Nov. 5, 1968 H. M. LONG 3,409,075

MATRIX HEAT EXCHANGE CORES

Filed Aug. 20, 1965 2 Sheets-Sheet 1

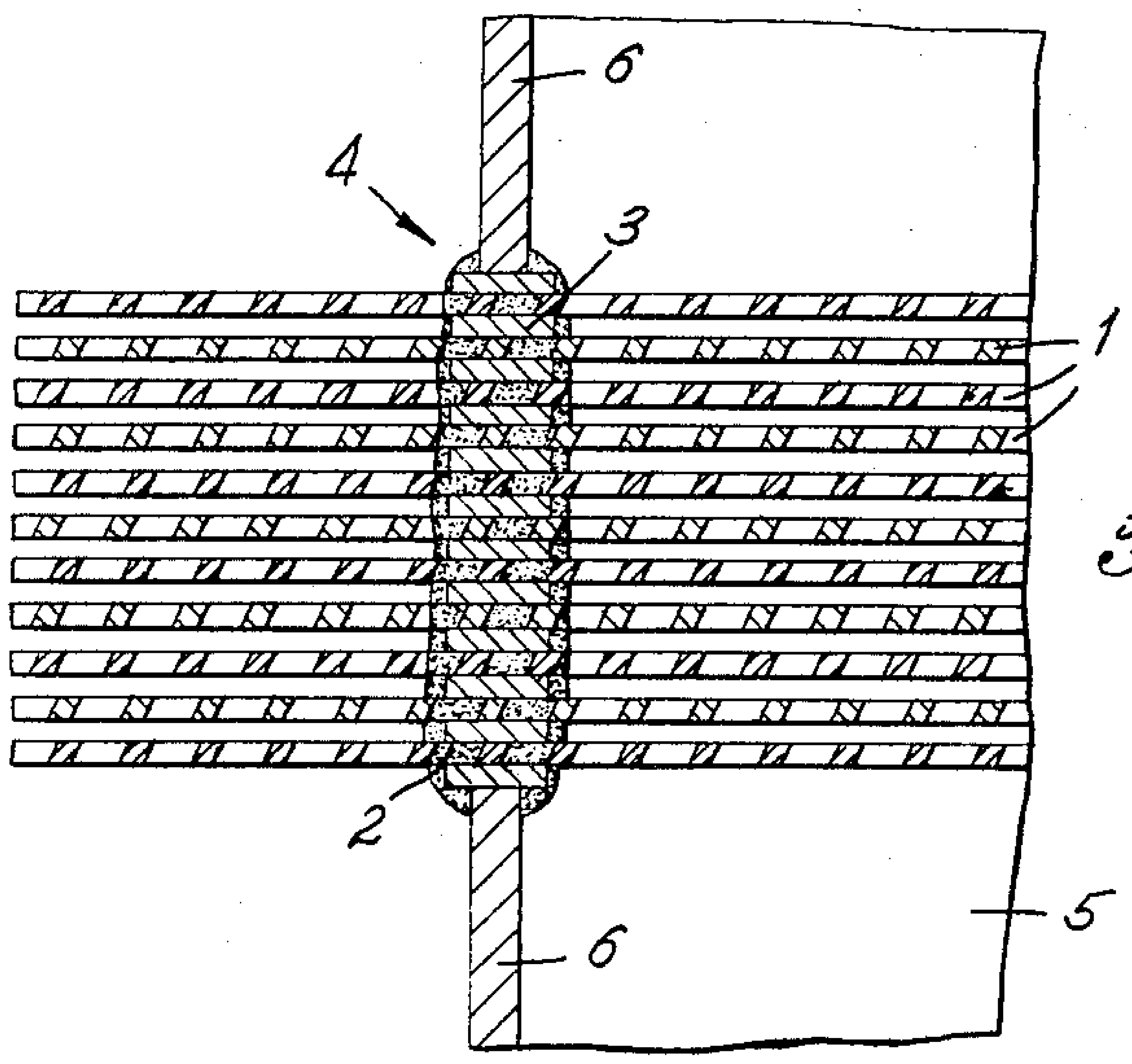

Fig. 1.

