

Sept. 15, 1964

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REFRIGERATION APPARATUS

3,148,512

Filed May 15, 1963

4 Sheets-Sheet 1

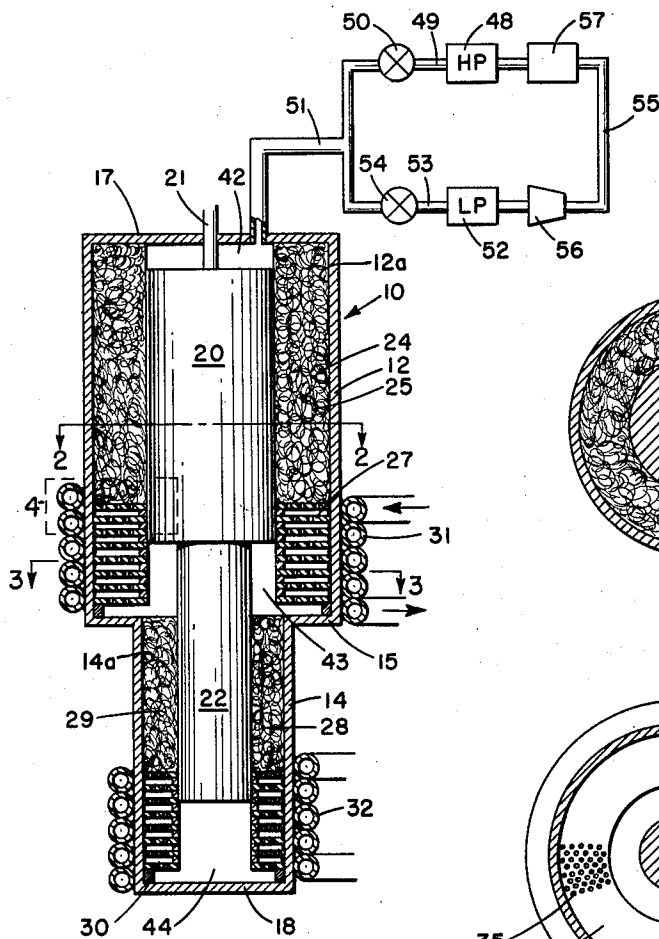


Fig. 1

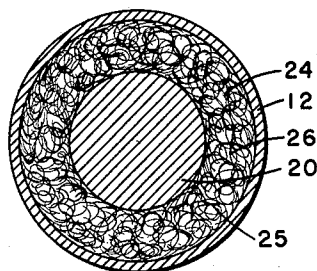


Fig. 2

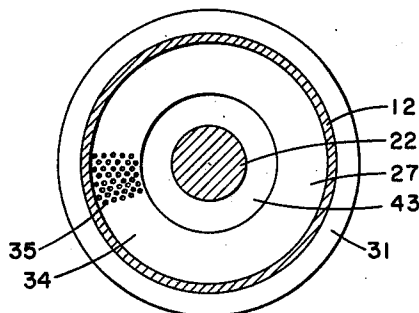


Fig. 3

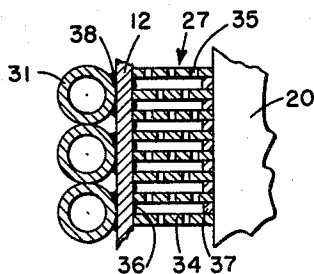


Fig. 4

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4 Sheets-Sheet 2

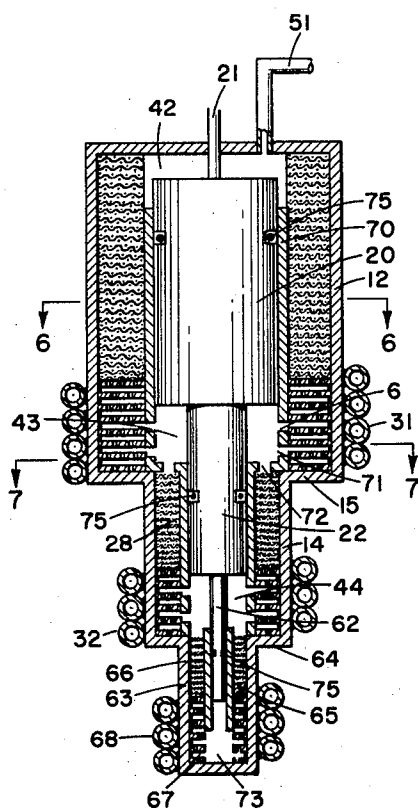


Fig. 5

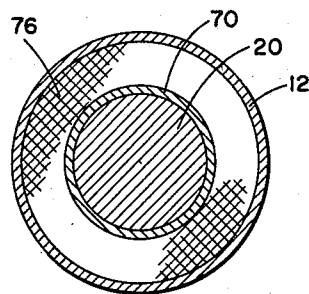


Fig. 6

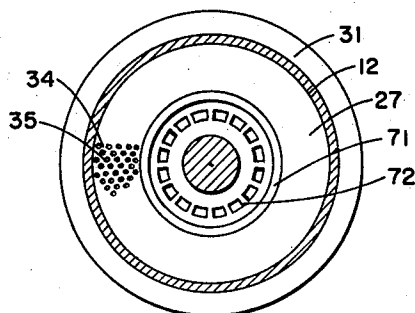


Fig. 7

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4 Sheets-Sheet 3

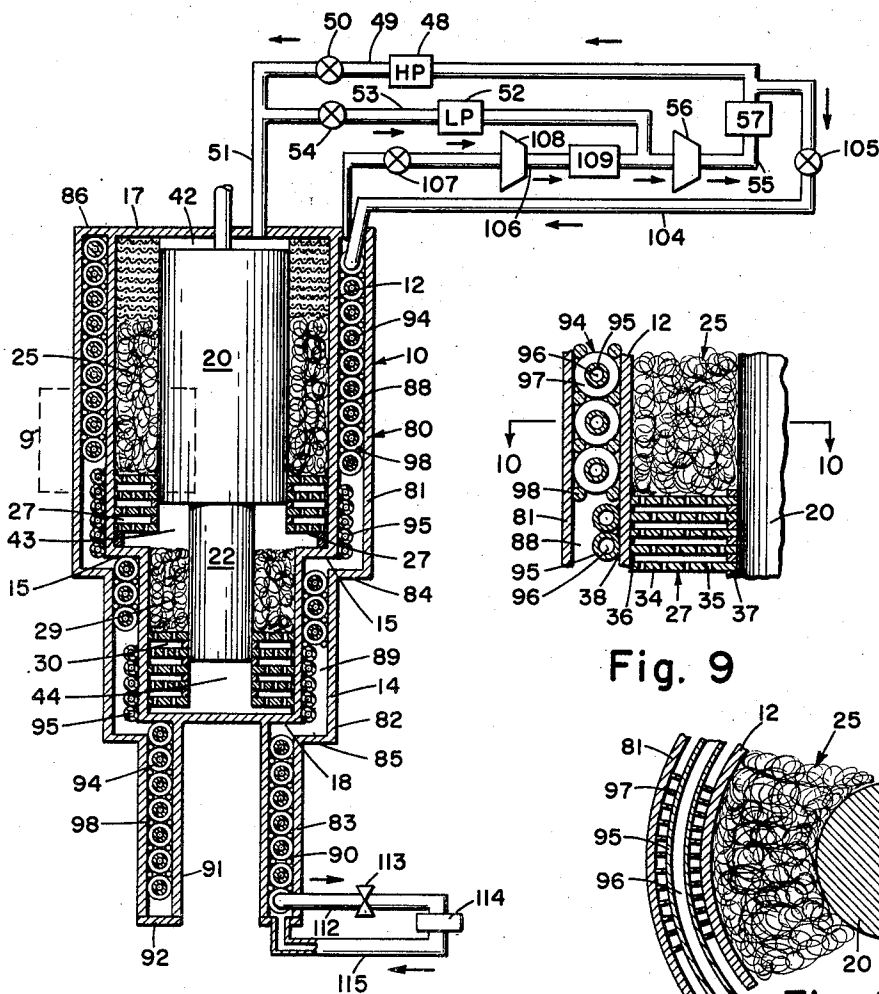


Fig. 8

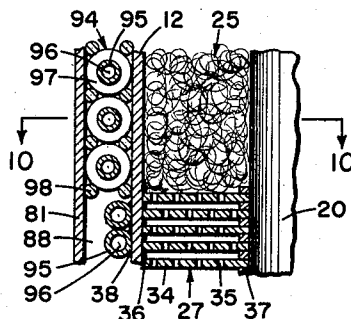


Fig. 9

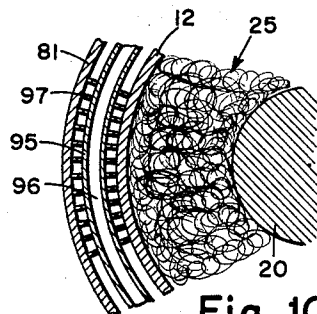


Fig. 10

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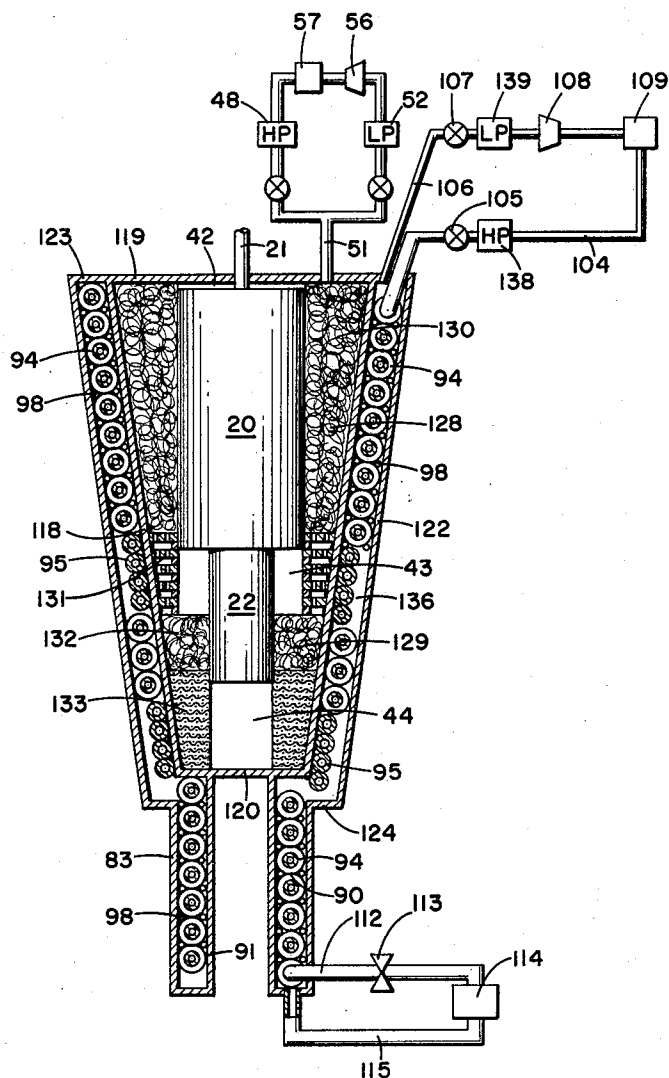


Fig. 11

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3,148,512

REFRIGERATION APPARATUS

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11 Claims. (Cl. 62—6)

This invention relates to novel refrigeration apparatus and more particularly to compact refrigeration apparatus suitable for carrying out refrigeration cycles designed to obtain extremely low temperature.

There are described and known in the prior art a number of cycles and their apparatus for achieving refrigeration. Many such cycles are based upon the use of expansion engines or turbines. Others involve complicated heat exchange systems while still others (although somewhat more simple in design) require tightly fitting pistons and sealing rings which must be capable of operation under extremely low temperatures.

