. 11

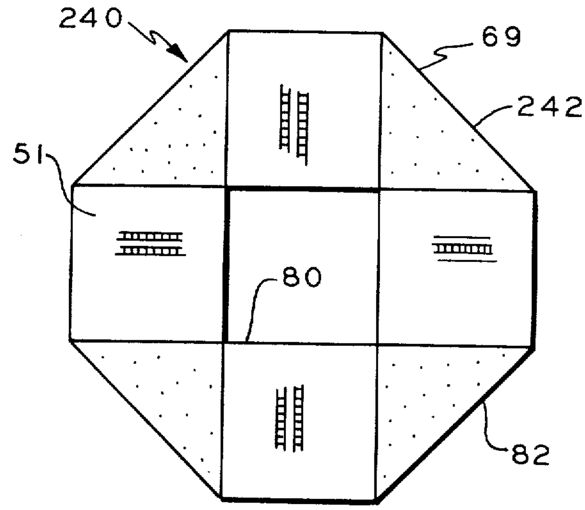


FIG. 12

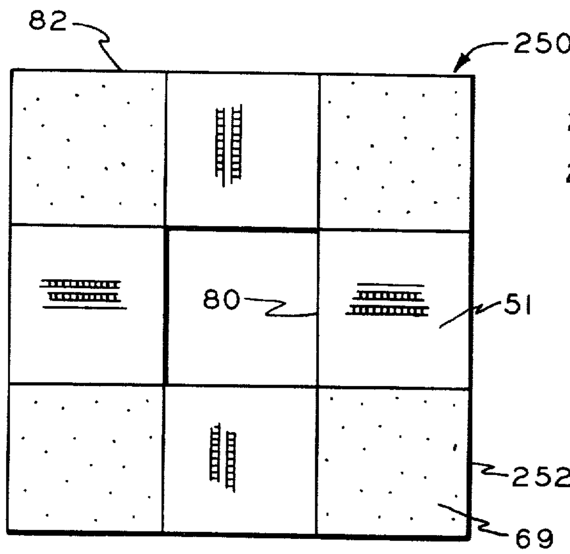


FIG. 13

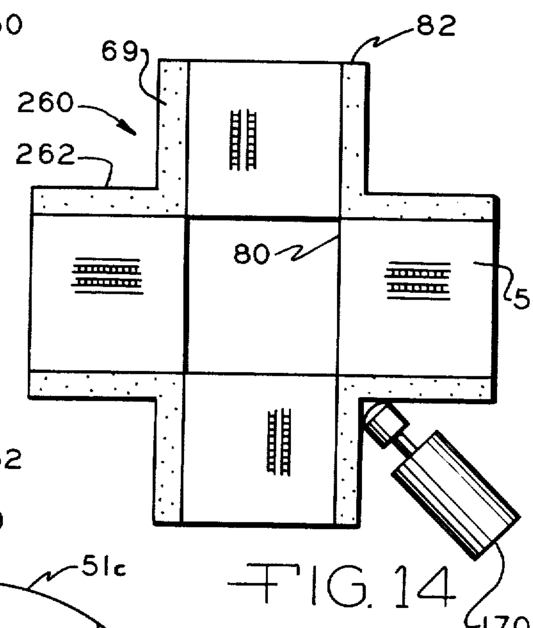


FIG. 14

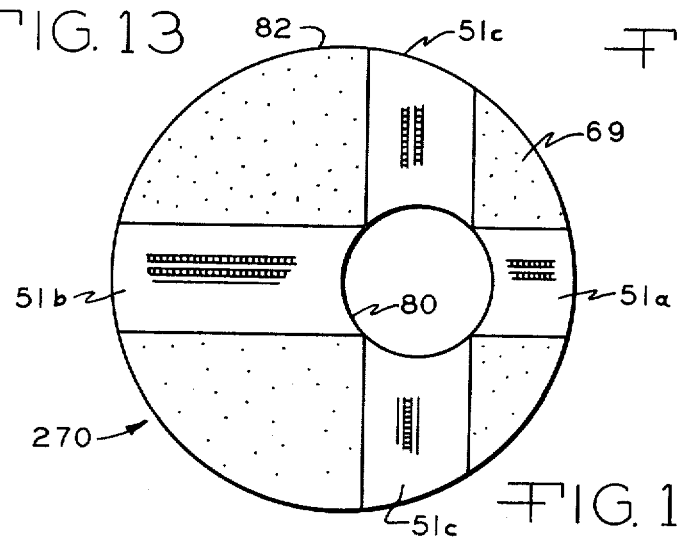


FIG. 15

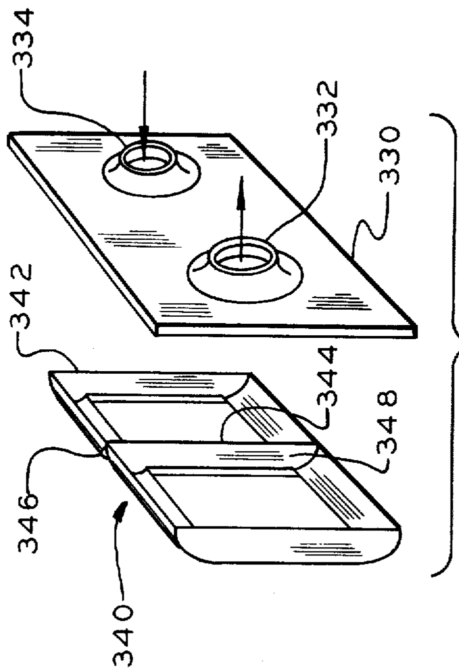
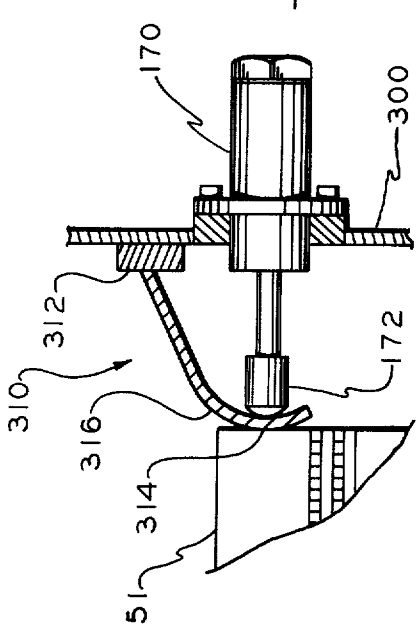


FIG. 18

FIG. 17



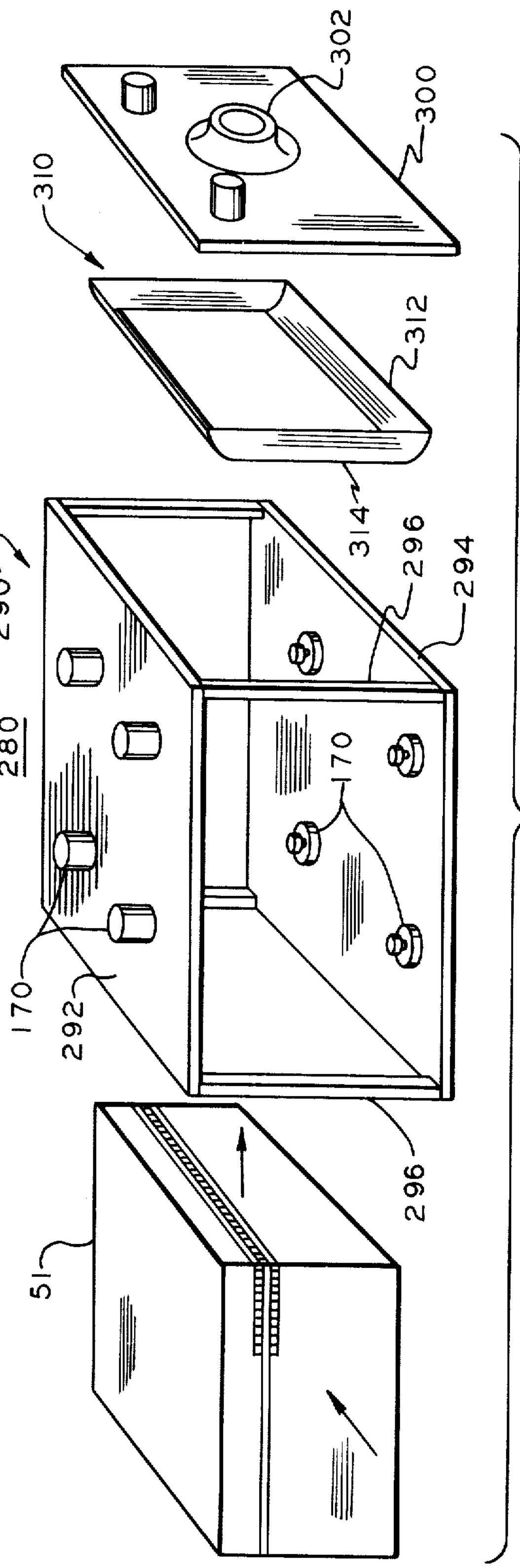


FIG. 16

RECUPERATOR STRUCTURES AND METHOD OF MAKING SAME

BACKGROUND OF THE INVENTION

This invention is illustrated in a combination with a heat exchange structure which utilizes a matrix module disclosed in the application of Y. K. Pei, Ser. No. 30,859, filed in the United States Patent Office on Apr. 22, 1970, and assigned to the assignee of the present invention.