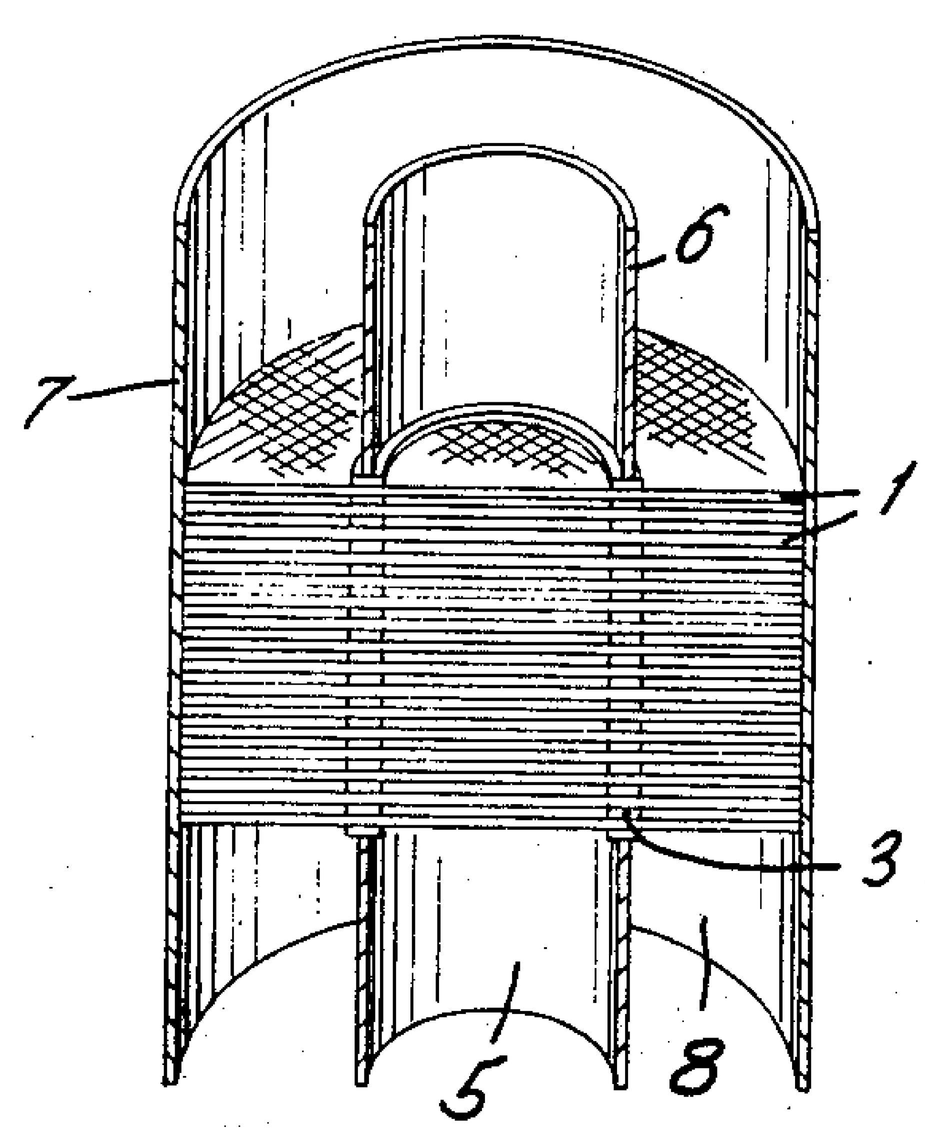

Fig. 2.

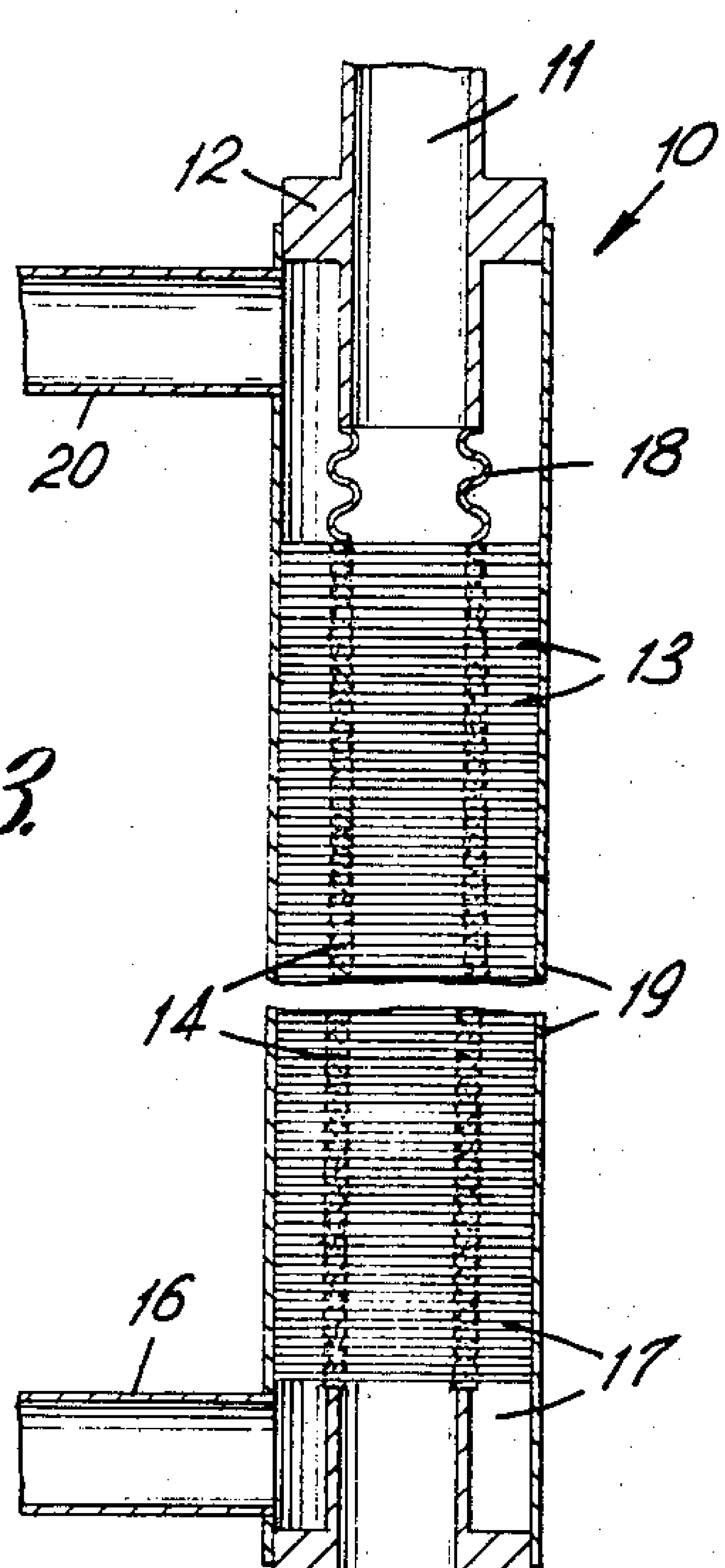

Fig. 3.