In order to overcome the disadvantages inherent in the prior art refrigeration cycles, method and apparatus were developed for materially lessening these disadvantages. These methods and apparatus are the subject of United States Patents 2,906,101 and 2,966,035. Basically, the generic cycle disclosed in the two above-identified United States patents comprises the steps of removing and storing heat from a high-pressure fluid during its supply along a path to initially cool the fluid, subsequent expansion of the cold high-pressure fluid to effect further cooling and then the discharging of the cold low-pressure fluid along the same path to receive the heat previously stored. The apparatus described herein is particularly suited to the performance of the cycle and its modifications described in United States Patents 2,906,101 and 2,966,035.

Although the embodiments of the apparatus disclosed in United States Patents 2,906,101 and 2,966,035 have been suitable for providing low temperature refrigeration down to liquid helium temperatures, some complications in their manufacture have been encountered due, primarily, to difficulties in using evacuated insulation means. In FIG. 10 of U.S. Patent 2,966,035, for example, it will be seen that all of that portion of the apparatus enclosed within the dotted line is insulated. Such insulation normally includes the providing of an evacuated atmosphere within the insulated volume and this in turn requires that vacuum-tight seals must be provided for all of the components which extend from the atmosphere into the vacuum insulation. Moreover, the apparatus of U.S. Patent 2,966,035 and U.S. Patent 2,906,101 provides for refrigeration to loads