In the above-noted application of Pei, there is disclosed a matrix module which is constructed by superimposing a plurality of layers of tubes, one layer above the other in successive parallel planes, with the tubes in each plane being essentially parallel to each other and transverse to the tubes in at least one of the adjacent layers. The matrix of tubes, each of the tubes having both ends sealed, is heated to soften, expand and fuse the tubes. The sealed ends are opened and a plurality of such matrices may be assembled into a toroidally-shaped structure, each matrix being separated from an adjacent matrices by a wedge-shaped member. The advantages of this heat exchange structure and the requirements for structures of this type are set forth fully in the Pei application and need not be repeated here.

The complete recuperator structure illustrated herein for obtaining a heat exchange between intake and exhaust gases has many advantages over the metal or ceramic recuperators of the prior art. Recuperators constructed entirely of metal have usually been made of nickel alloy which is expensive and difficult to shape and braze. Such recuperators often leak after repeated cycling. Recuperators have also been made of corrugated sheets of ceramic which are stacked to form a cross flow pattern and then sintered. However, it is difficult to make the joints of these prior art recuperators and failure of recuperators usually occurs in these areas. Heat-resistant materials used in the prior art recuperator bodies are expensive and often fail in thermal fatigue, while sintered ceramic recuperators are undesirably porous. The heat exchange body utilized in the structure herein is nonporous, has a very low expansion coefficient, and is not subject to thermal fatigue or to weaknesses at the joints.

However difficulties have arisen in centering and supporting glass-ceramic heat exchange bodies, in separating the two gas streams fed to the recuperator body for heat exchange, in maintaining seals with the low expansion or zero-expansion glass-ceramic body with fluid directing and collecting ductworks which have larger expansion coefficients, and in effecting and maintaining the seals required.

Accordingly, it is an object of this invention to provide a complete recuperator structure of superior properties, and particularly a recuperator structure which utilizes a low expansion heat exchange body such as made from glass-ceramic materials, which does not have the deficiencies of previous regenerator structures.

It is another object of this invention to provide an improved method and apparatus for centering and supporting a heat exchanging body or a plurality of such bodies in a recuperator chamber.

A still further object of this invention is to provide an improved method and apparatus for conducting fluids to the heat exchange passageways of the recuperator bodies, keeping the fluid streams separated, and maintaining seals between the ductwork directing the flow of the gas streams and the heat exchange body.

It is a still further object of this invention to provide centering and supporting means for a heat exchange body in a recuperator structure wherein the performance of the centering and supporting means is not impaired by temperatures or other deleterious characteristics of the fluids being channeled in heat exchange relationship with each other.

SUMMARY OF THE INVENTION

The above objects of this invention are illustrated in an embodiment herein which features a heat exchanging body having an internal surface defining an inner chamber formed in the body, a peripheral surface spaced outwardly from the internal surface, and spaced end surfaces connecting the internal and peripheral surfaces. The heat exchanging body includes a portion in which a first and a second series of longitudinal passageways are formed therethrough. The passageways of the first series extend and enable passage of a first fluid between the internal and peripheral surfaces. The passageways of the second series extend and enable passage of a second fluid between the two end surfaces. The walls of the first and second series of passageways are disposed in heat transmitting relationship with each other enabling a heat exchange between the first and second fluids passing through the first and second series of passageways.

First ductwork means are provided for channeling the first fluid to one of the inner chamber and peripheral surfaces and collecting the first fluid as it issues from the other of the inner and peripheral surfaces. Second ductwork means are provided for channeling a second fluid to one of the end surfaces and collecting the second fluid as it issues from the other of the end surfaces.

A housing means is shown which surrounds and supports the heat exchanger body in a substantially stationary position during relative expansion and contraction movements of components of the apparatus, to aid in maintaining inlets and outlets of the first and second series of passageways positioned for connection with the first and second ductwork means. The housing means may include an outer shell and a plurality of yieldable support member means extending between the outer shell and the recuperator body.

Each of the yieldable support member means may include a contact element extending toward and contacting the heat exchanging body, the contact element having a rod shaped portion. A cylinder is attached to the outer shell for slidably receiving the rod shaped portion of the contact element. Means associated with the cylinder yieldingly urges the rod portion, and thus the contact element, into supporting contact with the heat exchanging body. The yieldingly urging means advantageously comprises a spring means disposed in the cylinder. The portion of the cylinder which contains the spring means is advantageously located outside of the housing to remove the spring means from the direct influence of temperatures within the housing. Sealing means are advantageously disposed between the rod portion and the cylinder slidably receiving the rod portion to prevent penetration of fluids from in the housing into the portion of the cylinder which contains the spring means to prevent a deterioration of spring performance. Means are also provided for adjusting the force that the spring means exerts on the rod portion of the contact element.

The first ductwork means may include a first wall portion surrounding an inner chamber opening, which is adjacent to an end surface of the heat exchanging body, and extending between a perimetrical area adjacent the chamber opening and a continuation of the first ductwork means. A sealing means is provided between the first wall portion and the perimetrical area adjacent the inner chamber opening. Means are further provided for maintaining the first wall portion in contact with the sealing means. For example, the first wall portion may be constructed from spring material and connected between the first ductwork continuance and the sealing means in a flexed condition to maintain contact with the sealing means.

The sealing means may include a metal seal member having a configuration which covers the perimetrical area adjacent the inner chamber opening and may further advantageously include a high-temperature resistant, resilient gasket means interposed between the metal seal and the perimetrical area adjacent the inner chamber opening. The first wall portion may be positioned to forcibly engage the metal seal at an acute angle enabling a sliding sealing action between the first wall portion and the seal member in response to differential movement during expansion and contraction.

The first wall portion of the first ductwork means may also function as the wall portion for the second ductwork means. In this instance, the angle of engagement of the first wall portion with the metal seal is made acute with respect to the one of the ductwork means which is to carry the fluid under a lower pressure, thereby enabling fluid under a higher pressure in the other ductwork means to assist in maintaining the first wall portion in contact with the sealing means.

The first ductwork means may further include a second wall portion which surrounds a perimetrical area, adjacent the junction of one end surface and the peripheral surface of the body, and extending therefrom to a continuance of the first ductwork means. A third wall portion surrounds a perimetrical area adjacent the junction of the other end of the end surfaces and the peripheral surface of the recuperator body, and extends therefrom to a continuance of the first ductwork means. The second and third wall portions may engage a sealing means and be maintained in engagement with the sealing means in a manner similar to that described hereinbefore with respect to the first wall portion of the first ductwork means.

The second ductwork means may include a plenum for supplying a second fluid to one of the end surfaces of the body, and means for preventing entry of the second fluid into the inner chamber of the body. The plenum may include a first wall portion surrounding a perimetrical are adjacent the junction of the one end surface and the peripheral surface of the body. The second ductwork means may further include a second wall portion surrounding a perimetrical area adjacent the junction of the other of the end surfaces and the peripheral surface of the body and extending therefrom to a continuance of the second ductwork means. A third wall portion of the second ductwork means surrounds the perimetrical area adjacent the junction of the other of the end surfaces and the surface of the inner chamber and extends therefrom to a continuance of the second ductwork means. Sealing means between the first, second, and third wall portions of the second ductwork means, and means for maintaining the three wall portions of the second ductwork means in contact with the sealing means may be utilized which are similar to that described hereinbefore with respect to the first ductwork means.

The passageway portion of the heat exchange body advantageously comprises a plurality of assemblies of integrally fused tubes, each assembly including a plurality of contiguous layers of tubes. The layers of tubes define successive planes extending between the internal and peripheral surfaces, the tubes within each layer being essentially parallel to each other and transverse to the tubes in at least one of the adjacent layers to form the first and second series of passageways. A plurality of such tube assemblies may be disposed around the inner chamber. A like plurality of spacing elements may be interposed between the outer planes defined by the outer layers of the tubes of each assembly, the spacing elements being constructed to prevent cross flow between first and second fluids circulating through the first and second series of passageways. The yieldable support means extending inwardly from the outer shell preferably engages the impervious spacing elements to prevent interference with fluid flow in the externally opening passageways of the tube assemblies.