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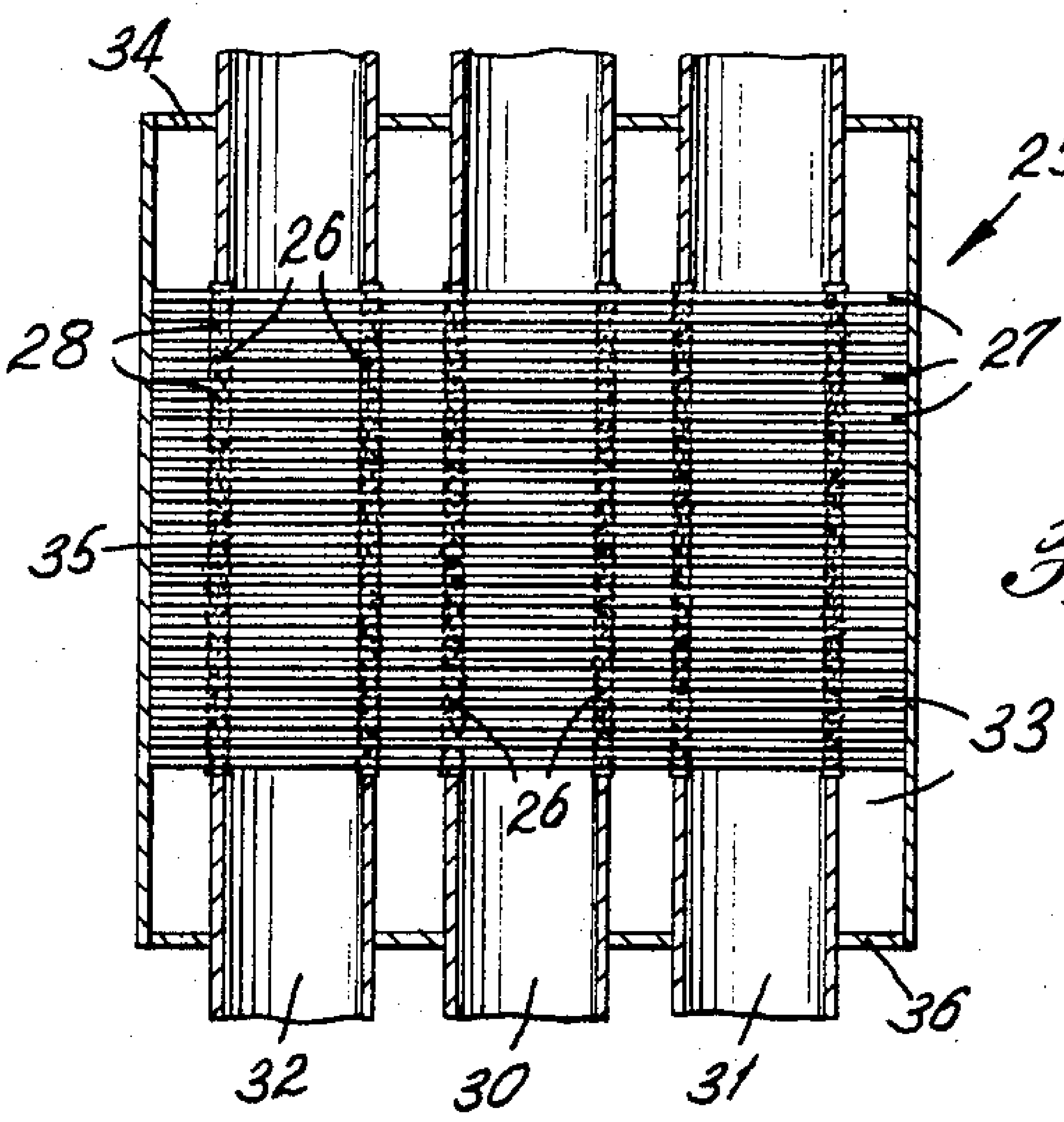

Fig. 4.

