

[54] **METHOD AND APPARATUS FOR
MINIMIZING MOTIONAL HEAT LEAK
IN CRYOGENIC APPARATUS**

[75] Inventor: **James A. O'Neil**, Bedford, Mass.

[73] Assignee: **Cryogenic Technology, Inc.**,
Waltham, Mass.

[22] Filed: **June 23, 1971**

[21] Appl. No.: **155,914**

[52] U.S. Cl. **62/6, 60/24**

[51] Int. Cl. **F25b 9/00**

[58] Field of Search **62/6; 60/24**

[56] **References Cited**

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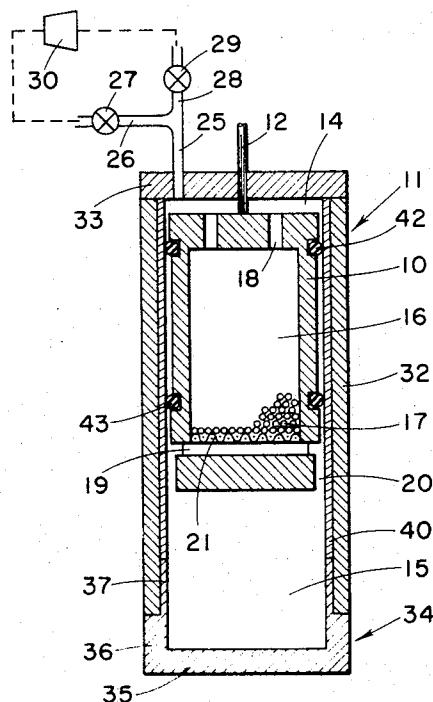
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Primary Examiner—William J. Wye
Attorney—Bessie A. Lepper

[57] **ABSTRACT**

Method and apparatus for reducing thermal losses due to motional heat leak brought about when a piston reciprocates between two different temperature levels to define one or more chambers of variable volume within the fluid-tight housing of a valved expansion engine, e.g., a cryogenic refrigerator, a thermal compressor or a Stirling engine. A sleeve liner formed of a nonmetallic material exhibiting low heat conductivity and low thermal capacity is located within the housing wall to present a continuous surface therewith, thereby effectively decreasing the transfer of energy between the piston and its housing as the piston reciprocates. If such thermal losses can be tolerated, then it is possible to reduce the void volume, or to partially reduce such thermal losses and also reduce void volume.