The tube assemblies and the spacing elements of the heat exchanging body are preferably constructed from glass-ceramic materials having a very low coefficient of thermal expansion, thereby substantially restricting relative expansion and contraction movements to the remaining components of the recuperator structure. The glass-ceramic material of the tube assemblies and the spacing elements preferably have essentially zero porosity, consist essentially of an inorganic crystalline oxide ceramic material, and have an average coefficient of lineal thermal expansion of about $-18°$ to $+15° \times 10^{°-7}/°C$ over the range 0°–300°C. The crystalline ceramic materials advantageously may have lower average coefficients of lineal thermal expansion than that just stated, for example $-12°$ to $+12°$, or even $-5°$ to $+5°$, $\times 10^{°-7}/°C$ over the range of 0°–300°C.

Other objects, features and advantages will become apparent from the following description taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a perspective schematic view of an embodiment of a matrix module utilized in this invention showing an enlarged arrangement of tubes in alternate layers with the tubes in each layer parallel to each other and transverse to tubes in at least one of the adjacent layers;

FIG. 2 is a perspective schematic view of the matrix module embodiment illustrated in FIG. 1 showing the arrangements of tubes before they have been expanded and fused together;

FIG. 3 is a perspective view of apparatus utilized in making a ribbon of the parallel tubing utilized in constructing the modules of FIGS. 1 and 2;

FIG. 4 is an enlarged perspective view of a portion of the apparatus of FIG. 3 showing the pair of burners fusing and sealing the ends of the tubes;

FIG. 5 is a perspective view of a jig assembly utilized in making a matrix module of the recuperator structure of this invention and showing a partial packing of tubes within the structure mounted on the assembly;

FIG. 6 is an isometric view of a heat exchanging body utilized in the recuperator structure of this invention which is formed from a plurality of matrix modules having the arrangement illustrated in FIG. 1;

FIG. 7 is an expanded view of a portion of the heat exchanging body illustrated in FIG. 6;

FIG. 8 is a cross sectional view from the side of a complete regenerator structure in which a heat exchange body similar to that illustrated in FIG. 6 is shown supported in a housing and aligned with ductwork for directing flow of the two fluids effecting a heat exchange with each other;

FIG. 9 is a cross sectional view of the apparatus illustrated in FIG. 8 taken along line IX—IX of FIG. 8;

FIG. 10 is an enlarged cross sectional view of an alternate structure for sealing ductwork walls to a glass-ceramic body;

FIGS. 11 through 15 are schematic, cross sectional representations of alternate heat exchange bodies useful in the combination of this invention;

FIG. 16 is an exploded perspective view of another embodiment of a complete recuperator structure of this invention;

FIG. 17 is an enlarged view of a ductwork wall sealing arrangement for the apparatus shown in FIG. 16; and

FIG. 18 is an exploded view of end wall and plenum components useful with the structure of FIG. 16 when a counter flow heat exchange body is utilized.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

A unitary foraminous glass-ceramic matrix structure 51 is illustrated in FIG. 1 wherein a plurality of layers 52 of tubes 53 are superimposed above the other in successive parallel planar layers, the tubes within each planar being essentially parallel to each other and transverse to tubes in adjacent planar layers, each being integrally fused to each adjacent parallel tube and each adjacent transverse tube. Although the structure illustrated in FIG. 1 shows that alternate layers of the tubes are disposed transversely, it is possible to practice the invention by utilizing adjacent layers in which the tubes in one layer are parallel to each other in that layer and are also parallel to the tubes in the second layer. These double layers of tubes then may be disposed transversely with respect to adjacent layers to provide a heat transfer between the adjacent transversely disposed tubes. In this instance, the interface between the two parallel layers of tubes in which all tubes are parallel to each other, will form a more semi-hexagonal configuration, while the interface with the tubes that are transverse to each other will have the substantially square configuration illustrated in FIG. 1.

When the tubes are essentially fully expanded, in the manner described hereinafter, each tube wall is a common wall with each tube adjacent thereto, including those in the same plane and those in adjacent parallel planes. Moreover, when fully expanded in the passageways formed in the structure of FIG. 1 are essentially in the shape of a parallelogram, usually a square or a rectangle. FIG. 2 illustrates the tubing layers before assembly, using round tubes, while FIG. 1 shows the matrix module with the tubes expanded to essentially square passageways. In FIG. 2 the tubes are shown as they would appear in cross section. The tubes of FIG. 2 are in fact sealed in both their ends, as to be described hereinafter, before heat treatment.

To facilitate the assembling of the tubes 53 in the layers 52 so the layers may be superimposed one upon another, with the tubes in one layer being transverse to the tubes in an adjacent layer, a plurality of tubes 53 are placed side by side in contact with adjacent tubes to form a ribbon running transverse to the axes of the tubes and of predetermined length. While maintaining the tubes in this parallel contacting relationship, the upper surface of the layer of tubes may be spray-coated, as illustrated on FIG. 3, with an air-setting bonding composition so that the ribbon of tubes becomes rigid enough to handle like a thin sheet of plastic material. A flame is applied to each side of the ribbon, as illustrated by the burners 64 on FIG. 4, and held in contact with the tubes to condition them in the ribbon formation. The tubes 53 are preformed to desired length and both ends are sealed by fusing the glass at each end. The end sealing is performed simultaneously with cutting a tube 53 length out of an infinitely long piece of drawn tubing. At the time the tube ends close, air is sealed within the tubes.

The method and means by which the end-sealed tubes 53 are initially formed and sealed is shown and described in the application of F. Finchman, Ser. No. 132,720, filed Apr. 9, 1971, commonly owned by the assignee of this application. The ribbon of tubes is then cut to form rectangular sheets and the sheets arranged in the manner illustrated in FIG. 2.

The air-setting bonding composition which can be used may be a polyurethane, although other compositions will be readily understood by the art as accomplishing the same purpose. For instance, a 2.5 to 3 weight percent solution of nitrocellulose and amyl acetate can also be used. The composition used should have the property of setting quickly so as to adhere the tubes to each other in the form of ribbon and yet volatize rapidly when exposed to the heat necessary to soften the tube walls and diffuse the contacting wall surfaces together to form a monolithic structure. Preferably, the bonding composition should leave no residue.

FIG. 3 illustrates one embodiment of an apparatus useful in making a continuous ribbon 54 of parallel tubes, which ribbon can be cut to desired lengths utilized in making the heat exchange body of the recuperator structure of this invention. A plurality of tubes 53 previously cut to a specified length are fed into a hopper 55 by means not shown. Hopper 55 may be continuously vibrated by means of a vibrator 56 in contact therewith, so that the tubes 53 are maintained in parallel relationship and are deposited individually through opening 57 at the base of the hopper onto a support layer 58 disposed directly below opening 57 and continuously moving in a direction away from the hopper 55. The support layer 58, which can be a plastic film, paper such as a thin paper used in making tea bags, cellophane, or other film material, is continuously unwound from a roll 59 which is rotatably mounted beneath the hopper 55. The support layer 58 passes over and is supported by a conveyor belt 60 continuously moving around a pair of support rollers 61, 62 with either or both rollers being driven by means not shown.

As the individual tubes 53 pass through the bottom of the hopper 55 from opening 57, they are disposed on the support layer 58 and moved in the direction away from the hopper. The rate of movement of the support layer 58 and the rate of deposit of the tubes 53 thereon are adjusted so that the tubes are deposited and maintained in parallel, contacting relationship with adjacent tubes. As the support layer and tubes move away from hopper **55,** the ends **63** of each tube pass through oppositely disposed burners **64** mounted on either side of the conveyor belt **60.** The burner flames **65** fuse and close the tubes to trap air within the tubes. The flames **65** can be directed so that they do not adversely affect the support layer **58,** but only impinge on the tube ends **63.**

As the ribbon **54** of parallel tubes continues along the conveyor after the tubes have their ends closed, a thin layer of air-setting bonding material **66** is sprayed onto the upper surface of the ribbon **54** by means of a nozzle **67** of a spray gun **68,** which material bonds the tubes together so that the ribbon of tubes becomes rigid enough to be handled like a thin sheet of plastic material. Alternatively, the layer of tubes can be sprayed with a bonding material prior to having their ends sealed by the flames **65.** The support layer **58** is readily separated from the ribbon **54.** The ribbon is then cut into rectangular sheets and may be arranged in layers. In this embodiment the tubes in alternate sheets of layers are disposed at 90° angles with respect to each other.