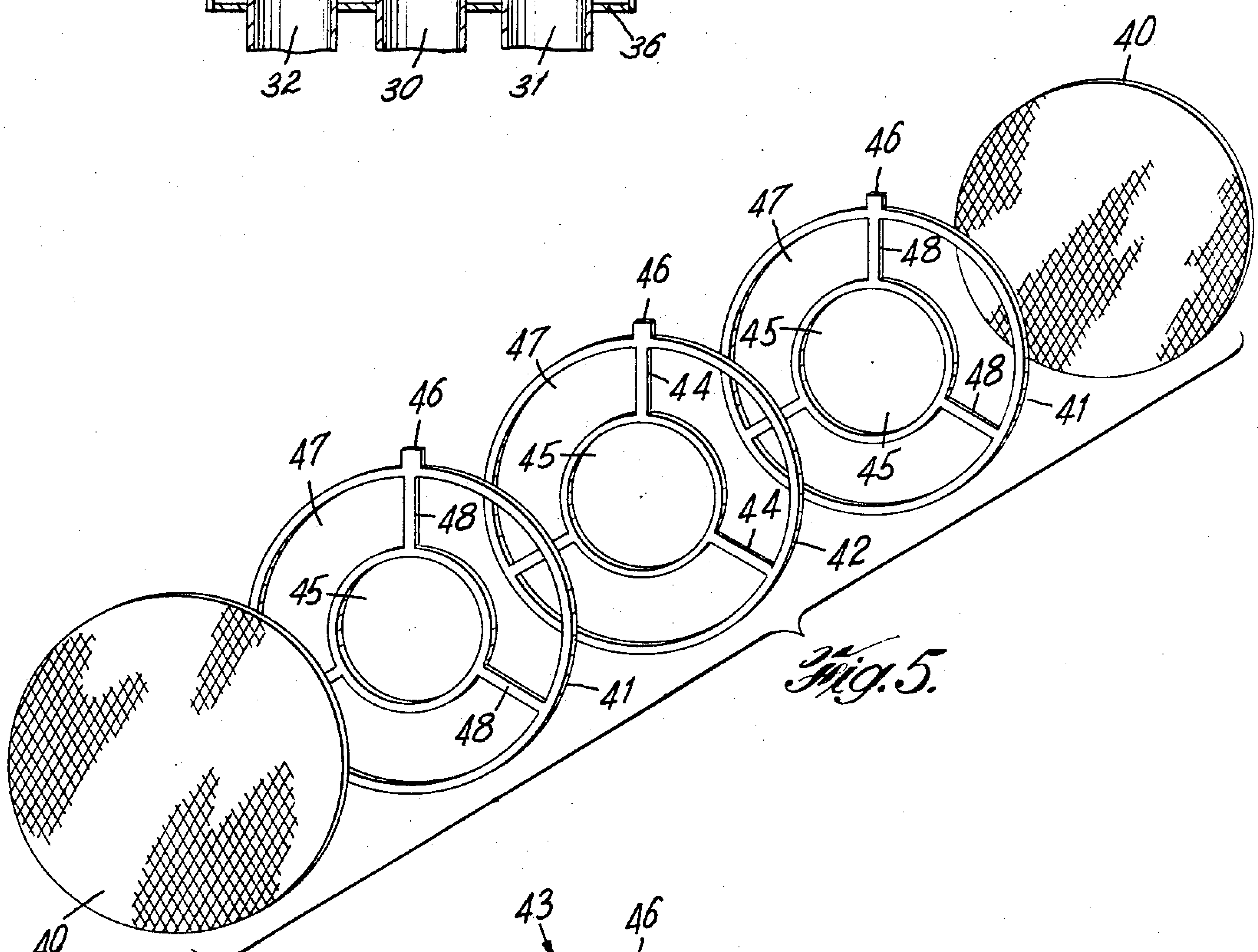

Fig. 5.

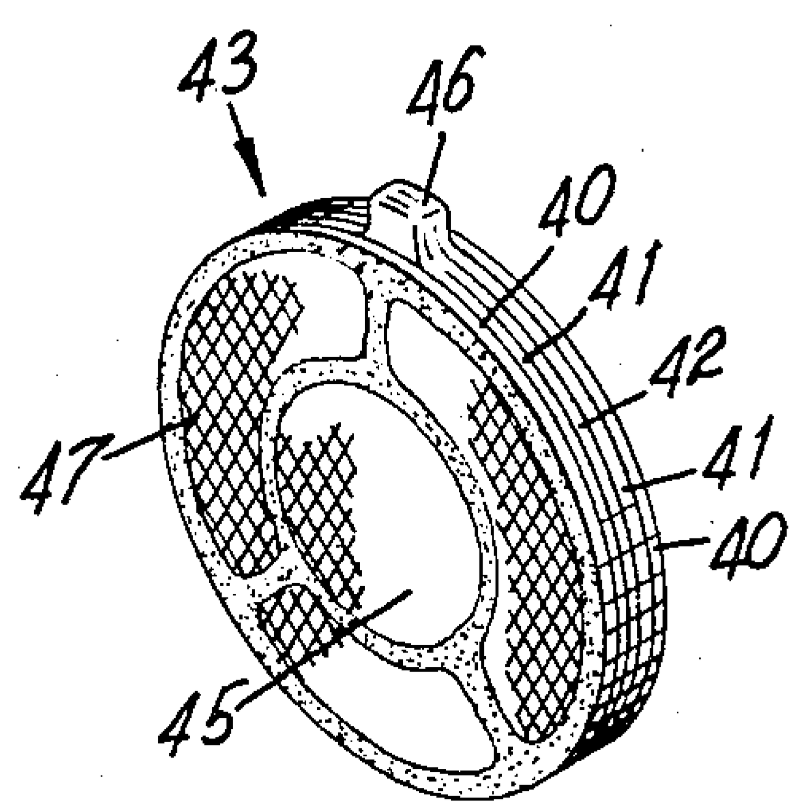

Fig. 5a.

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MATRIX HEAT EXCHANGE CORES

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ABSTRACT OF THE DISCLOSURE

A heat exchange core comprising a plurality of matrix sheets each having a multiplicity of apertures, and at least one fluid impervious wall which extends through and joins each sheet to form at least two discrete sections therein defining thereby at least one fluid pass. The wall comprises a portion of each sheet and an adhesive.

This invention relates to compact heat exchange cores having high heat transfer surface-to-volume ratios and particularly to such heat exchange cores adapted for heat exchange between two or more fluids at cryogenic temperatures.

There is an increasing need within many industries for very compact heat exchangers capable of transferring large amounts of heat. The increasing use of superconductive devices and maser applications, for example, requires operation at temperatures approaching absolute zero. It is well known that heat exchangers are required to produce these very low temperatures. However, just as there is a need for highly efficient and compact heat exchangers in cryogenic applications, there is also a need for reliable, rugged and compact heat exchangers for operation in systems at room temperatures and above.

There are many prior art heat exchange devices of light weight and size. For example, regenerators provide good heat storage and transfer within a compact space and obviate one of the problems in designing compact units through the use of particulate or fibrous packing material. This material acts to interrupt longitudinal heat conduction and hence to permit relatively large temperature differences to exist between the ends of the regenerator. However, regenerators suffer when performing at temperatures below 200° K. because of the loss of specific heat of the particulate or fibrous packing material and appreciable losses caused by the requirement for blowdown of cold dense gases. Thus, for efficient performance at low temperatures heat exchangers are preferable. Many prior art heat exchangers, however, do not meet the size, weight and efficiency requirements presently needed in many applications. For example, finned-tube type heat exchangers are inadequate because of the difficulty of providing sufficient heat transfer surface area within an allowed space and by low fin efficiencies.