20 Claims, 6 Drawing Figures



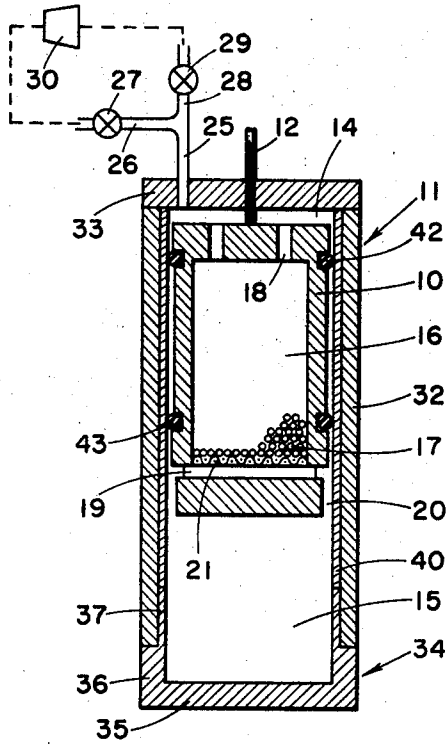


Fig. 1

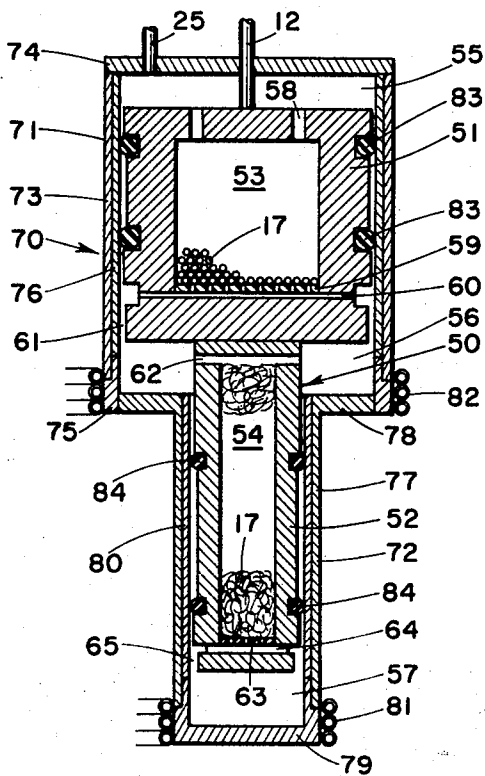


Fig. 2

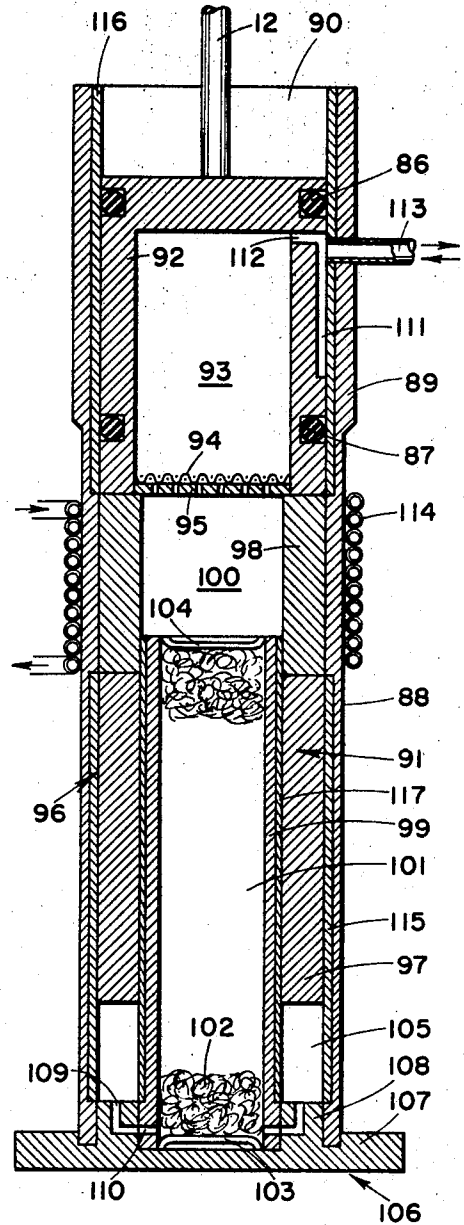


Fig. 3

James A. O'Neil
INVENTOR

BY *Bernie A. Lypper*

Attorney

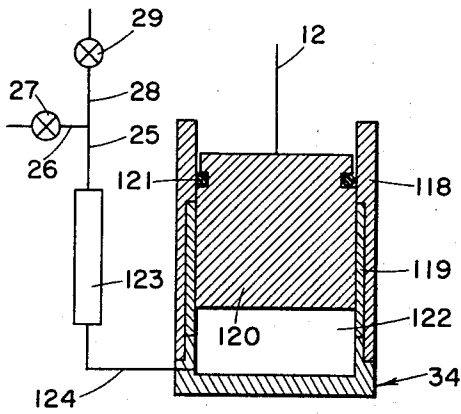


Fig. 4

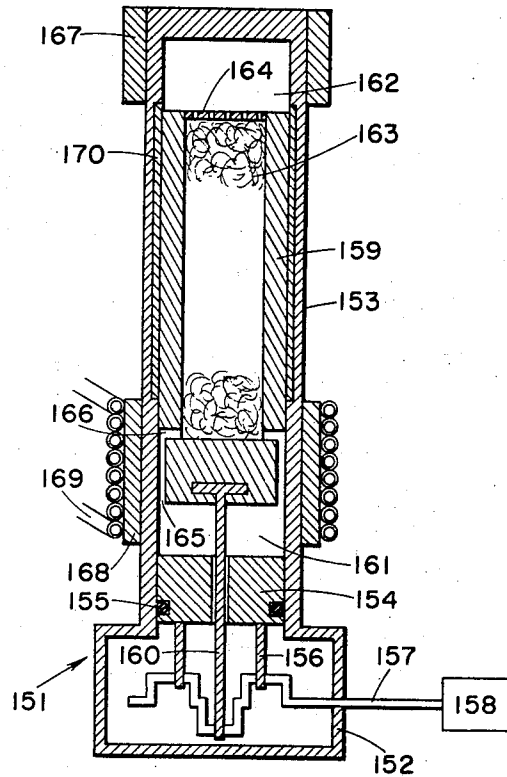


Fig. 6

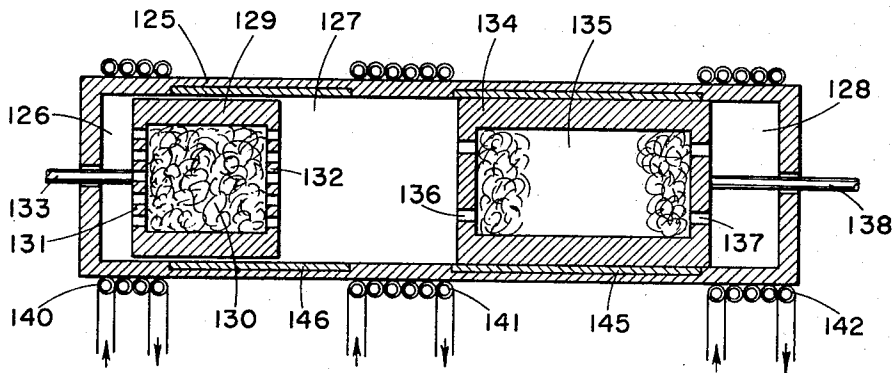


Fig. 5

James A. O'Neil
INVENTOR

BY *Bonnie A. Lygner*

Attorney

METHOD AND APPARATUS FOR MINIMIZING MOTIONAL HEAT LEAK IN CRYOGENIC APPARATUS

This invention relates to valved expansion engines and more particularly to cryogenic refrigerators and liquefiers which incorporate a body movable within a fluid-tight housing to define therein one or more refrigeration chambers of variable volume. The invention is, as will be seen, applicable to thermal compressors and valved expansion engines wherein a regenerator or other type of heat exchanger is used to isolate temperature levels. For convenience, the method and apparatus of this invention will be described as it pertains to cryogenic apparatus.

Cryogenic apparatus such as those described in U.S. Pat. Nos. 2,906,101, 2,966,034, 2,966,035, 8,045,436, 3,188,819 employ a movable body within a fluid-tight cylinder to define one or more chambers of variable volume, at least one of which is a refrigeration chamber adapted to deliver refrigeration to a load either by delivering a cold fluid externally of the chamber or by indirect heat exchange from the cold fluid within the chamber by way of a heat station to a load external of the chamber. Refrigeration is developed in these apparatus by introducing a high-pressure fluid through a regenerator to the refrigeration chamber and then expanding the cold high-pressure fluid back through the regenerator into a low-pressure reservoir.