As illustrated in FIG. **5** a rim or mold **10** is mounted on a jig which includes a support plate **26** selectively attached to a conventional vibrator **13.** Clamping means may be spaced about the edge of the support plate **26** and removably secure the rim or mold **10** thereto.

A plurality of layers of tubes **53** may then be arranged within the mold or rim **10** to obtain the configuration illustrated in FIG. **2.** The tubes in one layer are parallel to each other and are transverse to the tubes in at least one adjacent layer. Each of the glass tubes **53** has both ends sealed, thus trapping air or another thermally expansible fluid medium therein. Since the tubes are very small in size, the outer diameter of which may, for example, be about 0.030 inches and the wall thickness may be about 0.001 inches, end sealing is readily achieved.

Because it is desirable and important to have the layers of glass tubes as closely packed as possible so that each tube is in contact with adjacent tubes within the layer and with the tubes in adjacent layers, the support plate **26** is selectively connected with the vibrator **13.** Vibration imparted to the plurality of layers of tubes assists in more closely packing the tubes, particularly if the tubes are individually inserted as opposed to utilizing preassembled rectangles of tubes obtained from the apparatus illustrated in FIGS. **3** and **4.** It is to be understood that the mold **10** need not be manually packed but can be packed by other methods. It may be desirable for forming a unitary matrix structure **51,** in which case a thin coating of a bonding material is used between layers of tubes in the initial assembly (FIG. **2**).

An assembly **25,** comprising the support plate **26** which may be of stainless steel and have a silica-alumina cloth **27** on its upper surface between the mold **10** and the plate **26,** the mold or rim **10,** and the layers of closely packed glass tubes **53,** is removed from the jig to be placed in a furnace. Another silica-alumina cloth **29** may be placed on the upper surface of the assembly **25,** and a second stainless steel plate **30** is placed thereover. Each of the steel plates **26** and **30** may have perforations **28** formed therethrough.

A heavy member **31** is finally placed on top of the plate **30,** although a clamping means (not shown) may be utilized to hold the plates **26** and **30** to the rim or mold **10** to constrain the tubes in their tightly packed configuration. The entire assembly is then placed in a furnace and subjected to heat sufficient to soften the glass walls of tubes **53** to cause the walls to bloat or expand due to the heating of the fluid medium in each tube so that adjoining, contacting wall surfaces within the layers and between the layers are fused together to form a unitary matrix. As the individual tubes expand, the air or other gases in the interstices pass through the perforations **28** in the plates **26** and **30.** If desired, plates **26** and **30** need not be perforated, and the assembly can be placed under vacuum during the expanding or bloating step to assist in the removal of air which is within the interstices between the tubes.

The heating of the thin-walled tubes expands them into close contact with each other and into the interstices between the tubes and between the layers of tubes to a greater or lesser extent, ideally to an extent to substantially fill the interstices. In the latter event, if the tubes are transverse to each other in each of the adjacent layers, the resulting bloated tubes become essentially square or rectangular in cross section as illustrated in FIG. **1.** The glass tubes are fusing together and are also undergoing nucleation during the heat treatment, and heating of the structure is continued for a time sufficient to in situ crystallize the glass to an at least partially crystalline material, commonly referred to as a glass-ceramic.

After the assembly has been crystallized, and usually after cooling to room temperature, the outer surface portions of the assembly **25** are removed and the tube ends are removed by a diamond saw to obtain a matrix module in which all of the fused tubes now have open ended channels.

The tubing used in practicing the usual embodiments of this invention has a maximum inner diameter of up to about 0.1 inch, a wall thickness of 0.001 to 0.015 inch and an inside-diameter to wall-thickness ratio of at least **6.** Diameter-to-wall thickness ratios lower than **6** result in a relative ineffectiveness of the process to urge the tubes into a good fusion bond when using a temperature schedule which is also effective to properly nucleate and crystallize the glass tubes to a glass-ceramic during the expanding and fusing heating cycle. In a now preferred embodiment of the matrix module illustrated in FIG. **1,** the ratio of the inner-diameter to the wall-thickness of the thermally crystallizable glass tubes is at least 7.2 to 1.

When starting with round tubes having a ratio of the inner-diameter to wall-thickness of at least **6,** the open or free cross-sectional or frontal area of each face of the matrix module containing passageways is at least 32 percent. When starting with round tubes having an inner-diameter to wall-thickness ratio of 7.2, the open cross-sectional or frontal area of each face containing openings is at least 36 percent.

Well suited for use in the methods of this invention are thermally crystallizable glasses that are convertible by heating to glass-ceramic bodies. As used herein, a glass-ceramic is an inorganic, essentially crystalline oxide ceramic material derived from an amorphous inorganic glass by in situ bulk thermal crystallization.

Prior to thermal in situ bulk crystallization, the thermally crystallizable glasses can be drawn into tubing using conventional glass-forming techniques and equipment. After being assembled in the manner shown in FIGS. 1 through 5, the thermally crystallizable glass tubes are subjected to a controlled heat treatment until the tubes have been expanded and fusion sealed and crystallization has been effected.

Thermally crystallizable glass compositions and the glass-ceramics resulting from thermal in situ crystallization thereof which are useful in the method and product of this invention are those which have, in their crystallized state, a coefficient of thermal expansion in the range from −18° to +50° × 10^{-7}/°C over the range 0°–300°C and preferably as low as −12° to +12°, or −5° to +5°, × 10^{-7}/°C over the range 0°–300°C. The compositions usually used are those containing lithia, alumina and silica, together with one or more nucleating agents including TiO_2, ZrO_2, SnO_2 or other known nucleating agents. In general, such compositions containing in weight percent about 55 to 75 SiO_2, about 15 to 25 Al_2O_3 and about 2 to 6 Li_2O, together with about 1.5 to 4 weight percent of nucleating agents selected from one or more of TiO_2, ZrO_2 and SnO_2, can be employed. Preferably, not more than about 2,5 weight percent TiO_2 is usually used or the crystallization is undesirably rapid to be compatible with the fullest expansion of the tubes in the bloating process.

Other ingredients can be present in small amounts, as is understood in the art, such as even as much as 4 or 5 weight percent ZnO, up to as much as 3 or 4 weight percent CaO, up to as much as 8 percent MgO, and up to as much as 5 percent BaO, so long as the silica plus alumina plus lithia and the nucleating agent(s) are at least about 85, usually 90, weight percent of the total glass and the glass composition will thermally crystallize to a glass-ceramic having the desired low expansion coefficients set forth hereinbefore. Exemplary compositions which can be used in the process of the invention include those compositions disclosed in U.S. Pat. No. 3,380,818, those compositions disclosed in U.S. application Ser. No. 464,147 filed June 15, 1965, and corresponding British Pat. Nos. 1,124,001 and 1,124,002 dated Dec. 9, 1968, and also those compositions disclosed in U.S. application Ser. No. 866,168 filed Oct. 13, 1969, and corresponding Netherlands printed patent application No. 6,805,259, and also those compositions set forth in application Ser. No. 146,664, filed May 25, 1971.

In any event, the thermally crystallizable glass tubings in the lithia-alumina-silica field containing nucleating agents as before described, are assembled as previously set forth and the constrained bundles of sealed tubing (containing a heat-expansible fluid) are heated at any suitable rate that will not thermally shock the tubing up to a temperature range in the maximum nucleating range of the glass. The maximum nucleation range can be determined for all such glasses by the general method outlines in the above-referenced U.S. Pat. No. 3,380,818, beginning at Column 9, line 54.

For the process of the present invention, where sealing is to be effected or initiated while nucleation is occurring, it is preferred that the assembled tubes be heated in the range 50°F to 250°F above the annealing point for a period of one hour or more. This time can be extended to 10 or 20 hours, and even longer times are not harmful. During this time of heating in such temperature range, nucleation is effected, as well as fusion aided by pressure exerted by expansion of the entrapped fluid. Thereafter, the temperature is raised to a higher temperature than the first heating range, which higher temperature is at least 200°F above the annealing point temperature or may be as high as the final crystallization temperature (usually 1,800° to 2,300°F). The final crystallization can be effected at any such temperature range higher than the nucleation-expansion-fusion temperature (50° to 250°F above the annealing point temperature) and can be as low as 200°F above the annealing point or as high as 2,300°F or as high as the upper liquidus temperature.

If the final crystallization is effected at temperatures no more than 400° or 500°F above the annealing point, then the product will not have as high temperature stability as is desired for gas turbine use, but the product will be of the desired low expansion glass-ceramic. In any event, in this second stage of heating further expansion and the beginning of crystallization is effected, followed by the completion of crystallization on continued heating to a degree such that the matrix material has a coefficient of expansion in the range set forth hereinbefore.