Matrix type heat exchangers offer a solution to the size, weight and efficiency problems faced by the prior art. In general, a matrix heat exchanger utilizes stacked metal sheets, within a suitable container, each sheet having a multiplicity of apertures or interstices. Such sheets are typically porous or perforated metal, for example expanded metal, or woven wire cloth or screen. In operation, a fluid passes normal to the plane of the sheets through the interstices and exchanges heat with another media through the heat conductive material encountered in its flow path. The heat conductive material is normally a metal and forms the boundaries of the interstices. The matrix formed within a matrix heat exchanger can be visualized as a random distribution of short rods arranged to provide a constant resistance to fluid flow in any direction normal to the rods. This random distribution is closely approximated by, for example, the aforementioned woven

wire screen wherein the matrix of openings are defined by the interstices within the screen.

However, prior art matrix heat exchangers suffer from fluid and pressure loss owing to leaks which develop at the walls separating individual fluid passes. These walls are often formed through the use of gaskets and a portion of the areas of adjacent sheets, known as gasket surfaces. Thus, the surfaces of the sheets at the points where walls are formed must be smooth. Leaks develop between the sheets because of the great number of sheets used and inevitable flaws between the gasket and the gasket surfaces which materialize under pressure. The smooth surface requirement adds to fabrication costs in increased machining and dictates the use of materials which are not as readily available as expanded metal sheets and wire screens.

However, the most serious deficiency in prior art matrix heat exchangers arises in attempts to resolve the aforementioned problems. Matrix surfaces were terminated at the wall of one fluid passage and reestablished again in a second fluid passage. In other words, an individual matrix surface did not extend uninterrupted from one heat exchange medium to another, there being a wall separating the two and dividing the matrix surfaces. This results in an interrupted heat flow between two fluids and allows for longitudinal heat transfer from one end of a heat exchanger to the other by conduction through the separating wall. As was previously mentioned, increasing amounts of longitudinal heat transfer decreases the compactness of a unit.

It is an object of this invention, therefore, to provide a matrix type heat exchanger which substantially eliminates longitudinal heat transfer and offers an uninterrupted heat path from one heat exchange medium to another.

It is another object of this invention to provide a matrix type heat exchange core which does not develop leaks between adjacent matrix surfaces and which does not require smooth surfaces at the wall separating the heat exchange mediums.

It is still another object of the present invention to provide a matrix type heat exchange core which is economical in construction, highly efficient in operation, relatively light, rugged, and very compact.

These and other objects, advantages and features of the present invention will become more apparent from the following description, appended claims and drawings in which:

FIGURE 1 is a vertical partial section through a matrix heat exchange core which is constructed according to the present invention;

FIGURE 2 is a perspective view of the embodiment shown in FIGURE 1;

FIGURE 3 is a vertical axial view of another embodiment of the instant invention showing a complete heat exchanger;

FIGURE 4 is a vertical axial view of still another embodiment of the instant invention showing multiple fluid passes;

FIGURE 5 is a perspective exploded view of still another embodiment of the present invention; and

FIGURE 5*a* is a perspective view of the embodiment shown in FIGURE 5 as it would normally appear.

Briefly, and in accordance with the present invention, a highly efficient, compact and light weight matrix type heat exchange core is provided. A plurality of heat conductive sheets are arranged such that the upper surface of any one sheet is proximate to and substantially parallel to the lower surface of an adjacent sheet. Each sheet has a multiplicity of apertures extending over substantially the entire area of its upper and lower surfaces. These apertures provide fluid communication through each sheet and the plurality of sheets. At least one fluid-impervious wall extends through the sheets between the upper and lower surfaces thereof and joins adjacent sheets. This wall defines discrete sections within each sheet. Corresponding discrete sections of individual sheets unite to form at least one fluid pass. The wall comprises a portion of each sheet and an adhesive.

The instant invention also embraces highly efficient, compact and light weight matrix type heat exchangers. Within a cavity or suitable housing is a plurality of heat conductive sheets. Each sheet is proximate to and substantially parallel to adjacent sheets. A matrix of heat exchange surfaces is provided by a multiplicity of apertures or interstices extending over substantially the entire area defined by the upper and lower surfaces of individual sheets as, for example, are formed by expanded metal or wire gauze sheets. At least one fluid- and pressure-impervious wall is formed within each sheet and between adjacent sheets. This wall divides the plurality of sheets into sections for fluid mediums and effectively isolates any given fluid medium from any other fluid medium. In short, the wall(s) forms discrete fluid passes. The wall is formed of an adhesive material, preferably thermally cured expoxide resin, discussed in detail hereafter, in intimate contact with each sheet. Thus the heat conductive material of each sheet cooperates with the adhesive to produce a reinforced wall capable of sustaining relatively large pressure differences across the wall. Moreover, the individual sheets extend through the wall to provide an uninterrupted heat path. When viewed as a whole, the wall defines at least one fluid pass such that a fluid passes through individual matrix sheets and provides a pressure and fluid barrier within each sheet and between adjacent sheets. Means are also provided to introduce and withdraw fluids from their respective fluid passes. Such means include, for example, tubing or manifolds fabricated from a variety of materials.