Cryogenic apparatus operating on other cycles also employ a movable body, piston or displacer to define a refrigeration chamber of variable volume. Exemplary of such other apparatus are refrigerators built to operate on the so-called modified Taconis cycle (see U.S. Pat. No. 2,567,454 and Proceedings of the 1956 Cryogenic Engineering Conference of the University of Colorado, Boulder, Colo., Feb. 1957, pp. 188-196), the Philips Stirling engine (see for example U. S. Pat. No. 2,657,553) and the Vuilleumier apparatus (see U.S. Pat. No. 1,275,507).

In all of these cryogenic devices a sizable thermal loss is associated with the motion of the piston or displacer which defines the volume of the refrigeration chamber. This thermal loss, which for convenience is termed "motional heat leak" is caused by the moving of a displacer or piston which is cold at one end and warm at the other. Temperature gradients exist along the length of the piston (or displacer) as well as along the length of the cylinder, so that as the piston is moved to define a refrigeration chamber of increasing volume it enters a warm region and its surface is colder than the facing cylinder wall. Conversely, when the displacer is moved to define a refrigeration chamber of decreasing volume toward the cold temperature region, its surface is warmer than the facing cylinder wall. When the piston is in the warm region, it absorbs heat from the cylinder wall and then transfers this heat to the cylinder wall when it is in the low temperature region. In this way a thermal load is progressively "leap-frogged" down the cylinder wall and gives rise to motional heat leak. The thermal loss due to this motional heat leak may be as high as 30 percent of the total refrigeration produced.