While the temperature may be raised directly to the final crystallization temperature range at a suitable furnace heating rate usually in the range of 10° to 300°F per hour, it is usually preferred to allow crystallization to be effected slowly while further expansion of the tubes and concomitant fusion of tubes and rods is being effected by having an intermediate step between the first nucleation-and-fusion temperature range and the final crystallization temperature, which range is usually from 200°F to about 700°F, usually from 200° to 500°F, above the annealing point of the original glass. Exemplary holding times in this intermediate range are from 1 to 8 hours, after which the assembly is heated up to the final crystallization temperature, usually in the range of from about 1,800° to 2,300°F.

Obviously, no specific heat treatment instructions can be given suitable for all thermally crystallizable glass compositions. As is well-known, glass-ceramics do not have adequate strength if they are not sufficiently nucleated before crystals are allowed to grow appreciably in size, so that routine experiments known to those skilled in the art are used to determine what length of time is best to obtain an adequate number of crystallization centers or nuclei in the glass in the nucleation temperature range of 50° to 250°F above the annealing point.

Another point that must be kept in mind is that, if it is an object to obtain appreciable expansion beyond that necessary to get good fusion between the tubes, in other words to get appreciable reshaping of the tubes to fill the interstices between tubing, one should not raise the temperature too slowly when going from the nucleation temperature range to the intermediate range, since a rigid crystalline network may begin to set in and to prevent further expansion. It is found some compositions can be heated at a rate as low as 10° to 50°F per hour to this intermediate temperature range and still get sufficient expansion of the tubing effective to form the substantially hexagonal passages (round tubes used in close-packed configuration). On the other hand, some compositions have been found not to fully expand unless the heating rate from the initial nucleation-fusion temperature range to the intermediate temperature range is used, sometimes on the order of at least 200°F to 300°F per hour or higher.

The length of time of heating in the final crystallization temperature range of 1,800°F to about 2,300°F is from one-half hour to five or six hours, although longer times are in no way deleterious. After the crystallization has been completed, the structure can be cooled at furnace rate or in air because the structure is of such low expansion that thermal shock will not harm it.

After the heat treatment just described, the product can now be cooled and the sealed ends of the tubes cut or ground away to open each tube to atmospheric pressure. Alternatively, if the intermediate step of crystallization heat treating at a temperature range of 200° to 700°F above the annealing point temperature is used, the heat treatment can be interrupted after this intermediate step and cooled somewhat or even cooled to room temperature, and the ends of the tubes cut or ground away and opened to atmospheric pressure. Then the assembly can be heated up again into the final crystallization heat treatment range, where further and final crystallization is effected.

As shown on FIG. **6**, for example, a plurality of the elongated rectangular matrix modules **51** of FIG. **1**, each consisting essentially of tubes of thermally crystallizable glass fused together in a monolithic structure, are arranged in a mold in such a manner that each matrix is adjacent to and separated from each adjoining matrix by a wedge-shaped member **69.** The members **69** are of crystallizable glass and preferably of the same composition as that from which the tubes **53** in module **51** have been formed. The wedge-shaped member **69** has each of its outer surface edges **70** tapering inwardly to substantially a narrow end **71.** In the recuperator heat exchange body **72** illustrated in FIG. **6**, the inner surfaces **73** of each rectangular module **51** is separated by the extremely narrow edge **74** of a wedge member **69.** It is preferable that the edge **74** be as narrow as possible so that the inner surface of the recuperator is essentially defined by the inner surfaces **73** of the matrices, thus providing a maximum of passageways for gases or fluids to pass to the exterior.

The alternating arrangement of rectangular matrices and wedge-shaped members, form a toroidally-shaped structure when placed within the mold. As earlier described, the assembly is then placed in an appropriate furnace and heated to the nucleating temperature of the particular thermally crystallizable glass composition utilized in the structure. After nucleation is completed the nucleated structure is subjected to the temperature necessary to at least partially crystallize the glass and form a unitary structure or heat exchanging body for a recuperator apparatus, wherein the contacting surfaces of the rectangular matrices and wedge-shape members are firmly bonded or fused to each other. The heat treatment steps for the nucleation and crystallization of the recuperator member in FIG. **6** are those described above with respect to a matrix module **51.**

An alternate method for making a recuperator would be to thermally crystallize the individual matrix modules **51** and the individual wedge shape members **69** and then seal or bond the members together to form the structure of FIG. **6.** A thermally crystallizable sealing glass having a coefficient of thermal expansion which is substantially that of the members being sealed is applied to all contacting surfaces prior to assembling the members. The assembled structure is then subjected to the heat necessary to crystallize the sealing glass and bond the members together.

Because of the arrangement of the tubes **53** in the rectangular matrix modules in the structure **72,** a cross flow of gases through the heat exchange body is achieved. Cool exterior gases, as from a compressor, can pass through the open passageways of tubes **53** which are in a direction (indicated by arrows A in FIGS. **6** and **7**) parallel to the axis of the recuperator, while the hot exhaust gases of a gas turbine engine can flow outwardly (indicated by arrows B) from the center **77** of the recuperator and out through those passageways which are transverse to the axis of the recuperator. The direction of flow of one or both fluids or gases could, of course, be reversed, if desired. Thus, the cool fluid such as air, passing through the recuperator passageways is heated by the walls of such passageways which are, in turn, heated by the hot fluids, such as exhaust gases passing through the passageways which are transverse to the former and separated only by the common wall thickness.

Seal seating surfaces **75, 76** may be provided on the recuperator. The recuperator of FIG. **6** does not have to be rotated nor does it have to make a relatively movable contact with a seal bar, thus eliminating wear.

Referring to FIGS. **8** and **9** there is illustrated in cross-sectional views of the side and end elevations, a recuperator, heat exchange body or assembly **72** in a housing or shell. Ductwork is provided for directing the flow of two heat exchanging fluids and for preventing cross flow between the two fluid streams. Means are provided for the support and alignment of the body **72.**

The recuperator assembly **72** has been shown as toroidally-shaped, since this configuration is particularly adaptable for certain applications. A toroidally-shaped body is defined as a surface generated by the rotation of a plane closed curve about an axis lying in its plane and not intersecting the closed curve. While the principles of this invention are particularly applicable to a toroidally-shaped heat exchange body, the principles are also applicable to cubes, prisms, cylinders, and even irregularly shaped bodies, which have an inner chamber formed therein for air circulation in the manner noted in FIG. **8.** The principles are also applicable to other configurations which have other fluid flow arrangements to effect a heat exchange between the two fluids.

Because the principles of this application are applicable to other configurations, the toroidally-shaped body **72** will be generically defined as a body having an inner surface **80** defining an inner chamber **77** formed in the body, a peripheral surface **82** spaced radially outwardly from the internal surface **80,** and spaced end surfaces **84** and **86** connecting the internal and peripheral surfaces.

The body **72** includes at least one portion, and preferably a plurality, in which a first and second series of elongated passageways **88** and **90** are formed therethrough (best seen in FIG. **9**). The passageways of the first series **88** extend and enable passage of a first fluid between the internal surface **80** and the peripheral surface **82.** The passageways **90** of the second series extend and enable passage of a second fluid between the end surfaces **84** and **86** (FIG. **8**). This is best seen by noting the fluid flow arrows A and B in FIG. **8.** The walls of the first and second series of passageways are disposed adjacent one another in heat transmitting relationship enabling a heat exchange between the first and second fluids passing through the first and second series of passageways.

The structure in FIGS. **8** and **9** includes first ductwork means, generally designated at **100**, for channeling a first fluid to one of the inner chamber and peripheral surfaces and collecting the first fluid as it issues from the other of the inner chamber and peripheral surfaces.