Referring now more specifically to FIGURE 1, a plurality of spaced-apart and parallel heat conductive sheets **1** is bonded together through adhesive **2** integrated with spacers **3**. The resulting structure defines a wall **4** which in turn defines a circular fluid pass **5** for the heat exchange core of this invention. The wall **4**, while preferably circular, may be of any desired shape, for example, rectangular. The heat conductive sheets **1** extend through the wall **4** to provide an uninterrupted heat transfer path from a fluid media outside the wall to a fluid media within the fluid pass **5**. Outside the heat transfer regime, the wall **4** may be extended with any suitable material, for example, stainless steel or plastic. These extensions are shown by reference numeral **6** and are integrated into wall **4** through the use of adhesive **2**, and function to provide suitable connections to other components of a heat transfer system. The spacers **3** interposed between adjacent sheets **1** function to separate the sheets in order to prevent thermal shorts. That is, to prevent heat conduction paralleling the axis of the wall **4** or fluid pass **5**. The spacers may be of any suitable material such as, by way of example, plastic or metal. However, if a heat conductive material such as metal is used, adhesive is placed between the spacers and the screens to reduce longitudinal heat conduction through heat conductive sheets **1** to the spacers **3**. The spacers **3** also function to increase the strength of wall **4**. The use of spacers may reduce the compactness of a complete heat exchanger by making it longer than would otherwise be necessary for an equivalent amount of heat transfer area, that is, there is a reduction in heat transfer surface area per unit of volume. Accordingly, the heat exchange cores of the present invention are adaptable for construction without spacers. The desired space between adjacent sheets is then provided by the adhesive material itself. The adhesive or bonding material may be either metal brazing or soldering material or a suitable adhesive material such as epoxide resin plastic with the choice depending upon the pressure, temperature, and service condition desired. However, an adhesive material such as epoxide resin plastic is preferred because this class of materials reduces longitudinal heat conduction, thus permitting larger temperature differences to exist at the opposite ends of a given fluid pass and hence permits a shorter heat exchanger. If a plastic material is used as the adhesive material it need not provide a great deal of strength within itself. Strength against pressure and other forces are supplied by reinforcement of the adhesive material by the porous sheets. As seen in FIGURE 1, the adhesive material is intimate with the structural material of the sheets and fills the interstices therebetween. Thus, the flow control or pressure retaining wall **4** may be considered a metal-reinforced plastic tube. The sheets **1** are composed of, for example, perforated metal, expanded metal, or wire screen. The choice of material depends on its compatibility with the fluid medium which it intimately contacts, but must be of a heat conductive material, as was previously noted. The sheets also extend from one fluid medium to another in order to provide an uninterrupted heat path. Thus, the fluid within fluid pass **5** transfers or receives heat by way of the plurality of individual sheets; each sheet also contacting and transferring heat to or from a surrounding fluid medium.

The features of the present invention, discussed with reference to FIGURE 1 and other embodiments to be subsequently described, provide a great deal of design flexibility. For example, different materials can be used for the matrix sheets within a particular fluid pass or heat exchange core to accommodate any particular temperature level. Moreover, the wall **4** may be made circular, rectangular or any desired shape depending upon the particular application envisioned. Although for some applications the external dimension of the matrix sheet, the dimension outside of and normal to wall **4**, is usually about one half the diameter of the fluid pass **4**, other proportions may be used to suit specific requirements.

FIGURE 2 illustrates the concepts set forth in reference to FIGURE 1 in perspective and additionally shows an outer wall or shell **7**. Like numbers in the two figures refer to like items. The outer wall may be formed and constructed in accordance with the principles discussed with reference to wall **4** of FIGURE 1. Thus the outer wall **7** can be formed of an adhesive material cooperating with the sheets **1** to form a reinforced plastic tube. Alternatively, the outer wall **7** can be formed of any desired low conductive material such as stainless steel and not rely on the sheets for reinforcement; with this embodiment the sheets need not be in contact with the outer wall. The fluid pass **5** and a second fluid pass **8**, which is defined by the annular volume bound by wall **4** and outer wall **7**, can function as heat transferring mediums in any number of ways. For example, as is typical in cryogenic applications, a higher pressure warmer fluid can pass through fluid pass **5**, receiving heat from a lower pressure colder fluid circulated in fluid pass **8**. The streams of fluid can be made to flow in opposite directions, parallel, or one fluid can be relatively quiescent. The flow area of the lower pressure fluid in cryogenic systems is usually made larger than the corresponding area of the higher pressure fluid in order to avoid excessive pressure drops in the lower pressure portion of the system. Thus it is contemplated that the compass of this invention extend to many different fluid flow applications.

With reference to FIGURE 3, there is shown a complete heat exchanger **10**. A high pressure fluid is continuously introduced into fluid pass **11** through inlet header **12**. Simultaneously, a colder low pressure fluid is continuously introduced through low pressure inlet header **16** and into an annular low pressure fluid pass **17** in counter flow relationship to the high pressure fluid. Each fluid passes in intimate contact with the matrix sheets **13** which are in the form of woven wire screens. The screens extend along substantially the entire length of the heat exchanger. The inner wall **14** which defines the fluid pass **11** is formed from an epoxide resin material in intimate association with the interstices within wire screens **13** and is strengthened by that portion of metal in the screen which is in intimate relationship with the epoxide resin. The screens, while in very close proximity, are separated by an epoxide layer. Each screen occupies the entire area normal to the flow of the two fluids and extends through the inner wall **14** in one continuous sheet. Heat is therefore transferred from the low pressure to the high pressure fluid through and by means of the screens. The high pressure fluid thus heated leaves the heat exchanger through high pressure outlet header **15**. The low pressure fluid leaves the confines of the annular fluid pass **17** by means of low pressure outlet header **20**. The outer wall **19**, which together with the inner wall **14** form the fluid pass **17**, is shown as being constructed of a circular stainless steel tube. The use of an outer wall fabricated from metal may be dictated in applications requiring a rigid heat exchanger which can resist forces incurred in making connections to the outer wall. Otherwise these forces and other forces produced in operation or from elements in a heat transfer system can distort and possibly damage the wire screens and inner wall **14**. When the outer shell **19** is metal, it is often desirable to utilize a bellows **18** in series with the inner wall **14** and the high pressure inlet header **12**. The bellows compensates for differences in the coefficient of thermal expansion and temperature of the outer shell **19** and the inner wall **14**. However, as will become more evident subsequently, the outer wall may be formed of the same epoxide resin material and matrix sheets as is the inner wall and perform satisfactorily in a surprising number of applications. The headers **12, 15, 16** and **20** may be fabricated from any suitable material such as brass.