One obvious way to avoid the thermal losses due to motional heat leak is to increase the gap between the piston and the cylinder in which it reciprocates, but this

solution increases the void volume within the apparatus and hence increases pressurizing losses as well as regenerator losses. Therefore, it would be desirable to be able to reduce the motional heat leak while at the same time maintaining a low void volume. Alternatively, if thermal losses due to motional heat leak can be tolerated, then it would be desirable to be able effectively to reduce the void volume. Under some circumstances, it may also be desirable to be able to optimize these two factors. The apparatus and method of this invention make possible the achievement of these desiderata.

It should be noted in the descriptions of the apparatus of this invention that such words as "warm" and "cold" are relative and that the use of "up" and "down" are for convenience in describing one exemplary orientation of the apparatus since the devices under consideration may generally be operated in any orientation. It will also be convenient to refer to the movable body as a "piston" in general discussions and to use the term in its broadest sense in order to include a displacer within its meaning. Thus the term piston includes all sliding bodies moving within a cylindrical vessel whether or not they experience pressure differentials on their surfaces; while the term "displacer" is reserved for sliding bodies which experience essentially no pressure differential on their surfaces.

In the method and apparatus of this invention motional heat leak is minimized by decreasing the thermal capacity and conductivity of the internal wall of the cylinder defining the fluid-tight housing in which the piston moves. This is accomplished by lining that portion of the cylinder wall which is immediately adjacent to the moving piston, with a material having a low thermal conductivity and low heat capacity over the temperature range involved. The liner is terminated at the level of any heat station. In a preferred embodiment the lining for any one piston or piston section extends within the housing over a length which is essentially equivalent to the length of the piston or piston section operating between two different temperature levels plus the length of the piston or piston section stroke, with the exception that the lining is discontinuous along that length of the housing substantially defined between those levels corresponding to the position of any heat station associated with the housing. The lining may be applied by spraying, painting or otherwise applying a liquid to the inner wall of the cylinder or it may be inserted as a thin sleeve liner. The latter term is used throughout this description. However, it is meant to include a lining applied by any suitable technique which does not necessarily imply the formation of a separate sleeve for insertion into the cylinder. The final result is the same in all cases.

The liner is formed of a material which has both a low thermal capacity and low thermal conductivity over a temperature range from cryogenic temperatures to room temperature. Such materials include, but are not limited to, Micarta, polytetrafluoroethylene (filled or unfilled), ceramics and refractories (e.g., alumina). Generally, micarta and polytetrafluoroethylene are more suitable for cryogenic apparatus while the ceramics and refractories may be used at elevated temperatures. Preferably, the liner will be formed of a non-metallic material. The cylinder wall configuration is so

modified as to permit the liner to be adhered thereto in a way to define a continuous internal surface wall within the cylinder so as not to hinder the movement of the piston and to provide for free sliding motion of sealing rings. Wall surface continuity refers to overall continuity which permits piston motion; it does not, however, eliminate circumferential grooves used for seals and the like.

It is therefore a primary object of this invention to provide improved valved expansion engines wherein a regenerator or other type of heat exchanger is used to isolate temperature levels, the improvement lying in the reduction of thermal losses due to motional heat leak or the reduction of void volumes with attendant pressure losses, or a combination of both. It is another primary object of this invention to provide cryogenic apparatus, incorporating a piston movable within a cylindrical housing to define at least one refrigeration chamber of variable volume, which exhibits a marked decrease in motional heat leak and hence an increase in thermal efficiency. It is another principal object of this invention to provide a method for developing refrigeration, including the step of expanding a high-pressure cold fluid, which exhibits higher thermal efficiencies than otherwise attainable by minimizing motional heat leak associated with a movable body defining a refrigeration chamber of variable volume. Other objects of the invention will in part be obvious and will in part be apparent hereinafter.