The first ductwork means **100** includes a first wall portion **102** which surrounds the inner chamber opening adjacent the end surface **86** of the body **72** and extends between a perimetrical area **104** adjacent the opening of the chamber **77** and a continuation **106** of the first ductwork means. Bolts **107** or other suitable means may be utilized to secure the wall portion **102** to the continuation duct **106.** The wall portion **102** and the other similar wall portions herein are preferably constructed of a spring material which is resistant to high temperatures, such as a stainless steel. The wall portion **102** is generally of annularly bell-shaped configuration having a flared portion adjacent to the body **72** which will permit the wall portion **102** to engage a sealing means **76** at an acute angle **108.** Sealing means **76** is a flat ring that may be fastened or adhered to body **72** at the end surface **86.**

The wall portion **102** is advantageously flexed against the sealing means **76** to exert a sealing pressure thereon. The flexing of the wall portion **102,** thus comprises a means for maintaining the first wall portion **102** in contact with the sealing means **76,** the spring action yieldably biasing the wall portion **102** into contact with the seal **76.**

The sealing means **76** may advantageously be a metal seal member having a configuration which covers the perimetrical area **104** adjacent the opening of the inner chamber **77.** Since both the wall portion **102** and the sealing member **76** have metal surfaces, a sliding sealing action is enabled in response to differential movement of the components during expansion and contraction when temperatures in the housing vary. As an alternative the sealing means **76** may comprise a built up portion of glass-ceramic material, or a separate element of glass-ceramic material which has been bonded to the body **72,** and which has a contact surface which will provide a sealing action with the wall portion **102.**

The first ductwork means also includes a second wall portion **110** surrounding the perimetrical area **112** adjacent the junction of end surface **86** and the peripheral surface **82** of the body **72.** The second wall portion **110** extends from the perimetrical area **112** to a continuation of the first ductwork means, in this instance an outer shell **160** which forms one wall of a plenum that connects the fluid issuing from peripheral surface **82** to an exhaust portion **114** having an exhaust outlet **115.** An annular seal *75a* is provided between the perimetrical area **112** and the second wall portion **110** in a manner similar to that described for the first wall portion **112** and the seal **76.** The configuration of the second wall portion **110** is generally that of the surface of a truncated cone which, when assemblea in the housing or outer shell **160** is flexed inwardly toward the axis of the cone to maintain the sealing engagement as described hereinbefore with respect to wall portion **102.**

The first ductwork means also includes a third wall portion **116** surrounding a perimetrical area **118** adjacent the junction of the end surface **84** and the peripheral surface **82** of the body **72,** and extending therefrom to a continuance of the first ductwork means, in this instance the outer shell **160.** The third wall portion **116** also generally resembles the surface of a frustrum of a cone flexed against the sealing means *75b.*

The first ductwork means thus enables a flow of fluid in through the wall portion **102** to the inner chamber **77,** flow from the inner surface **80** through the passages **88** to the peripheral surface **82,** and then through the exhaust portion **114** to the exhaust outlet **115.**

A second ductwork means **128** is provided for channeling a second fluid to the end surface **84** and collecting the second fluid as it issues from the end surface **86.** The second ductwork means includes a plenum **130** receiving intake air under a relatively higher pressure supplied through an intake port **131** to the plenum **130.** A plate **132** blocks entry of the intake air into the chamber **77.** The plate **132** is advantageously formed from a glass-ceramic material having the same thermal expansion characteristics as the body **72,** and is bonded to the body **72** in a manner known in the art.

The second ductwork means may be defined as having a first wall portion **134** surrounding the perimetrical area **118** adjacent the junction of the end surface **84** and the peripheral surface **82** and extending to the continuance of the first ductwork means, in this instance the outer shell of the plenum **130.** In this embodiment the first wall portion **134** of the second ductwork means **128** is common to or is the same as the third wall portion **116** of the first ductwork means **100.** Therefore, the wall shape is the same. Since the pressure of the intake air is normally considerably higher than the pressure of the exhaust gases, the higher pressure in the plenum **130** assists in urging the wall portion **134–116** against the sealing means *75b.*

The second ductwork means **128** further includes a second wall portion **138** surrounding the perimetrical area **112** adjacent the junction of the end surface **86** and the peripheral surface **82,** and extends therefrom to a sandwiched connection at bolt **162** joining it together with the outer shell **160** and continuance **140** of the second ductwork means. Since the second wall portion **138** of the second ductwork means is common to or is the same as the second wall portion **110** of the first ductwork means **100,** the shape of that common wall portion, the flexing of the common wall portion, and the sealing of the common wall portion is the same as described for portion **110.**

The second ductwork means **128** also includes a third wall portion **142** surrounding the perimetrical area **104** adjacent the corner junction of the end surface **86** and the inner surface **80.** The third wall portion **142** extends from the peripheral area **104** and is fastened to continuation **140** of the second ductwork means by screw studs **107.**

The third wall portion **142** of the second ductwork means **128** is common to or is the same as the first wall portion **102** of the first ductwork means **100.** Therefore, the configuration as described hereinbefore is the same, permitting a flexing of the wall **102** into sealing contact with the ring sealing means **76.** Again, since the pressure in ductwork continuance **140** is higher than that in either of the adjacent plenums for the first ductwork means, the net pressure differential is exerted downwardly on the inwardly flexed wall portions **138,** 142, assisting in establishing a seal between the wall portions **110, 102** and the seal rings **75*a*** and **76**, respectively on end surface **86**.

It should be also noted that the flexing action of the wall portion **134** on surface **84**, and the flexing actions of the wall portions **138, 142** on end surface **86**, are in opposition and assist in maintaining the alignment of the recuperator body **72** in a desired position in the outer shell **160**. Moreover, the oppositely acting yieldably biasing forces assist each other in maintaining a seal between the inner edges of the wall portions and the end surfaces of the body **72**.

The housing means which surrounds and supports the heat exchanging body **72** in a relatively stationary position during contraction and expansion movements of components of the apparatus includes a plurality of yieldable support member means **170** extending between the outer shell **160** and the body **72**. The support member means **170** isolate or protect the glass-ceramic heat exchange body **72** from mechanical shock, and also aid in maintaining the inlets and outlets of the first and second series of passageways **88, 90** positioned for connection with the first and second ductwork means **100, 128**, respectively.

Each of the support member means **170** includes a contact head **172** having a rounded contact face **174** to achieve an essentially point contact with the recuperator body **72**. The contact heads **172** are preferably received by bores **173** formed in the body **72** to assist in maintaining a desired position for the body **72** with respect to the contact heads **172**.

The support member means **170** further includes a rod portion **176** which is slidably received in a cylinder **178**. The cylinder **178** has a first smaller cylinder bore **179** and a second larger cylinder bore **180**. Annular seals **181**, which may be high temperature metal sealing rings, such as chromium or stainless steel material, are disposed around the rod porton **176** in the first cylinder bore **179** to prevent the hot fluids or gases from entering the second or larger cylinder bore **180** in which a spring **186** is disposed. The end cap **182** closes the second cylinder bore **180** and provides a guideway **184** for rod **176**. This prevents the high temperature gases or fluids from affecting the performance of the spring means **186**.

One end of the spring **186** engages a flange **177** formed on the rod **176** to yieldably urge the rod **176**, and thus the contact head **172**, toward and into contact with the body **72**. A cylinder end cap **182** is threadably received by the spring-containing cylinder portion **187** which is located outside of the shell **160**. The location of the spring-containing portion **187** on the exterior of the shell further shields the spring means **186** from the influence of the temperatures within the recuperator and reduces the deleterious effects thereof on the spring means **186**.

The spring means **186** abuts at its other end the cylinder end cap **182**. The end cap **182** advantageously has a bore **184** formed therein to receive and guide the end of the rod portion **176** which is remote from the ceramic heat exchanger body **72**. The alignment provided by the bore **184** thus insures an easier movement of the rod portion **176** in the cylinder and a smoother response when absorbing mechanical shock received by the outer shell **160**. This alignment feature also reduces the wear in the first cylinder bore **179**. One or more shims **196** may be interposed between the cylinder end cap **182** and the cylinder portion **187** to adjust the force being supplied by the spring **186** to the rod **176**. The cylinder **178** has an outer flange **188** which is attached by bolts **190** to a cylinder support means **192**. The support **192** may be welded as indicated at **194** or otherwise suitably attached to the outer shell **160**.

Although the spring means **186** is shown as a spiral compression type spring, other means may be utilized for yieldingly urging the contact head **172** toward the body **72**. For example, a plurality of beveled spring washers may be inserted in place of the spiral compression spring **186**. In certain applications it may be possible to use a fluid or hydraulic pressure in the cylinder **186** which, when coacting with connected damping chambers, would yieldably urge the contact head **172** toward the body **72**. The support member means **170** illustrated in FIGS. **8** and **9** thus maintains the alignment of the body **72** with respect to the ductwork means supplying and collecting fluid for heat exchange. It is possible to use the support member **170** to also maintain the tranverse alignment of the body **72** in the same manner.