The instant invention is not limited to the heat exchanger depicted in FIGURE 3 but may take several forms. FIGURE 4, for example, shows a multiple pass matrix heat exchanger **25**. Multiple circular fluid passes **30, 31** and **32** are defined by walls **26** in the inner regions of the heat exchanger. Fluid occupies the volume **33** surrounding the fluid passes and defined within the shell **35**, the top header **34** and the bottom header **36**. The walls of the inner region are formed of adhesive and a portion of the sheets as previously discussed. The matrix sheets **27**, here shown as metal screens, extend across the heat exchanger and normal to the fluid passes terminating at the outer shell **35**. Alternatively, the shell **35** may be formed of an adhesive such as an epoxide resin in cooperation with the matrix sheets **27** in the same manner as the walls **26** are formed. Stainless steel or the like may also be used for shell **35**. If desired, spacers **28** may also be used to separate the sheets and strengthen the walls. The fluid passes terminate and are bonded to headers **34** and **36** or may extend for coupling with desired conduits (as shown). These headers may be formed of any suitable material such as, for example, bronze, plastic, or stainless steel. Additional fluid passes may, as well, be provided by simply extending their number in a plane parallel to the headers. Thus, fluid passes can describe various three dimensional configurations, for example, a cylinder, rectangular parallelepiped or cone. The configuration depicted may be used in either boiling or condensing service. A fluid is either boiled or condensed within the fluid passes **30, 31** and **32** by another surrounding fluid in volume **33**. As shown, this latter fluid would be confined in shell **35** between headers **34** and **36**. Formed heads or other enclosure may be added to contain the fluid being boiled or condensed. In boiling and condensing applications the temperature along the fluid passes is usually quite small eliminating the longitudinal heat conduction problem. In this event, metallic bonding of sheets **27** may be used to form walls **26**. By adding a flow control means such as a valve, the liquid level within the fluid passes may be controlled. The metallic bonded heat exchanger is capable of sustaining pressures of about 2,000 p.s.i.g. The configuration may also be used as a heat exchanger or, with appropriate openings, as a container. Depending upon the shape of the heat exchanger in a plane normal to the fluid passes, each fluid pass can be shaped circular, rectangular, square or the like. In operation each fluid pass may contain a separate fluid or alternate fluid passes can contain the same fluid for heat exchange between two fluids. Various flow arrangements are also suitable, for example, counter flow and parallel flow.

FIGURES 5 and *5a* are illustrative of the preferred embodiment of the instant invention. There is shown a plurality of expanded metal sheets **40** spaced apart by alternate preformed normally solid thermally curable epoxide resin rings **41** interspaced between metal spacers **42**. Thus in progressing from one expanded metal sheet to the next there is an epoxide resin ring, metal spacer, and another epoxide resin ring, etc. When fabricated, the epoxide resin rings insulate the expanded metal sheets from the metal spacers as well as space the sheets one from another as shown by the construction indicated by reference numeral **43** of FIGURE *5a*. The expanded metal sheets define a multiplicity of apertures which allows for fluid flow therethrough. Radial ribs **44** within spacers **42** serve to provide strength for the heat exchanger in flexure and to position the inner fluid passage **45** conveniently for fabrication purposes. The tabs **46** are for convenience of construction and serve to index respective parts. The ribs **44** can also serve to divide the outer fluid pass **47** into a plurality of sections which can be used as separate fluid passes. The epoxide resin ribs **48** serve, in final form to insure the fluid integrity of individual sections within the expanded metal sheets **40** and aid in the bonding of such sheets to the spacers **42**. A completed heat exchanger would be provided with appropriate inlet and outlet headers as discussed with reference to FIGURE 3.

FIGURE 5 is helpful in the discussion of the preferred manner of fabricating the heat exchangers of the instant invention. The normally solid thermally curable-epoxide resin rings **41** are checked to insure that they are clean and of uniform dimension. The expanded metal sheets **40** and spacers **42**, both fabricated from copper, are cleaned by vapor degreasing in trichloroethylene and an etch in a 15 percent nitric acid solution. The spacers and sheets are then rinsed thoroughly with water and dried in still air. The individual components are thereupon stacked in a fixture. Stacking begins with an epoxide resin ring, followed by an expanded metal sheet, an epoxide resin ring, spacer, epoxide resin ring, etc. The individual components are maintained in proper alignment in the fixture through the use of tabs **46**. When the fixture is filled the stack of components is loaded with, for example, a dead weight. The heat exchanger core (the epoxide resin rings, spacers, and sheets) is then ready for thermal curing. The temperature of the core is monitored to insure an even rise in temperature, during which time the dead weight causes the stack to settle until the desired bond thickness exists between the components of the stack. In a typical case the final cured length of a core will be about one third the original stack height. The rate of temperature rise is preferably set at that value which allows the correct settled length and the curing temperature to occur at substantially the same time. The core is then maintained at this curing temperature for the time required to fully cure the epoxide. After curing the core is allowed to cool slowly to a temperature at which it can be handled without deformation whereupon it is aircooled to room temperature. Sufficient cores made in this fashion can be bonded to each other by a similar heat curable epoxide to form a final core with sufficient surface area to accomplish a desired heat exchange task.