which are not directly connected to the refrigeration apparatus, as shown for example in FIG. 12 of U.S. Patent 2,966,035. Finally, in an apparatus designed to perform a multistage cycle where the enclosed expandable volumes are located in separate cylindrical housings and the regenerators are external of each of these cylindrical housings the maximum degree of compactness and efficiency is not obtained. It may also be shown in connection with the single stage apparatus disclosed in U.S. Patent 2,906,101 that the regenerator is external of the remaining portion of the refrigerating apparatus, thus requiring conduits between the fluid volume within the apparatus and the regenerator.

It is therefore the primary object of this invention to provide improved refrigeration apparatus suitable for carrying out a cycle involving supplying a cold high pressure to an expandable volume and the periodic storing and releasing of heat during fluid transfer in the cycle. It is another object of this invention to provide refrigeration apparatus of the character described which minimizes complications in construction. It is yet another object of this

invention to provide refrigeration apparatus suitable for developing refrigeration at extremely low temperatures wherein the refrigeration loads are thermally bonded directly to the refrigerator. It is another object to provide such a refrigeration apparatus which is reliable, efficient and economic to construct and to operate. It is yet another object to provide such apparatus which is adaptable to the construction of very small refrigeration devices. Other objects of the invention will in part be obvious and in part be apparent hereinafter.