Referring now to FIG. **10** there is shown an alternative construction which may be utilized with the apparatus shown in FIGS. **8** and **9**. A corner of a recuperator body **72** is illustrated as receiving a compound sealing means **200**. The sealing means **200** includes an annular resilient seal **202** which may be located in a seal seat **204** which has been routed around or formed in the end surface of the body **72**. The resilient seal **200** must have the ability to withstand the high temperatures present in most recuperator structures and may be made from fiberfrax, asbestos, or a woven material such as a combination of impregnated asbestos and stainless steel fibers. The double element sealing means **200** also includes an annular metal ring **206** to provide a relatively rigid contact surface for the walls of the ductwork and to enable a sliding action of the walls with respect to the sealing ring **206**. A flange **208** is shown extending from the ring **206** toward the body **72**. The flange **208** may function to hold the metal ring **206** in position on the body **72**, and to maintain the resilient seal element **202** in cooperative sealing relationship with the metal ring **206**. Similar results may be achieved by providing a flange of the resilient material **202** which extends toward and retains the annular metal ring **206** in position.

A ductwork wall portion **210** is shown extending between its bolted position between two sections of the outer shell **160** and the surface of the metal sealing ring **206**. A bellows type section **214** of the wall portion **210** is shown intermediate a seal contacting section **216** and an outer shell connecting section **212** of the wall **210**. The bellows section **214** may accommodate further expansion and contraction of the wall portion **210**, particularly in view of the means that may be utilized in the embodiment in FIG. **10** for yieldingly urging section **216** of the duct wall portion **210** against the sealing means **200**.

It is possible to connect the duct wall portion **210** by bolting at **162** through the section **212** in order to flex the wall **210** against the sealing means **200** and achieve a satisfactory seal. However, in some applications it may be desirable to utilize additional means for yieldingly urging the wall **210** against the sealing means **200**. One of the yieldable support members **170** has been utilized to illustrate this application. A contact head **172** is positioned against one side of the duct wall **210** to force the other side of the duct wall **210** into sealing engagement with the annular ring **206**. If a seal is effected in this manner it is possible that a sliding sealing action may be more difficult to achieve or might product an undesirable misalignment. Therefore the bellows section **214** of wall **210** will permit expansion and contraction with relatively little sliding sealing movement, while the support member **170** is yieldingly urging the duct wall portion **216** against the sealing means **200**. In this instance the support member means, or a plurality thereof, may also be utilized to align the body **72** in a desired position in the housing or shell **160**. The duct wall **210** may again serve as a common wall separating two plenums and having a first ductwork side **220** and a second ductwork side **222**.

Referring to FIG. **11** there is illustrated a first alternate embodiment **230** of a heat exchanger body which may be utilized in this invention. The embodiment **230** has a centrally located cylindrical inner chamber defined by the surface **80** and a cylindrical peripheral surface **82**. Separator elements **69** support and align the matrix modules **51**. In this embodiment, however, it will be noted that the separator elements **69** are generally wedge-shaped but have truncated portions **232** adjacent the inner surface **80** since the matrix modules do not take up the entire inner surface. However, the generally wedge-shaped portions of the separator elements **69** still point toward the inner surface **80**.

Referring to FIG. **12** there is illustrated still another embodiment **240** in which the inner surface **80** is square or rectangular in cross section. In this instance the separator elements **69** are triangular as noted at **242** and thus the peripheral surface **82**, around the modules **51** and the elements **69**, is octagonal in cross section. The separator elements **69** still have generally wedge-shaped portions pointing toward inner surface **80**.

Referring to FIG. **13** there is shown still another embodiment **250** in which the inner surface **80** is square or rectangular in cross section. However, the separator elements **69** have a square or rectangular cross section **252** so that the peripheral surface of the embodiment **250** is also square or rectangular. Again, though, there are generally wedge-shaped portions of the separator elements which point toward the inner surface **80**.

Referring to FIG. **14** there is shown another embodiment **260** in which the inner surface **80** is square or rectangular in cross section. However, the separator elements **69** are angle shaped as illustrated at **262**. Again, however, there are generally wedge-shaped sides of the angle elements **262** pointing toward the inner surface **80**. The periphery of the embodiment **260** defines the shape of a cross.

Referring to FIG. **15** there is illustrated an embodiment **270** which points out that different heat exchange rates may be desired so that a displacement of the inner surface **80** from the center of the peripheral surface **82** may be desirable. In this instance the module **51a** will be shorter than the module **51b**, therefore providing different heat transfer capabilities. Each of the modules **51***c* will provide substantially the same heat transmitting or heat transfer capability, but this capability is different from both that of the matrix module **51***a* and the matrix module **51***b*. Separate plenums can be arranged to receive heated fluids issuing from modules **51***a*, **51***b*, and **51***c*, all of which will have different temperatures.

In addition to the more or less regular configurations discussed hereinbefore it should be kept in mind that highly irregular configurations may be utilized to achieve different heat transfer characteristics. The principles of this invention are also applicable to recuperator bodies having counter flow as well as cross flow heat transfer characteristics.

Referring to FIG. **16** there is illustrated, in an exploded view, components of a recuperator apparatus **280** in which a single large cross flow type matrix module **51** is utilized. An outer shell **290** includes a top plate **292**, a bottom plate **294**, and support columns **296** separating and connecting the plates **292, 294**. A plurality of heat exchange body support elements **170** are shown extending up through the bottom plate **294** and down through the top plate **292** to position the matrix module **51** in the outer shell or housing **290** in an aligned desired location.

An end plate **300** is shown for connection to the outer shell **290**. A port connection **302** enables connection of an intake fluid to or the exhaust of a fluid from the matrix module **51**. The end plate **300** may be bolted or otherwise suitably attached to the top and bottom plates or the support columns. Assuming that the four open faces of the shell **290** have the same dimensions, then another opposing end plate will be provided which is identical to end plate **300**, and two opposing side plates may be provided which are identical to the end plate **300**.

Ductwork for directing fluid to or collecting fluid from one of the series of passageways in the matrix module **51** is indicated generally at **310**. The ductwork **310** is generally shaped like the frustrum of a pyramid and has a rectangular outer edge for sealing against the plate **300**. An inner face **314** of the ductwork **310** is provided for sealing against the matrix module.

Referring to FIG. **17** a wall of the ductwork **310** is illustrated in cross section and shows the outer edge **312** in a suitable sealing relationship with respect to the plate **300**. The wall advantageously curves inwardly toward the module **51** so that it may be flexed into a sealing position similar to that discussed hereinbefore with respect to the plenum walls in FIG. **8**. The flexing of the wall **310** yieldingly urges the wall portion against the matrix module **51**.

To encourage a sliding sealing engagement the innermost portion of the wall may have a cupped or curved portion **316** as shown in cross section in FIG. **17**. If the sliding seal engagement caused by a flexing of the walls of the plenum **310** is insufficient to properly maintain the seal, or if it is undesirable to flex the material of the wall of the plenum **310**, then a support member **170** as disclosed hereinbefore may be utilized to yieldingly urge the wall portion **316** against the matrix module **51**. Use of the support member **170** in this position also enables a horizontal alignment of the matrix module **51** in the outer shell **290**. Similarly, the flexing of the wall of the plenum **310** under pressure may also serve to yieldingly align the matrix module **51** in the outer shell **290**.

Referring to FIG. **18** there are illustrated an end plate **330** and a double plenum **340** that may be utilized if the glass-ceramic heat exchange body utilized in the shell **290** is of the counter flow type, as opposed to the cross flow type illustrated in FIG. **16**.

The end plate **330** has a first port connection **332** for a first fluid and a second port connection **334** for a second fluid. The double plenum **340** is similar in construction to the plenum **310** illustrated in FIG. **16** and functions in the same manner. The difference in FIG. **18** lies in the provision of a central dividing edge **344**, intermediate end edges **342** for enabling a seal between the ports **332, 334** on the inside of the end plate **330.** A first dividing wall portion **346** extends toward the heat exchange body and away from the center of the double plenum, while a second dividing wall portion **348** extends from the central dividing edge **344** toward the glass-ceramic heat exchange body in the shelf **290** and also away from the center of the double plenum. It may be advantageous in some applications to utilize a single wall between the double plenum chambers of the element **340,** wherein the single wall has a bellows type construction to enable the retention of a seal while separating the fluids entering and leaving ports **332,** 334. Two individual plenums may also be utilized for the two ports.

There has thus been described herein novel recuperator structures and a novel method for making recuperators. A heat exchanging body for two fluids is constructed of glass-ceramic material and has formed therein a first and a second series of passageways to receive the two fluids to effect a heat exchange therebetween. The first and second fluids are channeled to the first and second series of passageways and prevent cross flow between the two fluids by yieldingly urging inlet and outlet plenum walls for the first and second fluids into a sealing relationship against the glass-ceramic body to accommodate expansion and contraction of the plenum walls without losing the sealing relationship with the glass-ceramic body. The method further includes yieldably supporting the glass-ceramic body in a housing to prevent transmission of a deleterious mechanical shock to the body. A glass-ceramic body is also advantageously yieldably supported in the housing with the inlet and outlet plenums in alignment with the first and second series of passageways to enable expansion and contraction of the housing while maintaining alignment between the plenums and passageways.