Several commercially available epoxide resins may be used as the adhesive, the selection depending upon the particular application envisioned for the heat exchange core. For example, as is well known in the art, different epoxide resins are more suitable for the cryogenic application than others, and conversely a resin suitable for such service may not be suitable for high temperature application. However, regardless of the type of epoxide resin employed the resins must be confineable in a desired bonding area, that is capable of conforming to a desired geometry. Thus, several thermally and chemically curable epoxide resins are well adapted for use in the instant invention. The preferred epoxide resins used in the practice of this invention are normally solid thermally curable. One desirable bonding material is an unsupported dry thermosetting film compounded from an epoxide resin with a filler such that only limited flow occurs at the curing temperature. Another is a thixotropic paste compounded from an epoxide with a filler such that there is no flow or drip during cure.

A heat transfer apparatus constructed in accordance with the principles of the instant invention displays a remarkably high heat transfer area per unit of volume. By way of example and not by limitation, heat exchanger cores as depicted in FIGURES 5 and *5a* have been constructed with 550 circular expanded metal sheets of 1.5 inches outer diameter in a length of 13.75 inches or slightly over 40 screens per inch. A similar construction using 120 screens yielded an overall length of about 3.375 inches for a screen count per inch of about 35. Each of the above exemplary heat exchanger cores were constructed in the above fusion by placing a normally solid thermally curable epoxide resin ring between individual sheets and spacers. The heat transfer area per unit of volume of these heat exchangers, depending upon a particular application, exhibit values between 700 to 1500 square feet per cubic foot. Moreover, values of 7500 square feet per cubic foot are readily achievable.

The walls constructed in accordance with the principles of this invention have been pressure tested. The walls were fabricated from normally solid thermally curable epoxide resin, metallic spacers, and expanded metal sheets as discussed with reference to FIGURES 5 and *5a*. The tests were conducted with helium within a sealed fluid pass. The walls successively withstood 500 p.s.i.g. static pressure without failure. The shear stress of the epoxide resin used was between 2,000 and 3,000 p.s.i. Thus, even higher pressures can be sustained within the fluid passes of this invention.

Heat transfer apparatus constructed in accordance with the principles of the instant invention display a remarkably wide range of hydraulic radii, defined as the ratio of the flow passage volume to area of the sides of the flow passage, and therefore may be designed to accomplish widely varying heat transfer tasks. In particular this invention allows the use of very small hydraulic radii without encountering the fabrication problems associated with small diameter tubing or closely spaced plates, By way of example and not by limitation, heat exchanger cores as depicted in FIGURES 5 and *5a* have been constructed with hydraulic radii of 0.021 cm. and 0.011 cm. Moreover values of 0.00265 cm. are readily achievable.

The heat exchange apparatus of this invention is admirably suited for cryogenic systems. In such applications it has been found that the conductivity from a warmer to a colder fluid is of the highest and most efficient in the art. The apparatus has very low longitudinal conductivity and pressure drop along its fluid passes. These advantages are not limited, however, to cryogenic systems and are useful in myriads of other applications. Slight modifications of the instant invention, for example, can carry its advantages into heat exchange applications with temperature between 500 and 1000° F. These advantages can be obtained by fabricating the matrix sheets from high conductive materials such as beryllium or beryllium oxide. Thus, many modifications may be made without departing from the spirit and scope of the appended claims, and, therefore, the embodiments of this invention discussed cannot be construed as limiting.

What is claimed is:

1. A heat exchanger comprising:

a plurality of spaced heat conductive sheets, each sheet having an upper and lower surface and a multiplicity of apertures extending through substantially each of the surfaces to provide fluid communication through the sheet, the plurality of sheets being arranged such that the upper surface of any one of said sheets is proximate to and substantially parallel to the lower surface of the next adjacent of said sheets; and

at least one fluid impervious reinforced wall longitudinally extending through and joining each of a substantial number of adjacent sheets thereby partitioning said sheets into at least two discrete sections such that at least one fluid pass is formed, the wall comprising an adhesive coextensive and in intimate relationship with a portion of said substantial number of adjacent sheets and which fills the interstices therebetween throughout the length of said wall; an outer shell bounding at least a substantial number of the individual perimeters defined by the individual edges of said sheets such that at least one additional fluid pass is formed between the reinforced wall and the outer shell;

means for communicating a low pressure fluid through one of said fluid passes; and means for communicating a substantially higher pressure fluid through the other of said fluid passes whereby said sheets provide an uninterrupted transverse flow of heat from one fluid to the other exclusively through said fluid impervious wall.

2. A heat exchanger according to claim **1** wherein the outer shell is a reinforced wall comprising an adhesive coextensive and in intimate relationship with a portion of at least a substantial number of adjacent sheets.

3. A heat exchanger according to claim **1** wherein between at least a substantial number of any two adjacent of said sheets there is provided at least one rib, said rib comprising a portion of said adjacent sheets and an adhesive and connects the outer shell to the wall.

4. A heat exchanger according to claim **1** wherein the adhesive comprises an epoxide resin.

5. A heat exchanger according to claim **4** wherein the epoxide resin is normally solid and thermally curable.

6. A heat exchanger according to claim **1** wherein a spacer is positioned between the upper surface of each of at least a substantial number of said sheets and the lower surface of an adjacent one of said sheets, each spacer forming a part of the wall.

7. A heat exchanger according to claim **3** wherein a spacer is positioned between the upper surface of each of at least a substantial number of said sheets and the lower surface of an adjacent one of said sheets, each spacer forming a part of the wall, the shell, and the at least one rib, and spaced apart from said surfaces by said adhesive.

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