The apparatus of this invention may be described as comprising a fluid tight housing of circular cross-section decreasing from end to end; displacer means movable within the housing and defining fluid volume variable with their movement within the housing, the displacer means being a series of connected cylindrical displacers of decreasing diameters and of such dimensions as to define a fluid passage between the displacers and the inner wall of the external housing; fluid-permeable thermal regenerator means occupying that portion of the fluid passage defined by the upper portions of the displacers and the housing; fluid permeable heat station means thermally bonded to the wall of the housing and occupying the remaining portion of the fluid passage whereby the flow of fluid between the fluid volumes is exclusively through the thermal regenerator means and the heat station means; means external of the housing substantially corresponding in location to the heat station means for delivering refrigeration to an external load; and valve-controlled high-pressure fluid delivery means and low-pressure receiving means in communication with the fluid volumes.

The invention accordingly comprises the features of construction, combinations of elements and arrangements of parts which will be exemplified in the construction hereinafter set forth, and the scope of the invention will be indicated in the claims.

For a fuller understanding of the nature and objects of the invention reference should be had to the following detailed description taken in connection with the accompanying drawings in which:

FIG. 1 is a longitudinal cross-sectional view of a refrigerator constructed in accordance with this invention;

FIG. 2 is a cross-sectional view taken along the lines 2—2 of FIG. 1;

FIG. 3 is a cross-sectional view taken along lines 3—3 of FIG. 1;

FIG. 4 is an enlarged detail of the area enclosed by dotted lines in FIG. 1;

FIG. 5 is a longitudinal cross-sectional view of another modification of the refrigerator of this invention;

FIG. 6 is a cross-sectional view taken along 6—6 of FIG. 5;

FIG. 7 is a cross-sectional view taken along lines 7—7 of FIG. 5;

FIG. 8 is a longitudinal cross-sectional view of another modification of the refrigerator of this invention;

FIG. 9 is an enlarged detailed drawing of the area enclosed by dotted lines in FIG. 8;

FIG. 10 is a partial cross-sectional view taken along lines 10—10 of FIG. 9; and

FIG. 11 is a longitudinal cross-sectional view of yet another modification of the refrigerator of this invention.

In the following detailed description of this invention reference will be made from time to time to displacers and pistons, and in keeping with common practice the term "piston" will be used to include a sliding body, moving within a cylindrical vessel, whether or not it experiences pressure differentials on its surface, and whether or not it responds to changes in the thermodynamic characteristics of the fluids acting upon its surface to generate mechanical work. The term "displacer" will be reserved for

a similar sliding body which experiences essentially no pressure differentials on its surface and which generates or delivers no external work. Thus, the term "piston" includes displacers and is used in a generic sense. Where it is possible to construe the roll of the sliding body as either it will be referred to as a piston.

Further, with respect to terminology, it will be noted in the detailed description of the apparatus of this invention that the portions of the apparatus are referred to as "upper" and "lower." This is done wholly for convenience and to relate the description to the orientation of the apparatus in the drawings. It will be appreciated that the apparatus can function in any position or orientation and it is within the scope of this invention to have it do so.

FIG. 1 illustrates one modification of the refrigeration apparatus of this invention. As will be apparent, the decreasing diameter of the fluid-tight refrigeration housing is obtained in discrete steps. In this figure, the overall fluid-tight housing is generally indicated by the numeral 10, and it will be seen to be formed of an upper cylindrical housing 12 and a lower cylindrical housing 14, these two sections being joined by a suitable shoulder 15. The housing is completed by top 17 and bottom 18. Within the upper portion of cylindrical housing 12 is a displacer 20 which is movable within it (in a vertical direction as shown in FIG. 1). As an integral part, and permanently attached to displacer 20, is a smaller-diameter displacer 22 which is movable within a portion of the upper cylindrical housing 12 and within the bottom cylindrical housing 14. Movement of these displacers is controlled through shaft 21.