While there have been shown and described and pointed out the fundamental novel features of this invention with reference to the preferred embodiments thereof, those skilled in the art will recognize that various changes, substitutions, omissions and modifications in the methods and structures described may be made by those skilled in the art without departing from the spirit of the invention.

We claim:

1. Recuperator apparatus, comprising

a. A glass-ceramic heat exchanging body having an internal surface defining an inner chamber formed in said body, a peripheral surface spaced outwardly from said internal surface, and spaced end surfaces connecting said internal and peripheral surfaces;

b. said body including a portion in which a first and a second series of passageways are formed therethrough, the passageways of said first series extending and enabling passage of a first fluid between said internal and peripheral surfaces, the passageways of said second series extending and enabling passage of a second fluid between said end surfaces, the walls of said first and second series of passageways being disposed in heat transmitting relationship with each other enabling a heat exchange between first and second fluids passing through the first and second series of passageways; and

c. first ductwork means for channeling a first fluid to one of said inner chamber and peripheral surfaces and collecting said fluid as it issues from the other of said inner chamber and peripheral surfaces,

d. second ductwork means for channeling a second fluid to one of said end surfaces and collecting said second fluid as it issues from the other of said end surfaces, and

e. housing means for surrounding and supporting said heat exchanging body in a relatively stationary position during relative expansion and contraction movements of components of said apparatus to aid in maintaining inlets and outlets of said first and second series of passageways positioned for connection with said first and second ductwork means,

f. said housing means, including an outer shell disposed around and spaced from said peripheral surface of said body and a plurality of yieldable means extending between said outer shell and said body,

g. said first ductwork means including a first wall portion surrounding an inner chamber opening adjacent an end surface of said heat exchanging body and extending between a perimetrical area adjacent said chamber opening and a continuation of said first ductwork means, and means for maintaining said first wall portion in contact with said perimetrical area during expansion and contraction of said recuperator apparatus.

2. Recuperator apparatus as defined in claim **1** in which each of said yieldable means includes a contact element extending toward and contacting said heat exchanging body, said contact element having a rod portion, a cylinder attached to said outer shell for slidably receiving said rod portion of said contact element, and means associated with said cylinder for yieldingly urging said rod portion and thus said contact element into supporting contact with said heat exchanging body.

3. Recuperator apparatus as defined in claim **2** in which said yieldingly urging means comprises spring means disposed in said cylinder.

4. Recuperator apparatus as defined in claim **3** in which the portion of said cylinder containing said spring means is located outside of said housing to remove said spring means from the direct influence of temperatures within said housing.

5. Recuperator apparatus as defined in claim **3** which further includes sealing means disposed between said rod portion and the cylinder slidably receiving said rod portion to prevent penetration of fluids in said housing into the portion of said cylinder containing said spring means.

6. Recuperator apparatus as defined in claim **2** in which each support member means further includes means for adjusting the force said yieldingly urging means exerts on said rod portion of said contact element.

7. Recuperator apparatus as defined in claim **1** in which said yieldable support means includes

a. a plurality of peripheral surface support means extending inwardly from said housing and yieldably contacting said peripheral surface to maintain the transverse position of said heat exchanging body, and

b. a plurality of end surface support means extending inwardly from said housing and yieldingly contacting each of said end surfaces to maintain the axial position of said heat exchanging body.

8. Recuperator apparatus as defined in claim **1** in which said first ductwork means further includes

a. means for providing a sealing means between said first wall portion and said perimetrical area adjacent said inner chamber opening, and

b. means for maintaining said first wall portion in contact with said sealing means.

9. Recuperator apparatus as defined in claim **8** in which said means for maintaining said first wall portion in contact with said sealing means includes means for yieldably biasing said portion into contact with said sealing means.

10. Recuperator apparatus as defined in claim **8** in which said first wall portion is constructed from spring material and is connected between said first ductwork continuance and said sealing means in a flexed condition to maintain contact therewith.

11. Recuperator apparatus as defined in claim **8** in which said sealing means between said first wall portion of said first ductwork means and said perimetrical area adjacent said chamber opening includes

a. a metal seal member having a configuration which covers the perimetrical area adjacent said inner chamber opening,

b. said first wall portion forcibly engaging said metal seal at an acute angle enabling a sliding sealing action in response to differential movement during expansion and contraction.

12. Recuperator apparatus as defined in claim **11** in which said sealing means further includes high temperature resistant, resilient gasket means interposed between said metal seal and said perimetrical area adjacent said inner chamber opening.

13. Recuperator apparatus as defined in claim **11** in which

a. said first wall portion of said first ductwork means also functions as a wall portion for said second ductwork means,

b. the angle of engagement of said first wall portion with said metal seal being acute with respect to the one of the ductwork means which is to carry fluid under a lower pressure, thereby enabling fluid under a higher pressure in the other ductwork means to assist in maintaining said first wall portion in contact with said metal seal.

14. Recuperator apparatus as defined in claim **1** in which said first ductwork means includes

a. a second wall portion surrounding a perimetrical area adjacent the junction of one end surface and the peripheral surface of said body and extending therefrom to a continuance of said first ductwork means,

b. a third wall portion surrounding a perimetrical area adjacent the junction of the other end surface and the peripheral surface of said body and extending therefrom to said continuance of said first ductwork means,

c. means for providing a sealing means between each of said second and third wall portions and the respective perimetrical areas adjacent the junctions of said end surfaces with said peripheral surface, and

d. means for maintaining said second and third wall portions in contact with their respective sealing means.

15. Recuperator apparatus as defined in claim **14** in which each sealing means for said second and third wall portions includes

a. a metal seal having a configuration which covers the perimetrical area adjacent the junction of an end surface and said peripheral surface,

b. said second and third wall portions forcibly engaging the respective metal seals at an acute angle enabling a sliding seal action in response to differential movement during expansion and contraction.

16. Recuperator apparatus as defined in claim **15** in which said seal means further includes high temperature resistant, resilient gasket means interposed between each of said metal seals and their respectively adjacent perimetrical areas.

17. Recuperator apparatus as defined in claim **15** in which

a. said second and third wall portions of said first ductwork means also function as wall portions for said second ductwork means,

b. the angle of engagement of said second and third wall portions with their respective metal seals being acute with respect to the one of the ductwork means which is to carry liquid under a lower pressure, thereby enabling fluid under a higher pressure in the other ductwork means to assist in maintaining said second and third wall portions in contact with their respective metal seals.

18. Apparatus as defined in claim **1** in which said second ductwork means includes

a. a plenum for supplying a second fluid to one of said end surfaces of said body,

b. means for preventing entry of said second fluid into said inner chamber of said body,

c. said plenum including a first wall portion surrounding a perimetrical area adjacent the junction of said one end surface and the peripheral surface of said body,

d. a sealing means between said first wall portion and said perimetrical area adjacent the junction of said one end surface and the peripheral surface of said body, and

e. means for maintaining said first wall portion of said plenum in contact with said sealing means.

19. Apparatus as defined in claim **18** in which said second ductwork means further includes

a. a second wall portion surrounding a perimetrical area adjacent the junction of the other of said end surfaces and the peripheral surface of said body and extending therefrom to a continuance of said second ductwork means,

b. a sealing means between said second wall portion and said perimetrical area adjacent the junction of said end surface and said peripheral surface, and

c. means for maintaining said second wall portion in contact with said second wall sealing means,

d. a third wall portion surrounding the perimetrical area adjacent the junction of the other of said end surfaces and the surface of said inner chamber and extending therefrom to a continuance of said second ductwork means,

e. a sealing means between said third wall portion and said perimetrical area adjacent the junction of the other end surface and the surface of said inner chamber, and

f. means for maintaining said third wall portion in contact with said third wall sealing means.

* * * * *

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,889,744
DATED : June 17, 1975
INVENTOR(S) : James A. Hill; George E. Keefer

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

Col. 3, line 57, "are" should be --area--

Col. 4, line 67, "recuperator" should be --regenerator--

Col. 5, line 37, after "each" insert --tube--

line 58, delete "in"

line 66, after "sealed" change "in" to --at--

Col. 6, line 64, "disposed" should be --deposited--

Col. 7, line 23, "of" should be --or--

Col. 9, line 57, "outlines" should be --outlined--

Col.12, line 28, "exchange" should be --exchanger--

Col.13, line 59, "112" should be --102--

Col.15, line 8, "yieldably" should be --yieldingly--

line 46, "yieldably" should be --yieldingly--

Signed and Sealed this

thirteenth **Day of** *April 1976*

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks