

[54] **IN-LINE MULTISTAGE CRYOGENIC APPARATUS**

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[51] Int. Cl. F25b 9/02

[58] Field of Search 62/6

[56] **References Cited**

UNITED STATES PATENTS

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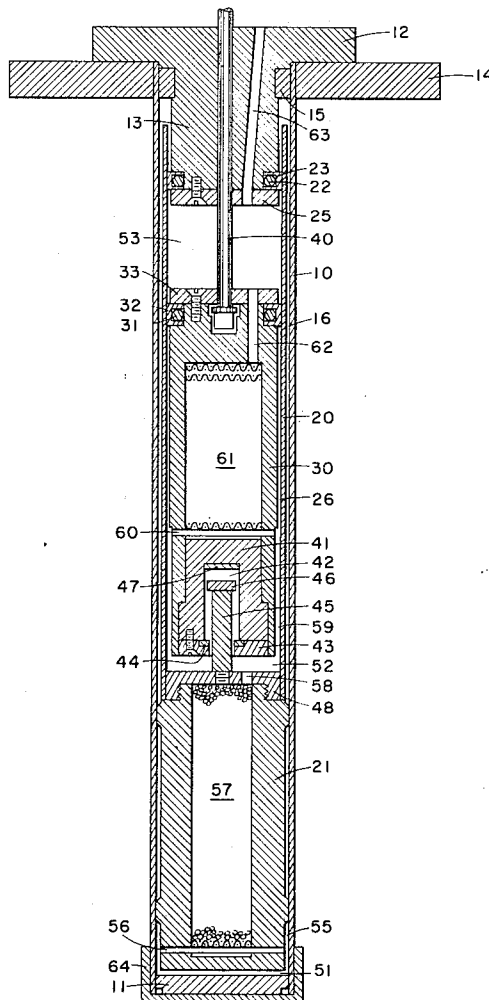
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[57] **ABSTRACT**

Improvement in the construction of cryogenic refrigerators which operate on one of several cycles (Gifford-McMahon, Stirling or Vuilleumier) and in the apparatus of which two or more displacers, reciprocating within an enclosure define chambers of variable volume. Each of the displacers moves within a separate axially aligned concentric enclosure thereby making it possible to locate all of the sealing means at a warmer end of the refrigerator and to use a housing of straight cylindrical configuration in place of a stepped configuration.

7 Claims, 11 Drawing Figures



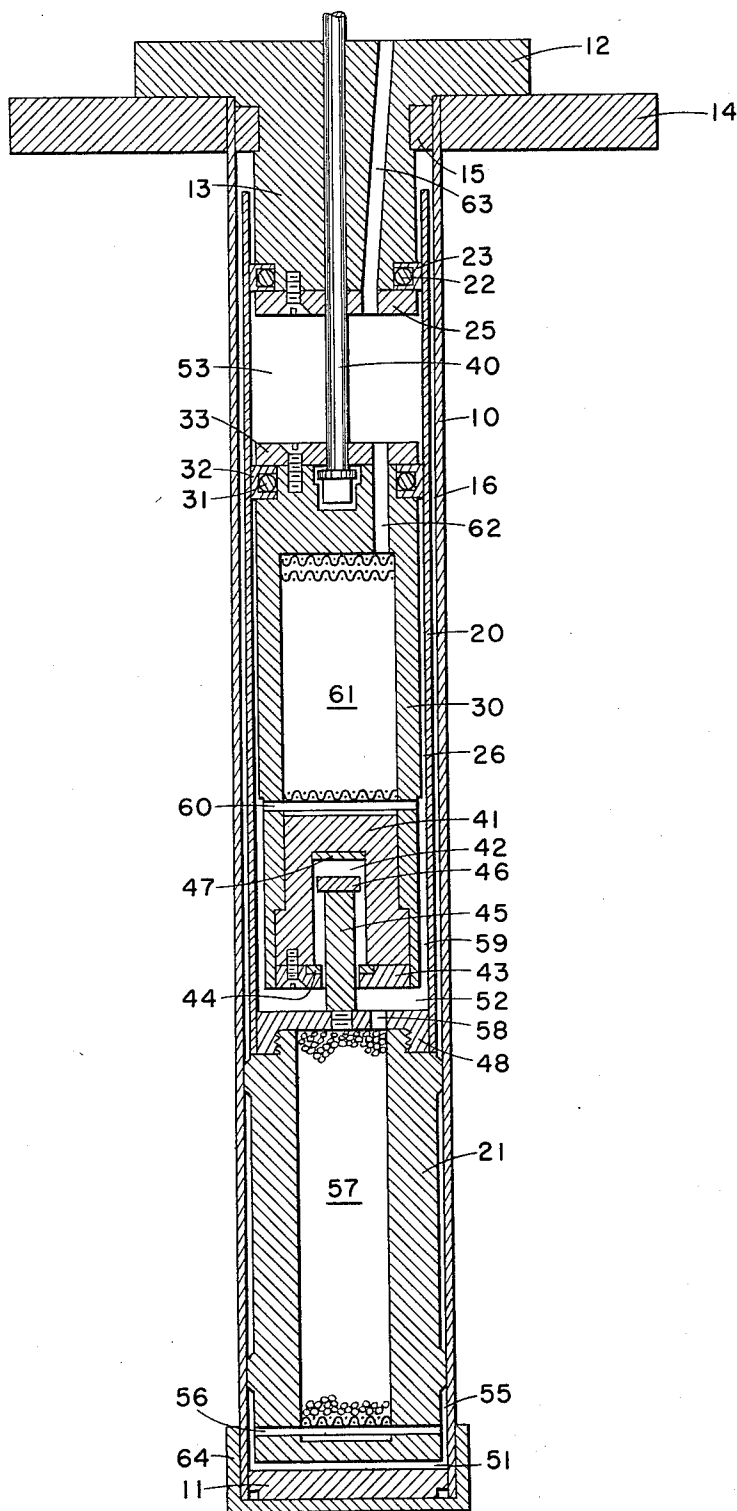


Fig. 1

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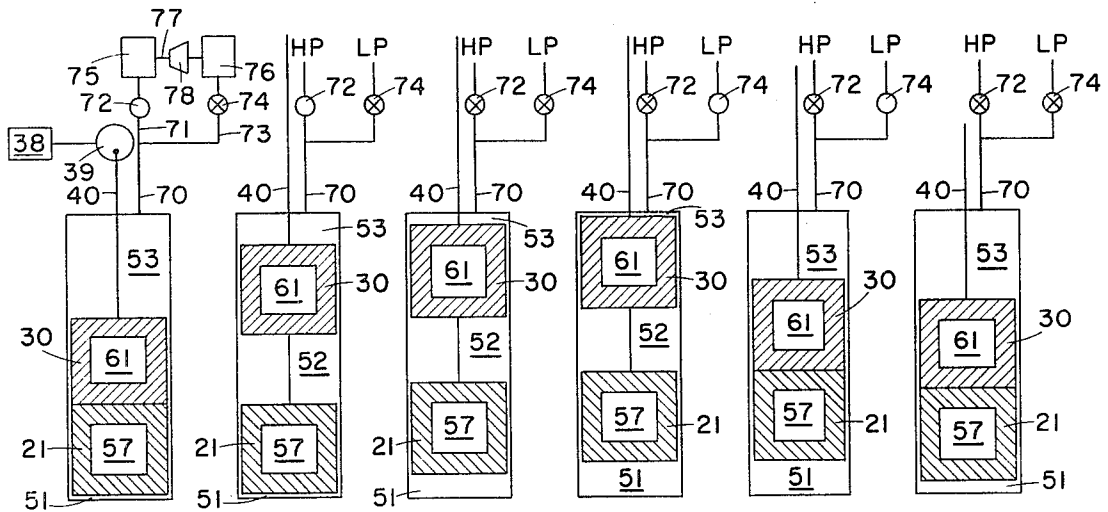


Fig. 2 Fig. 3 Fig. 4 Fig. 5 Fig. 6 Fig. 7

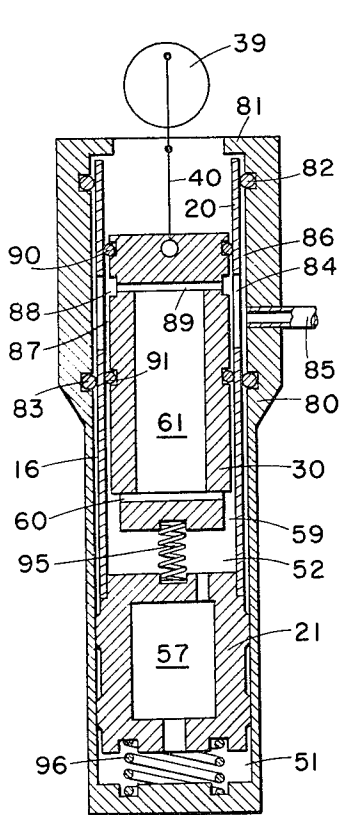


Fig. 8

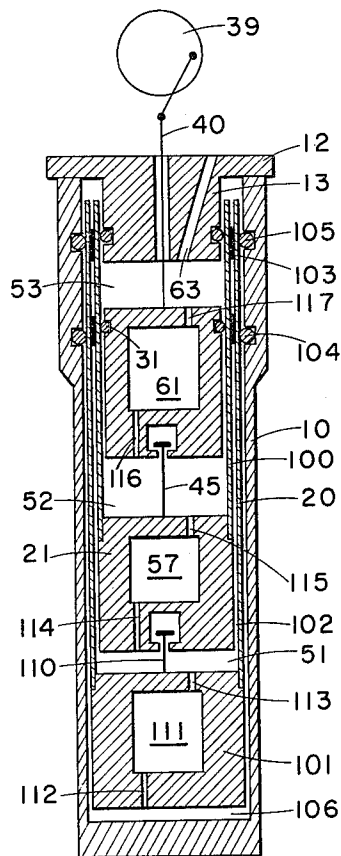


Fig. 9

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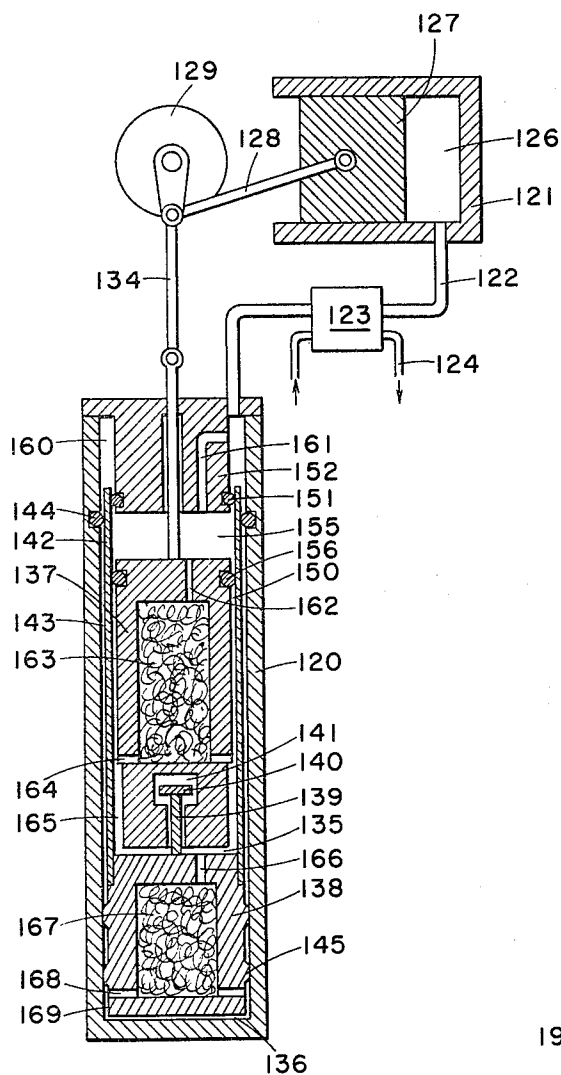


Fig. 10

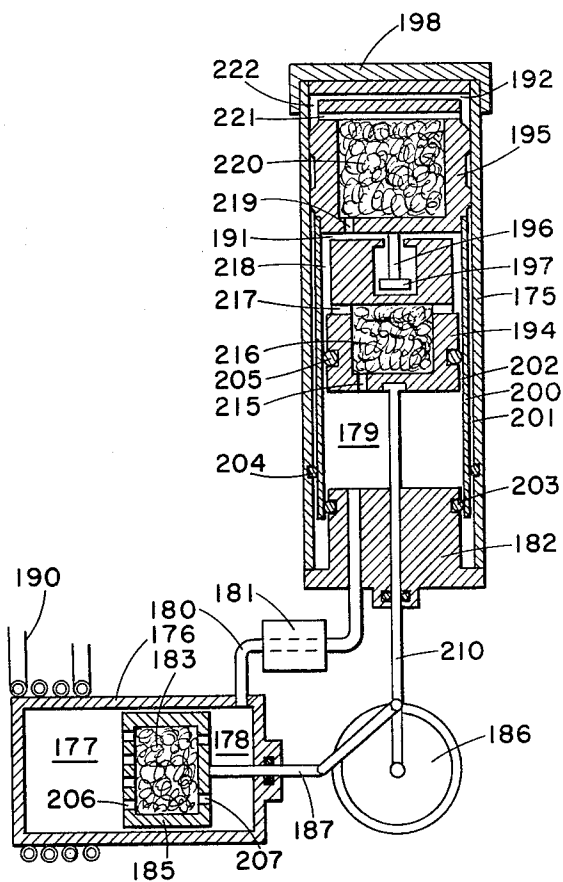


Fig. 11

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IN-LINE MULTISTAGE CRYOGENIC APPARATUS

This invention relates to cryogenic apparatus and more particularly to an apparatus capable of delivering refrigeration down to about 15° to 20° K and of operating on the cycle described in U.S. Pat. No. 2,906,101, and more particularly to the form of that cycle described in U.S. Pat. No. 2,966,035. The invention is also applicable to apparatus for carrying out the Stirling and the Vuilleumier cycles.

One of the most serious problems constantly encountered in the construction of low-temperature apparatus is that of seals. The various fluid chambers within an apparatus which incorporates a movable member to define the chambers must be isolated to construct an efficient refrigerator. This isolation requires the use of some form of seals. The most convenient sealing means, e.g., o-rings employed with or without additional polytetrafluoroethylene rings, are not satisfactory at low temperatures and tend to deteriorate rapidly. In the single-stage embodiment of the refrigerator disclosed in U.S. Pat. No. 2,906,101 or in U.S. Pat. No. 2,966,035 the sealing problems are resolved by using seals only at the warmer ends of the apparatus. However, if it is desired to stage the refrigerator to obtain lower temperatures, any seals in the low-temperature regions become a problem. Similar problems may also be encountered in temperature-staged Stirling engines and Vuilleumier apparatus. Moreover, staging sometimes requires constructing the housing in a stepped configuration which can present problems in construction and assembly.

In more complicated, expensive apparatus, the sealing problem can be solved in such ways as using precisely machined surfaces, carefully purifying the fluid to remove dust and condensables and the like; and the added expense of forming a stepped configuration can be tolerated. It would, however, be desirable to have available a relatively simple, inexpensive, multistage cryogenic refrigerator which eliminates low-temperature seals and hence is reliable over an extended operating period. It would also be desirable to have an in-line, temperature-staged refrigerator.

It is, therefore, a primary object of this invention to provide a simple, multistage cryogenic refrigerator wherein no low-temperature sealing problems are present and wherein controllably sized temperature-staged expansion chambers may be supplied without the need for forming the refrigerator housing in a stepped configuration. It is another object of this invention to provide apparatus of the character described which is relatively easy and inexpensive to construct. It is yet another object to provide such apparatus which is flexible in design, being readily converted into a single-stage machine. Other objects of the invention will in part be obvious and will in part be apparent hereinafter.

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

The cryogenic apparatus which achieves the object of this invention is an in-line device having an inner enclosing means affixed to the upper end of a lower displacer. This displacer moves within an outer enclosing means and defines a volume in which another displacer moves. Thus, each displacer moves within its own separate, fluid-tight, axially aligned concentric enclosure, an arrangement which permits adequate sealing means to be provided at the warm end of the refrigerator where no problems are encountered in the operation of o-rings and polytetrafluoroethylene rings. The displacers are connected by means which permit the upper displacer to be moved, if desired, over a portion of its stroke prior to engagement with the lower displacer. Thus, there are defined within the enclosure an upper refrigeration chamber and a lower refrigeration chamber, the latter being smaller in volume than the former to make the necessary adjustment in mass flow. This invention may be applied to apparatus designed to operate on the so-called no-work cycle of U.S. Pat. No. 2,966,035, on the work cycle of U.S. Pat. No. 2,906,101, on

the Stirling cycle (see for example U.S. Pat. No. 2,657,553) and the Vuilleumier cycle (see for example U.S. Pat. No. 1,275,507). The fluid flow path which provides fluid communication among the chambers is contained entirely within the refrigerator housing and regenerators, as part of the fluid flow path, are positioned within the displacers.

For a fuller understanding of the nature and object 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 section drawing of an exemplary refrigerator constructed in accordance with this invention and designed to operate on the no-work cycle of U.S. Pat. No. 2,966,035;

FIGS. 2 through 7 are diagrammatic representations of the refrigerator of FIG. 1 showing the steps of the cycle and the operation of the high-pressure and low-pressure valves;

FIG. 8 is a longitudinal cross section of an exemplary refrigerator constructed in accordance with this invention and designed to operate on the work cycle described in U.S. Pat. No. 2,906,101;

FIG. 9 is a longitudinal cross section of a refrigerator constructed in accordance with this invention, having three temperature-staged refrigeration chambers and designed to operate on the no-work cycle;

FIG. 10 is a longitudinal cross section of an exemplary refrigerator constructed in accordance with this invention and designed to operate on the Stirling cycle; and

FIG. 11 is a longitudinal cross section of an exemplary refrigerator constructed in accordance with this invention and designed to operate on the Vuilleumier cycle.

FIG. 1 is a longitudinal cross sectional view of a refrigerator constructed in accordance with this invention, and designed to operate on the no-work cycle described in U.S. Pat. No. 2,966,035. In this embodiment the refrigerator is contained within an outer enclosing means such as a cylinder 10 which is closed on the bottom with a plate 11 and at the top with an upper member 12 which has integral with it an extension 13 adapted to fit within the housing. A fluid-tight seal is effected between the upper member extension 13 and the outer enclosing means 10 through a sealing ring 15 which also serves as a stop for the upward travel of the inner enclosing means. The outer enclosing means defines within it a fluid-tight volume 16. Within this volume is positioned an inner enclosing means such as cylinder 20, the bottom end of which is permanently attached to the upper end of the lower displacer 21. The inner enclosing means moves up and down and there is, therefore, provided a sliding seal on which the inner wall of inner enclosure 20 may move and maintain the necessary fluid-tight conditions within the inner enclosing means. This sliding seal is shown in FIG. 1 to comprise an o-ring 22 and a sealing ring 23 formed of polytetrafluoroethylene associated with it. The entire sealing assembly is maintained in position by a plate 25 which is affixed to the upper member extension 13.

It should be appreciated that in the descriptions given, the terms "upper" and "lower" are used strictly for convenience to indicate the orientation of the apparatus as illustrated in the drawings. These relative positions may, however, be reversed, since the apparatus may be operated in any orientation desired.

Within the inner enclosing means 20 there is a fluid-tight volume 26 in which a second or upper displacer 30 operates. An o-ring seal 31 and polytetrafluoroethylene ring 32 associated with it are affixed to the upper end of displacer 30 by means of a plate 33. Upper displacer 30 is in turn mechanically linked to any suitable driving means by rod 40. The driving means may be a motor and crankshaft or the rod 40 may be removed and the displacers driven pneumatically such as shown in U.S. Pat. No. 3,188,819.

The upper displacer 30 has a lower removable piece 41 which contains a recess 42. This removable piece is maintained in normal position through the use of a plate 43 and it has associated with it a leather washer 44 to make sliding con-

tact with a lower displacer engaging rod 45 which is joined to the lower displacer 21 through removable top plate 48. Rod 45 has an upper flange 46 to engage the shoulder (formed by leather washer 44) in the upward motion of the displacer 30 to impart upward motion to displacer 21 after displacer 30 has moved through a predetermined portion of its upward stroke; and to engage a leather pad 47 (at the top of recess 42) to impart downward motion to displacer 21 after displacer 30 has moved through a predetermined portion of its downward stroke. For ease of construction and assembly the lower displacer is constructed to have a screw-on top piece 48.

The movement of displacers 21 and 30 within the housing system described above defines three distinct isolated chambers; namely, a low-temperature refrigeration chamber 51, an intermediate-temperature refrigeration chamber 52, and a warm chamber 53. The flow path of the fluid through the apparatus may be traced as follows beginning with the low-temperature refrigeration chamber. From the low-temperature refrigeration chamber 51 the fluid flows in annular passage 55 into a series of radial passages 56 which are in fluid communication with the bottom end of regenerator 57 positioned within displacer 21. From the top end of regenerator 57 the fluid flows by means of a short vertical passage 58 into intermediate-temperature refrigeration chamber 52 and then by means of the annular passage 59 and a series of radial passages 60 into regenerator 61 located in the upper displacer 30. Finally, regenerator 61 is in fluid communication with the warm chamber 53 by means of a passage 62. Chamber 53 in turn is in fluid communication with a high-pressure fluid source (not shown) and a low-pressure reservoir (not shown) through passage 63 (see FIGS. 2 through 7 for the high-pressure fluid source and low-pressure fluid reservoir).

In keeping with known refrigerator design, a heat station 64 may be associated with the low-temperature refrigeration chamber 51. This heat station may take any desirable form, and is designed better to deliver refrigeration to an external load.

In FIGS. 2 through 7, which are drawn in a very diagrammatic fashion, like numbers refer to like reference numerals in FIG. 1. In addition, it will be seen that FIG. 2 illustrates diagrammatically the remaining portion of the equipment required to make up the refrigerator. Hence, there is provided a crank 39, driven by motor 38, for driving rod 40 to move the displacers in the required sequence. An external conduit 70 connects the interior of the refrigerator with a high-pressure fluid source 75 through a high-pressure line 71 (controlled by valve 72) and to a low-pressure reservoir 76 through line 73 (controlled by valve 74). In accordance with known design for an entirely closed system, the low-pressure reservoir 76 may be connected with the high-pressure fluid source 75 by means of a line 77 which contains a compressor 78 and any other auxiliary equipment such as a cleanup system which is not shown.

To begin a description of the cycle, as illustrated in FIGS. 2 through 7 (in which like numerals refer to like elements in FIG. 1 and in which most details are omitted) assume that the cycle has been finished with the sweeping out of most of the low-pressure cold fluid from the refrigerator and that the two displacers have reached their lowermost position as illustrated in FIG. 2. At this point the high-pressure valve 72 is opened to permit high-pressure fluid to enter into chamber 53. With the beginning of the introduction of high-pressure fluid into the apparatus the rod 40 is moved upwardly drawing with it displacer 30 and transferring at least a portion of the fluid from chamber 53 by way of regenerator 61 into the intermediate-temperature chamber 52 as shown in FIG. 3. The fluid entering chamber 52 is, of course, initially cooled as it passes through regenerator 61. The connecting means between displacers 30 and 21 is so designed that when the chamber 52 has reached a predetermined volume it will engage displacer 21 to pull it upwardly, thus transferring some of the initially cooled high-pressure fluid into chamber 51 by way of regenerator 57. The fluid which enters chamber 51 is colder than that in

chamber 52 since it has been further cooled in its passage through regenerator 57 in displacer 21. Before the two displacers 21 and 30 have reached their uppermost position, it may be desirable to close the high-pressure valve 72 (FIG. 4) and continue the upward movement until the displacers have reached their uppermost position. This means that there will be some expansion of the fluid within the chambers 52 and 51 to develop some additional cooling. Subsequent to the point at which the displacers reach their uppermost position, the low-pressure valve 74 is opened (FIG. 5) permitting the high-pressure cold fluid from chambers 51 and 52 to exhaust and expand into the low-pressure reservoir 76. In this final expansion step the fluid is cooled in both chambers to its lowest temperature and refrigeration is developed in chambers 51 and 52. While the low-pressure valve remains open (FIG. 6), the displacers are caused to move downwardly, first displacer 30 and then displacer 21. The cold, low-pressure fluid is then swept from chambers 51 and 52. If desired, the low-pressure reservoir may be closed just prior to the attainment by the displacers of their lowermost positions (FIG. 7). The displacers are then in position to begin another cycle. A major portion of the energy delivered externally is in the form of thermal energy by virtue of fluid compression in chamber 53 as detailed in the full description of the cycle in U.S. Pat. No. 2,966,035.

FIG. 8 is a longitudinal cross section of a refrigerator constructed in accordance with this invention, and designed to operate on the cycle described in U.S. Pat. No. 2,906,101. It differs from the refrigerator of FIG. 1 in that the third or uppermost chamber is not present. In accordance with the difference of the two cycles involved, the cycle of FIG. 8 delivers some external mechanical energy in place of the thermal energy delivered by the refrigerator of FIG. 1 operating on the no-work cycle.

In FIG. 8 like reference numerals are used to refer to like elements shown in FIG. 1. As noted above, the outer enclosing means 80 is open at the top. However, it may be desirable that this top end terminate in an inwardly extending flange 81 in order to serve as a stop for the upward travel of the inner housing enclosure 20, which, as in FIG. 1, is attached to the upper end of the lower displacer 21. The volume 16 of the apparatus is maintained fluid-tight below the o-ring seal 82. In addition, a second o-ring seal 83 is provided to make fluid-tight contact with the slidably moving inner enclosure means 20. Some modification is required in the inner enclosure means 20 inasmuch as the high-pressure fluid must be introduced directly into and low-pressure fluid exhausted directly from regenerator 61. This modification in FIG. 8 takes the form of a multiplicity of slots 84 in the wall of the inner enclosing means 20. High-pressure fluid is brought into the system and low-pressure fluid exhausted from it through line 85 which is, of course, equivalent to line 70 of FIGS. 2 through 7. This external conduit is in fluid communication with the regenerator through an outer annular passage 86, a plurality of slots 84, an inner annular passage 87, an annular passage 88 cut into the side of the displacer wall and a series of radial passages 89 leading into regenerator 61. The fluid flow path between chambers 52 and 51 by way of regenerator 61 is identical with that described above for FIG. 1. Sealing rings 90 and 91 are provided so that displacer 30 may make fluid-tight contact with the inner wall of the inner enclosing means 20. Finally, the apparatus of FIG. 8 illustrates the use of spring 95 to join displacers 61 and 57. A second spring 96, held in recesses in the bottom of displacer 21 and in the inner wall of the bottom of the housing, may be used to assist in maintaining a desired spacing between the displacers in their motions.

The refrigerators shown in FIGS. 1 and 8 may readily be converted into single-stage devices. Thus, for example, in the apparatus illustrated in FIG. 1 this may be done by unscrewing the portion of displacer 21 containing regenerator 57 and replacing it with a solid piece of a desired length. The engaging rod 45 is removed and replaced with a suitable plug. Seal and stop 15 are replaced with a longer member to prevent movement of inner enclosing cylinder 20. The results are a

single-stage refrigerator with a single adjustable refrigeration chamber.

FIG. 9 illustrates how the apparatus of FIG. 1 may be adapted to a greater degree of staging, i.e., to the use of three refrigeration chambers. In FIG. 9 like reference numerals refer to like components in FIG. 1. Within the housing of the apparatus of FIG. 9 there is a third enclosing means 100 which is fixed to a third displacer 101 and which defines a third fluid-tight enclosure 102. This requires additional seals 103, 104, and 105 and defines a third refrigeration chamber 106 which achieves the lowest temperature in the apparatus. This embodiment also requires an additional connecting rod 110 with an associated flange, and a third regenerator 111 located within displacer 101. The apparatus of FIG. 9 also illustrates a somewhat simplified flow path in that the annular and radial passages which connect the refrigeration chambers with the displacers are replaced by a series of vertical conduits such as 112 through 117 associated with the displacers 101, 21 and 30. The cycle of the refrigerator of FIG. 9 is essentially the same as that described in FIGS. 2 through 7.

FIG. 10 illustrates the application of this invention to one embodiment of a Stirling engine. In this embodiment the expansion-refrigeration portion of the housing 120 is separated from the compressor housing 121. These are joined by a suitable fluid conduit 122 having an aftercooler 123 incorporated in it. Conduit means 124 is provided to circulate a cooling fluid through the aftercooler. Compression of the fluid within the engine takes place in chamber 126 and is effected by means of a piston 127 driven by rod 128 from a suitable driving means 129. In keeping with this invention the expansion is accomplished in two staged expansion chambers 135 and 136 through the movement of an upper displacer 137 and a lower displacer 138. The displacers are mechanically linked through a rod 139 and a flange 140 which engages the shoulders of a recess 141. Attached to the lower displacer 138 is a cylinder 142 which moves within the volume 143 defined by the housing. A warm end seal 144 is provided along with displacer lands 145 to seal off expansion chamber 136.

Within the volume 150, which is defined by the cylinder 142, seals 151, and a header 152, the upper displacer 137 moves to define the expansion chamber 135 and an intermediate-temperature chamber 155. Seals 156 are provided to isolate the expansion chamber 135 from the intermediate chamber 155. The flow path within the expansion portion of the apparatus will be seen to be comprised of the enlarged annular passage 160, the passage 161 drilled in the header 152, intermediate-temperature chamber 155, passage 162, regenerator 163, radial passages 164, annular passage 165, the first expansion chamber 135, passage 166, regenerator 167, radial passages 168, annular passage 169, and the coldest refrigeration chamber 136. Inasmuch as the Stirling cycle is well known, it will not be further detailed here.

FIG. 11 illustrates the application of this invention to a refrigeration apparatus designed to operate on the Vuilleumier cycle. The operation of this cycle requires that there be provided a hot chamber and a chamber of intermediate-temperature and one or more cold expansion chambers, these terms being relative for any one system. It is a completely closed cycle and the flow path which joins these chambers includes heat storage means such as regenerators. In the apparatus of FIG. 11 the expansion chambers along with a portion of the intermediate-temperature chamber is found in housing 175, whereas the hot chamber along with the remaining portion of the intermediate-temperature is found in a housing 176. Within housing 176 is located a warm (or hot) chamber 177. The intermediate-temperature chamber is made up of a combination of chambers 178 located within housing 176 and chamber 179 located in housing 175. These are joined through a conduit 180 which has associated with it a heat exchanger 181. Conduit 180 passes down through the header 181 which serves as one end of housing 175. Within housing 176 is a displacer 185 containing a regenerator 183. It is, of course, within the scope of this invention and in the operation

of the cycle to locate the regenerator external of the housing if this is desired. Displacer 185 is driven by means of a suitable driving means such as a crank 186 to which the displacer rod 187 is mechanically linked. Inasmuch as the operation of this cycle requires that heat (thermal energy for compression) be introduced into the system in the fluid in the hot chamber 177, there is provided a coil 190 which is in thermal contact with the outer wall of housing 176 and through which a heating fluid may be passed. Alternatively, if the temperature of the refrigerator is such that the heat put into the fluid in chamber 177 is at room temperature, the coils may be replaced with heat transfer fins. Within housing 175, there are defined two expansion chambers, the first which is at an intermediate low-temperature 191 and the second 192 which is at the coldest temperature of the refrigerator. These are defined through the movement of displacers 194 and 195 which are joined through a rod 196 and flange 197, an arrangement essentially identical to that described in detail for the apparatus of FIG. 1. Inasmuch as refrigeration is to be delivered from the fluid chamber 192, it may be desirable to place a suitably designed heat station 198 at the end of housing 175. This heat station may be constructed in any known manner.

In accordance with the teaching of this invention, the displacer 195 has attached to it a cylinder 200 which reciprocates within the volume 201 defined within housing 175 and in turn defines within it a volume in which the displacer 194 reciprocates. Also, in accordance with the teaching of this invention, there are provided a series of seals including seals 203, 204, and 205, all located at the warmer end of the apparatus included within housing 175. The displacers 194 and 195 are driven by a displacer rod 210 which is also attached to crank 186. Generally, rods 187 and 210 will be about 90° out of phase; however, this may be varied and may easily be determined for any set of conditions by one skilled in the art.

The fluid flow path within the apparatus will be seen to comprise (reading from chamber 177 to chamber 192) the passages 206, regenerator 183, passages 207, chamber 178, conduit 180, chamber 179, passage 215, regenerator 216, radial passages 217, annular passage 218, chamber 191, passage 219, regenerator 220, radial passages 221, annular passage 222, and chamber 192.

Inasmuch as the cycle itself is not part of this invention, it need not be described in detail. A complete description of the cycle on which this apparatus operates can be found in U.S. Pat. No. 1,275,507.

It will be seen from FIGS. 10 and 11 that in the modified Stirling and Vuilleumier apparatus of this invention, it is possible to construct in-line temperature staged refrigerators which require sealing means only at the warmer end or ends of the apparatus. Moreover, the means by which the displacers are joined may be so designed as to control the relative volumes of the refrigeration or expansion chambers. This is important, inasmuch as these chambers are maintained at different temperature levels and, hence, must work with different fluid flow masses.

Because the refrigerator is of a straight line design, the honing of the engine cylinders is not critical and no distortions are introduced from welding in the seal areas. Flexibility is provided both with respect to the design of the apparatus as well as to its performance, the choice of volume ratios between the temperature-staged chambers being within the skill of the art. These volumes may be so adjusted as to obtain the maximum efficiency for any two temperature levels.

It will thus be seen that the object 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 drawings shall be interpreted as illustrative and not in a limiting sense.

I claim:

1. In a cryogenic apparatus in which a working fluid is introduced into and discharged from a warm end and in which at least two movable bodies, having heat storage means located internally thereof, define in their motion at least two refrigeration chambers of variable volume, characterized in that each of said movable bodies moves within a separate concentric cylindrical housing which defines a fluid volume, that all of said movable bodies except that body movable within the innermost housing are affixed to the housing defining the next inner volume adjacent to that in which said body moves, that said housings extend to said warm end of said apparatus, that all sealing means isolating said fluid volumes are located near said warm end of said apparatus, and that said movable bodies are mechanically linked whereby movement of said body in said innermost housing moves the other of said movable bodies in a predetermined sequence.

2. A temperature-staged cryogenic apparatus, comprising in combination

- a. outer enclosure-defining means having a warm end in which a working fluid is introduced into and discharged from and having a cold refrigeration end;
- b. at least one inner enclosure-defining means, having a warm end and a cold end, movable within said outer enclosure-defining means, concentric therewith and extending up to said warm end of said outer enclosure-defining means;
- c. a body movable within each of said enclosure-defining means defining in its motion at least one chamber of variable volume, each of said movable bodies except that one movable within the innermost enclosure-defining means being affixed to the said cold end of the enclosure-defining means defining the next inner volume adjacent to that in which said body moves;

d. sealing means located within said warm ends of said enclosure-defining means adapted to make the volumes within each of said enclosure-defining means essentially fluid-tight;

e. driving means adapted to move the body within said innermost enclosure-defining means;

f. connecting means mechanically linking said movable bodies; and

g. a fluid flow path within said apparatus, including heat storage means located within said movable body, providing fluid communication among said chambers.

3. A cryogenic apparatus in accordance with claim 2 wherein said movable body within the innermost enclosure-defining means defines two chambers of variable volume, one of which is located in said warm end of said innermost enclosure-defining means.

4. A cryogenic apparatus in accordance with claim 3 including means to deliver high-pressure fluid to said one of said chambers located in said warm end of said innermost enclosure-defining means.

5. A cryogenic apparatus in accordance with claim 4 wherein said means to deliver high-pressure fluid is mechanically linked to said driving means.

6. A cryogenic apparatus in accordance with claim 2 wherein said connecting means comprises a flanged rod member affixed to each of the driven movable bodies and means associated with each of the driving movable bodies adapted to engage said flanged rod member at a predetermined point in its motion.

7. An apparatus in accordance with claim 2 wherein said connecting means comprises spring means.

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