The upper displacer 20 and the internal walls 12a of the upper housing 12 define between them an annular space 24 which contains within it a regenerator 25 which will be seen from FIG. 2 to consist of fine wires 26 closely packed in the space 24. These wires should be of a metal which exhibits good heat capacity at the temperatures encountered, e.g., lead. A heat station 27 occupies the remaining portion of the annular space 24. In similar manner, the internal walls 14a of lower cylindrical housing 14 and displacer 22 in its vertical motion define between them an annular space 28, which contains a regenerator 29 in the upper section and a heat station 30 in the lower portion. Corresponding essentially to the location of the two heat stations 27 and 30 are external refrigeration loads represented in this case by hollow tubing 31 and 32 wrapped about the lower portions of housing 12 and 14. A typical heat station is shown in top-plan view in FIG. 3 and in an enlarged cross-sectional view in FIG. 4. Thus, it will be seen from FIG. 4 that the heat station 27 (and likewise the heat station 30) preferably consists of a series of annular rings 34, constructed of materials which have high heat conductivity at the temperatures encountered. Typically, such material will be copper. In order to make the heat stations fluid-permeable, they have perforations 35. Further, in order to transfer refrigeration from the heat stations to the external load, they are bonded to the interior of the wall 12 with a suitable thermal bonding material 36. They are held in spaced relationship by means of spacers 37 which are located around the inner periphery of the annular rings and are formed of materials which exhibit minimum heat conduction. In similar manner, the refrigeration load represented by hollow tubing 31 in FIG. 4 may be thermally bonded with the use of thermal solder 38 to the exterior of the wall 12. It will be seen from FIG. 4 that there is good heat conduction achieved between the annular rings 34 of the heat station and the external load 31, in the arrangement shown.

Within the fluid-tight housing 10 of FIG. 1, there are defined three distinct fluid volumes 42, 43 and 44. In the operation of the apparatus these will of course be maintained at different temperatures, decreasing in temperature from fluid volume 42 to volume 43 to volume

44. Communicating with the upper fluid volume 42 is a source of high-pressure fluid 48 which furnishes high-pressure fluid to volume 42 through conduit 49, which is controlled by valve 50, by way of common conduit 51. In like manner low-pressure fluid is discharged from the system into a low-pressure ballast 52, through conduits 51 and 53, the latter being controlled by valve 54. Joining the high-pressure and low-pressure ballasts is conduit 55, compressor 56 and a cooler 57.

The apparatus of this invention is suitable for performing the refrigeration method of U.S. Patent 2,906,101. However, it is particularly suitable for carrying out a modification of the cycle represented by that method. This novel cycle modification may be described as one which directs high pressure fluid along an enclosed path, removing heat from the fluid, initially expanding the high-pressure cooled fluid, further expanding the cooled fluid by discharging it into a region of lower pressure and storing refrigeration in the path furnished by the cold expanded fluid.

Using FIG. 1 to illustrate this cycle, it may be assumed to begin that the displacers 20 and 22 occupy their bottom-most positions, thus maximizing the volume of fluid volumes 42 and minimizing that of fluid volumes 43 and 44. When the displacers 20 and 22 have reached this bottom-most position valve 54 to the low-pressure ballast 52 is closed thus leaving fluid volume 42 filled with fluid at low pressure. At this point valve 50 connected to the high-pressure source 48 through conduit 49 is opened, thus permitting high-pressure warm fluid to flow by way of conduits 49 and 51 into fluid volume 42 and to compress the initial low-pressure fluid remaining in volume 42, thereby raising this fluid temperature. The displacers 20 and 22 are now moved upwardly with high-pressure valve 50 remaining open and the high-pressure fluid is forced through regenerator 25 and heat stations 27 to fluid volume 43 and through regenerator 29 and heat station 30 to fluid volume 44. Additional high-pressure fluid entering the warm end of regenerator 25 is mixed with the heated fluid from fluid volume 42 to enter the regenerator 25 at an intermediate temperature, but higher than the supply temperature of the fluid.

This high-pressure fluid is initially cooled in its passage through the regenerators 25 and 29 before entering fluid volume 43 and 44, respectively. Before completion of the stroke, i.e., before the displacers 20 and 22 have reached their topmost position, valve 50 is closed and now the fluid is displaced from the warm end fluid volume 42 into the cold end fluid volumes 43 and 44; and consequently an initial reduction in fluid pressure, or an initial expansion of the fluid in the system, takes place with attendant further fluid cooling. While the displacers 20 and 22 are permitted to dwell in their topmost position, valve 54 to the low-pressure ballast 52 is opened giving rise to a second and final reduction in pressure and consequent expansion of the fluid throughout the system with consequent final cooling of the fluid. The low-pressure fluid, during the step, is transferred to the low-pressure ballast 52 through conduits 51 and 53. It is then recompressed in compressor 56, and transferred by conduit 55 and cooler 57 to the high-pressure source 48.

Then by moving the displacers 20 and 22 downwardly the cold expanded fluid from fluid volumes 44 and 43 is initially passed through heat stations 30 and 27, respectively, within which the fluid can be heated to substantially the same temperature as that at which it reached the regenerators 29 and 25 during the pressurizing step, thereby providing refrigeration to the external loads represented by 32 and 31. The fluid further passes through regenerators 29 and 25 to be further heated and to leave the warm ends of these regenerators at substantially the same temperature as that at which the fluid entered during the pressurizing step. Since the fluid entering the first regenerator 25 was at a higher temperature than the supply fluid from high-pressure supply source 48, the exiting fluid

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from regenerator 25 is at a higher temperature than the supply fluid and its thermal energy is extracted from the system. This is equivalent to the refrigeration provided in the system at the lower temperatures. At the end of the cycle the heat exchangers are then in condition to contribute to the cooling of the fluid in the next cycle and displacers 20 and 22 are at their bottom most position to begin another cycle.

FIG. 5 shows a modification of the refrigerator of FIG. 1. It illustrates the use of more than two displacers and, also, the use of an internal cylinder in which the displacers operate. In this figure, like numbers refer to like elements in FIG. 1. There is in the refrigeration apparatus of FIG. 5 a third displacer 62, which is movable in a third chamber 63, which in turn is joined to the second chamber 14 through a suitable shoulder 64. Within this third chamber 63 there is also defined an annular space 65 which contains a regenerator 66 in its upper portion and a heat station 67 in its lower portion. There is a third external load 68 which is located essentially in the same position as the heat station 67 within the housing.

Positioned within the vacuum-tight housing 10 is a second internal housing 70 in which the displacers move. Because the housing is in itself fluid-impermeable, it is necessary to supply it with ports 71 which are in the vertical part of the housing, and ports 72 which are shown to be present in the horizontal portion of the housing. These ports, of course, provide for the flow of fluid from the heat stations to the corresponding fluid volumes and thus permit the continuous flow of fluid first in a downwardly direction and then in an upwardly direction. There is, of course, in the three-stage refrigerator of FIG. 5 an additional fourth fluid volume, 73. Because the displacers operate within internal housing 70, it is necessary to maintain them in fluid tight seal relationship with this housing, and therefore, sealing means such as O-rings 75 are provided.

As will be seen from FIGS. 5 and 6, the regenerator in this modification takes the form of stacked fine screening 76 of copper or other suitable metal. It is of course, possible to use this type of regenerator in the apparatus of FIG. 5. Other suitable regenerator constructions are also contemplated.

As in the case of the external housing, the internal housing is made up of stepped cylinders joined by suitable shoulders. High-pressure warm fluid is supplied to fluid volume 42 and is removed in the form of low-pressure fluid through conduit 51 and through the associated compressors and coolers as indicated in FIG. 1.

The apparatus of FIG. 8 is the refrigerator of FIG. 1 with the provision of an additional heat transfer system including a Joule-Thomson loop and a different form of external load. In FIG. 8 the refrigeration apparatus is essentially the same as in FIG. 1, except that it illustrates that it is possible to construct the regenerator 25 of the two different types of materials, or forms of materials, in order to take advantage of the thermodynamic properties of various metals over the temperature gradient which prevails from one end to the other of the regenerator.

Around the refrigeration apparatus which is defined within fluid-tight housing 10, is a second external shell 80 which is formed of an upper cylindrical housing 81, an intermediate cylindrical housing 82, and a lower cylindrical housing 83, all joined through shoulders 84 and 85 to give a fluid-tight housing. The top 17 of the refrigerator is suitably extended such as by ring 86 to completely enclose the external shell. Housing 10 and external housing 80 define between them a series of internal annular spaces, the upper one being designated 88, the intermediate one 89, and the lower 90. This lower housing is not complete in that it does not contain a displacer or its associated regenerator and heat station. It is rather an annular housing defined by

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the inner shell 91 and an annular ring bottom 92. With-in the spaces 88, 89 and 90 are additional means for the transfer of heat. These included finned tubing 94, which can be seen from FIG. 9 to consist of hollow tubing 95 having helically wound fins 97 bonded thereto. This finned tubing is maintained within the space 88 by means of cord packing 98. This packing also serves to create a tortuous helical path throughout space 88 for low-pressure cold fluid to flow as will be apparent in the following description. That portion of tubing 95 which corresponds to the location of the heat stations does not have fins but is bonded directly to the housing of the refrigerator.

In addition to the high-pressure and low-pressure ballast systems and their associated compressor and cooler which are required to deliver high-pressure fluid into fluid volume 42 and to discharge low-pressure fluid therefrom, there is also provided in the apparatus of FIG. 8 the necessary associated equipment to deliver high-pressure warm fluid into finned tubing 94 and to remove low-temperature fluid from the annular space 88 as it returns. This is done by providing a second high-pressure conduit 104 controlled by valve 105, and a low-pressure conduit 106 controlled by valve 107. There are also auxiliary compressor 108 and auxiliary cooler 109. It will be apparent from the drawing in FIG. 8 that these two fluid systems are interconnected. However, they may not be and separate high-pressure and low-pressure ballasts may be provided for each side of the device so that two different fluids may be used, one in the refrigeration system, the other in that heat transfer system, which is located between the two walls 12 and 80.

As fluid passes down through the high-pressure side, or the small diameter tubing 95 of this heat exchange system, it is, of course, cooled not only by low-pressure cooled fluid flowing up through passage 88 but also by virtue of the fact that it is in thermal contact with the heat stations 27 and 30 of the refrigeration system. Thus, these high-pressure tubings are thermally bonded to the external side of wall 12 as shown in FIG. 9. This is conveniently done by the use of thermal solder 38. The fluid on the high-pressure side becomes colder as it is directed downwardly until it is taken out of the system through conduit 112, passed through Joule-Thomson valve 113, where at least a portion of it is liquefied, delivers refrigeration to an external load 114, and is returned into the low-pressure side of the system (i.e., the tortuous path around the finned tubing) through conduit 115. During its return the low-pressure cold fluid cools the incoming high pressure fluid and reaches atmospheric temperature by the time it leaves passage 88. In its return, it in turn cools the high-pressure fluid going into the Joule-Thomson loop. Thus, there is provided a unique arrangement where there is literally three-way heat transfer between the heat station and the low-pressure cold gas flowing around the finned tubing and the high-pressure gas flowing within the finned tubing.

As pointed out in connection with FIG. 1, the decreasing diameters of the cylindrical housing in that modification was obtained through the use of stepped cylinders, joined through shoulders, having discrete differences in diameters. Another modification of the apparatus of this invention is shown in FIG. 11. In this case, the decreasing diameter is continuously achieved, thus providing a conically shaped housing. This has some distinct advantages in that it makes it possible to supply larger volumes of regenerators and heat stations in the upper or warmer portions of each of these heat exchanges where more heat transfer is desirable. The refrigeration apparatus of FIG. 11 is shown to have the same external or additional heat transfer system as described in connection with the apparatus of FIG. 8. It should be understood, however, that the conically-shaped housing of the apparatus of FIG. 11 is equally adaptable to the refrigerator apparatus of FIGS. 1 and

5, and it is within the scope of this invention to construct these modifications with conically-shaped fluid-tight housings in place of the stepped cylindrically-shaped housings shown.

Turning now to FIG. 11 it will be seen that this refrigeration apparatus consists of a conical inner wall 118, which is completed by a top 119 and a bottom 120. This inner wall is surrounded by a conical outer wall 122, which has an extension 123 to seal it at the top, and suitable shoulders 124 which join it to a bottom, annularly-shaped heat exchange system, such as shown in FIG. 8. Between displacer 20 and the conical inner wall 118, there is defined a spacing 128 which is of decreasing volume as the displacer moves downwardly. Likewise, a passage 129 of decreasing volume is defined between the lower displacer 22 and the lower portion of the conical housing 118. Within these spacings are located a regenerator 130 and a heat station 131 in the upper portion and a regenerator 132 and heat station 133 in the lower portion. It will be appreciated that the regenerators 130 and 132 correspond to regenerators 25 and 29 of FIG. 1 and that heat stations 131 and 133, in turn, correspond to heat stations 27 and 30 of FIG. 1. However, as pointed out, these decrease in volume toward the colder end of each of the stages, and this is advantageous in that it is desirable to have the major portion of the heat transfer take place at the higher temperature or the upper ends. As in the apparatus of FIG. 8, there is defined between the internal conical housing 118 and the outer conical housing 122 a spacing 136 which contains finned tubing 94, cord packing 98 and unfinned tubing 95 comparable to those of the heat exchange system of FIG. 8. Likewise, there is provided a Joule-Thomson loop and the associated low-pressure and high-pressure ballast systems to accompany this Joule-Thomson loop. The function of the apparatus is identical with that of the function of the apparatus of FIG. 8.

In the apparatus of FIG. 11, however, it is shown how two distinct low-pressure and high-pressure ballast systems may be provided for each side of the heat exchanger so that it is possible to use two different fluids within the system. Thus, there are added to the apparatus of FIG. 11, a second high-pressure ballast 138 and a second low-pressure ballast 139 and the fluid conduits are not joined.

An examination of FIGS. 1-11 shows that there is provided in the apparatus of this invention certain distinct advantages over the prior art. First, the external load (as represented by the tubing 31 and 32 of FIG. 1 or by the separate heat transfer system, including the finned tubing and Joule-Thomson loop, of FIGS. 8 and 11) is directly and thermally bonded to the refrigerator thus eliminating any losses due to the necessity for conducting cold fluid from the refrigerator to the external load and back to it. Moreover, by the use of regenerators and heat stations, it is possible to choose the materials which have the proper characteristics at low temperatures. For example, the regenerator will typically be formed of a material which has relatively high heat capacity at low temperatures, such as lead, while the heat transfer station will be constructed of material which has a relatively high heat conductivity at these temperatures, preferably copper or a metal similar to it in thermal properties. It will also be seen from the drawings that the apparatus is extremely compact and that the insulation which surrounds it, which will normally be a vacuum, may have the minimum amount of vacuum-tight seals leading to the ambient atmosphere. Finally, it will be seen from the various embodiments of the apparatus of this invention that the apparatus possesses a great deal of flexibility in its operation, and is adaptable to a novel cycle. It is, moreover, relatively easy to construct inasmuch as the heat stations and the regenerators may be built up by merely packing the necessary metallic material

within the housing as illustrated in the drawings. The type of heat exchange tubing, illustrated in FIGS. 8 and 11, is well known and there is a great deal of experience in its construction and assembly into passages such as illustrated.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above constructions without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawing shall be interpreted as illustrative and not in a limiting sense.

We claim:

1. A refrigerator, comprising in combination
 - (a) a fluid-tight housing of circular cross-section decreasing from end to end;
 - (b) displacer means movable within said housing and defining fluid volumes variable with their movement within said housing, said displacer means being a series of connected cylindrical displacers of decreasing diameters and of such dimensions as to define a fluid passage between said displacers and the internal wall of said housing;
 - (c) fluid-permeable thermal regenerator means occupying that portion of said fluid passage defined by the upper portions of said displacers and said housing;
 - (d) fluid-permeable heat station means thermally bonded to said internal wall and occupying the remaining portion of said fluid passage whereby the flow of fluid between said fluid volumes is exclusively through said thermal regenerator means and said heat station means;
 - (e) means external of said housing substantially corresponding in location to said heat station means for delivering refrigeration to a load; and
 - (f) valve-controlled high-pressure fluid delivery means and low-pressure fluid receiving means in communication with said fluid volumes.
2. Refrigerator in accordance with claim 1 wherein said fluid-tight housing decreases in cross-section by discrete increments and assumes a stepped configuration.
3. Refrigerator in accordance with claim 1 wherein said fluid-tight housing continuously decreases in cross-section and assumes a conical configuration.
4. Refrigerator in accordance with claim 1 wherein said heat station means comprises foraminous metal disks maintained in spaced relationship.
5. Refrigerator in accordance with claim 1 wherein said means for delivering refrigeration comprises tubing thermally bonded to said housing and adapted for circulation of a fluid therethrough.
6. Refrigerator in accordance with claim 5 wherein said tubing is the high-pressure side of a Joule-Thomson loop.
7. A refrigerator comprising in combination
 - (a) a fluid-tight housing of circular cross-section decreasing from end to end;
 - (b) a casing positioned internally of said housing and defining an annular passage with the internal wall of said housing;
 - (c) displacer means movable within said casing and defining therein fluid volumes variable with the movement of said displacer means, said casing having ports adapted to permit passage of fluid along a path comprising said annular passage and said fluid volumes;
 - (d) fluid-permeable thermal regenerator means occupying the upper portion of said annular passage;
 - (e) fluid-permeable heat station means thermally bonded to the outer wall of said casing and occupying the remaining portion of said annular passage;
 - (f) means external of said housing substantially corresponding in location to said heat station means for delivering refrigeration to a load; and

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(g) valve-controlled high-pressure fluid delivery means and low-pressure fluid receiving means in communication with said fluid volumes.

8. Refrigerator in accordance with claim 7 wherein said fluid-tight housing decreases in cross-section by discrete increments and assumes a stepped configuration. 5

9. Refrigerator in accordance with claim 7 wherein said fluid-tight housing continuously decreases in cross-section and assumes a conical configuration.

10. A refrigerator, comprising in combination 10

(a) a fluid-tight housing of circular cross-section decreasing from end to end;

(b) displacer means movable within said housing and defining fluid volumes variable with their movement within said housing, said displacer means being a series of connected cylindrical displacers of decreasing diameters and of such dimensions as to define a fluid passage between said displacers and the internal wall of said housing; 15

(c) fluid-permeable thermal regenerator means occupying that portion of said fluid passage defined by the upper portion of said displacers and said housing; 20

(d) fluid-permeable heat station means occupying the remaining portion of said fluid passage whereby the flow of fluid between said fluid volume is exclusively through said thermal regenerator means and said heat station means; 25

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(e) fluid passage surrounding said housing;

(f) heat exchange means within said fluid passage means adapted to transfer heat between warm high-pressure fluid and cold low-pressure fluid;

(g) a fluid conduit loop including an expansion valve communicating between the high-pressure and low-pressure sides of said heat exchange means;

(h) valve-controlled high-pressure fluid delivery means and low-pressure fluid receiving means in communication with said fluid volumes; and

(i) valve-controlled high-pressure fluid delivery means and low-pressure fluid receiving means in communication with said fluid passage.

11. Refrigerator in accordance with claim 10 wherein said high-pressure fluid delivery means and low-pressure fluid receiving means in communications with said fluid volumes also serve as said high-pressure fluid delivery means and low-pressure fluid receiving means, respectively, for said fluid passage.

References Cited in the file of this patent

UNITED STATES PATENTS

2,567,454	Taconis	Sept. 11, 1951
2,907,175	Kohler	Oct. 6, 1959