The invention accordingly comprises the several steps and the relation of one or more of such steps with respect to each of the others, and the apparatus embodying features of construction, combinations of elements and arrangement of parts which are adapted to effect such steps, all as exemplified in the following detailed disclosure, 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 cross section of a single stage cryogenic apparatus constructed in accordance with this invention and operating on the cycle described in U.S. Pat. No. 2,966,035;

FIG. 2 is a cross section of a multistage cryogenic apparatus constructed in accordance with this invention and operating on the cycle described in U.S. Pat. No. 2,966,035;

FIG. 3 is a cross section of one embodiment of a cryogenic apparatus operating on the cycle of U.S. Pat. 2,906,101 and modified in accordance with this invention;

FIG. 4 is a cross section of another embodiment of cryogenic apparatus operating on the cycle of U.S. Pat. 2,906,101 and modified in accordance with this invention;

FIG. 5 is a cross section of a cryogenic apparatus operating on the cycle of U.S. Pat. No. 1,275,507 and modified in accordance with this invention; and

FIG. 6 is a cross section of a Philips Stirling engine modified in accordance with this invention.

The apparatus shown in FIGS. 1 and 2 operate on a cycle described in U.S. Pat. No. 2,966,035 in which a high-pressure fluid (e.g., helium) is introduced into a

refrigeration chamber within a system as cold high-pressure fluid, expanded and discharged from the system as low-pressure fluid at a temperature higher than that at which the high-pressure fluid entered the system. In the single-stage embodiment shown in FIG. 1, a displacer 10 is moved up and down within a fluid-tight housing, generally indicated at 11, by a suitable driving means (not shown) through rod 12. The displacer 10, in its motion, defines a warm chamber 14 of variable volume and a refrigeration chamber 15 also of variable volume. A regenerator 16 filled with a suitable heat storage material 17 such as lead balls retained on screen 21 is located within displacer 10, and fluid communication between chambers 14 and 15 is by way of a fluid flow path which includes regenerator 16, upper fluid ports 18 and a lower fluid flow system comprising a plurality of radial passages 19, and an annular passage 20 defined between the displacer and the internal housing wall. (This particular fluid flow path is described in U.S. Pat. No. 3,218,815.) High-pressure fluid is introduced into chamber 14 and low-pressure fluid is withdrawn therefrom through a common conduit 25 which in turn is connected through branch conduit 26, having valve 27, to a source of high-pressure fluid and through branch conduit 28, having valve 29, to a low-pressure reservoir. Typically, the high-pressure fluid source and low-pressure fluid reservoir are combined in a fluid compressor 30.

It will be seen that the fluid-tight housing 11 of FIG. 1 is formed of three different basic sections which, in combination, form an enclosed cylinder. Thus the top 33 and the major portion of the outer cylinder wall 32 are of a material such as stainless steel which provides structural strength while at the same time exhibits relatively low conductivity for a metal at cryogenic temperatures. The housing terminates at its lower end in a heat station 34 which is formed of a metal, such as copper, exhibiting high heat capacity and high thermal conductivity. This heat station 34 may take various forms, the one shown in FIG. 1 comprising a relatively thick bottom disk section 35, a first thick cylindrical section 36 and a thin cylindrical section 37. (See also U.S. Ser. No. 807,606, now U.S. Pat. No. 3,600,903, Aug. 24, 1971, filed in the names of Fred F. Chellis and James A. O'Neil for "Cryogenic Heat Station and Apparatus Incorporating the Same" and assigned to the same assignee as the present invention.) The term "heat station" has now been accepted to mean a thermal mass, usually of a high heat conductivity material, which connects a refrigeration source such as an expanding fluid or evaporating cryogen to some object to be refrigerated or to an auxiliary refrigeration transfer means such as a heat transfer path to a Joule-Thomson loop or a thermal link to some refrigeration load.

The inner wall of the cylindrical housing, down to the thin-walled section 37 of the heat station, is lined with a thin sleeve liner 40 of a material (preferably nonmetallic) having both low heat capacity and low thermal conductivity such as Micarta or polytetrafluoroethylene (Teflon). Liner 40 and the thin-walled section 37 of the heat station are made of the same thickness, thus permitting the outer cylinder wall 32 to be formed of a uniform thickness throughout its length. Although this liner wall thickness may vary over a wide range e.g., from about 0.002 to 0.10 inch and is not critical, a

minimum thickness of about 0.025 inch is preferred from a construction and performance point of view if the liner is in the form of a thin sleeve inserted into the cylinder. With a Micarta liner as shown in FIG. 1 having a wall thickness of 0.025 inch it is possible to attain an 80 percent dampening of the temperature wave. The o-ring seals 42 and 43, which isolate chambers 14 and 15 from each other and force all fluid to flow by way of the fluid flow path described, contact the surface of sleeve liner 40 at all times.

In constructing the housing assembly shown in FIG. 1, the sleeve liner 40 is inserted into the cylinder wall 32 and bonded thereto by a suitable adhesive or held in position by heat station 34 or end plate 33. As noted above, the liner 40 may also be applied by spraying, dipping and the like. The copper heat station, as a single piece, is then soldered to the inside of the stainless steel cylinder at a temperature lower than the softening temperature of the liner material. Soldering of a copper heat station inside of a stainless steel cylinder can be tolerated, in spite of the differential in thermal expansion coefficients of these two materials, because the stresses are very small.

In the multistaged apparatus of FIG. 2, the displacer 50 is of a stepped configuration and it is formed of an upper larger-diameter section 51 and a lower smaller-diameter section 52. Within each displacer section is a regenerator 53 and 54 and the motion of the displacer defines a warm chamber 55 and two refrigeration chambers 56 and 57, all of variable volume. The fluid flow path within the refrigerator which provides fluid communication among the three chambers comprises upper ports 58, regenerator 53, the openings in the foraminous plate 59, radial passage 60 and annular passage 61 associated with upper displacer section 51 and radial passages 62, regenerator 54, the openings in foraminous plate 63, radial passages 64 and annular passage 65 associated with lower displacer section 52.

The stepped housing 70 is formed of an upper, larger diameter section 71 and lower, smaller-diameter section 72. Each of these sections is, in turn, constructed in a manner similar to housing 11 of the apparatus of FIG. 1. The upper housing section 71 is comprised of an outer cylinder wall 73 and a top member 74 of stainless steel, a heat station 75 of copper and a sleeve liner 76. The lower housing section 72 is comprised of an outer cylinder wall 77 which is integral with an annular flange 78 attached to heat station section 75 of the upper housing section and which is formed of stainless steel, a heat station section 79 forming the lower end of the housing and a sleeve liner 80 which extends up to refrigeration chamber 56. Refrigeration may be extracted at two temperature levels, namely at the temperatures of the fluid in chambers 56 and 57, the latter being at the lower temperature. To do this, coils 81 and 82, each suitable for circulating a fluid therein, are affixed in heat exchange relationship to the other surfaces of the heat stations. O-ring seals 83 and 84 are used with the two displacer sections 51 and 52.

In the operation of the cryogenic apparatus of FIG. 1 valve 27 is opened to begin the cycle and valve 29 is closed. At this point in the cycle the displacer is in its lowermost position having swept the cold low-pressure fluid from chamber 15. Ambient-temperature high-pressure fluid is introduced into warm chamber 14 and

with the movement of displacer 10 upwardly, it is caused to flow into chamber 15, via the flow path including the regenerator, where it undergoes an initial cooling while remaining at an elevated pressure. The residual fluid remaining in chamber 14 is compressed and heated as it is mixed with the incoming high-pressure fluid. The flow of high-pressure fluid is preferably cut off while the displacer is still rising; and after valve 27 is closed, valve 29 is opened allowing the fluid to expand in chamber 15, as it is increased in volume with upward motion of displacer 10, as well as into the flow path and the low-pressure fluid reservoir. When the displacer has reached its uppermost position, valve 29 is closed, and the cycle is ready to begin again with the opening of high-pressure valve 27.

The apparatus of FIG. 2 operates in the same manner, except that a portion of the initially cooled, high-pressure fluid is expanded in refrigeration chamber 56 and a portion in chamber 57.

It will be seen from this brief description of the cycle, that as the displacers in the apparatus of FIGS. 1 and 2, experience their reciprocal motions they are continuously and alternately being exposed to regions maintained at different temperatures. Taking displacer 10 of FIG. 1 as exemplary, it will be seen that when it is moving upwardly it enters a region which is at a higher temperature and its surface will be colder than the facing cylinder wall. Conversely, as displacer 10 travels downwardly, it will enter a low temperature region where its surface will be warmer than the facing cylinder wall. There are of course ways of reducing motional heat leak including increasing the clearance between the cylinder and displacer, increasing the length of the apparatus, decreasing the length of the stroke or reducing the reciprocation rate of the displacer. Increasing the clearance increases the void volume of the refrigerator which in itself decreases the efficiency of the system; while increasing the length of the apparatus may place undue structural limitations on the device; and decreasing the displacer stroke or its reciprocation rate may place unwanted limitations on the performance of the apparatus. There is, in fact, very little freedom in the variations of length, stroke and speed since these parameters are usually set by factors other than motional heat leak.

Through the use of the sleeve liner of this invention, the motional heat leak is reduced by as much as 80 percent, a very material reduction, particularly in small cryogenic units. This is brought about by the fact that the sleeve liner, having a low thermal capacity and being a poor thermal conductor, will have its surface temperature rapidly changed by only a very small transfer of energy to it from the piston or to the piston from it. A typical stainless steel cylinder wall has properties which cause its temperature to vary through its complete depth in a radial direction. With the sleeve liner on the cylinder the temperature of the liner surface quickly comes to the temperature of that portion of the piston adjacent to it while the interior of the liner and the cylinder wall stay at a uniform temperature. The decrease in motional heat leak is, therefore, a result of the interior wall material's being substantially unchanged in temperature as the piston moves within it.

As pointed out, motional heat leak is a factor in any cryogenic apparatus or thermal compressor or engine in which fluid is transferred to an expansion or compression chamber, through a flow path incorporating a regenerator or other type of heat exchanger, by the reciprocating motion of a piston and/or by gas valving. FIGS. 3-6 illustrate three other apparatus which may be modified in accordance with this invention. The apparatus of FIG. 3 operates on the cycle described in U.S. Pat. No. 2,906,101 and its particular construction shown is that disclosed in Ser. No. 867,661 filed in the name of James A. O'Neil wherein a single in-line displacer is used in a multistaged refrigerator. It is of course within the scope of this invention to use a sleeve liner in the apparatus of U.S. Pat. No. 2,906,101 as well as illustrated in FIG. 4. The apparatus of FIG. 3 was chosen as one example of the cycle of that patent since it illustrates the use of a sleeve liner which extends only between heat stations.

The apparatus of FIG. 3 differs from that of FIGS. 1 and 2 in that the housing is open at the top and no warm chamber is provided. This requires that seals 86 and 87 must be used at the warm end of the apparatus, and therefore the housing is preferably somewhat modified to strengthen the upper section. Therefore, the housing is shown to comprise a lower housing section 88 and an upper housing section 89, the latter being opened at the top 90, as indicated. The in-line, multistaged displacer 91 is formed of an upper section 92, which contains a first regenerator 93 filled with suitable regenerator packing material such as stacked screens 94 and terminating at its lower end in a foraminous disk 95, and an annular section 96 which in turn is formed in two parts. The first part of the annular section 96 is a lower annular portion 97 formed of a low thermal conductivity material such as Micarta and the second is an upper annular portion 98 of a length which approximates the maximum height of the intermediate temperature refrigeration chamber (comparable to chamber 56 of FIG. 2), formed of copper or some other suitable high thermal conductivity material. The inner wall of the annular section 96 of displacer 91 makes a sliding fluid seal with the outer wall of a tubing 99 which extends from the bottom of the apparatus to a predetermined height which defines the maximum volume of a first, intermediate-temperature refrigeration chamber 100. The second regenerator 101 required for a staged refrigerator of this type is located within the tubing 99 and it may be comprised of any suitable packing material shown in FIG. 3 to be a metallic wool 102 held in place by foraminous plates 103 and 104. As displacer 91 reciprocates, it defines refrigerator chamber 100 between regenerators 93 and 101 as well as the colder annularly configured refrigerator chamber 105, both of variable volume. A heat station 106 is formed of a thick copper disk 107 and an annular copper ring 108 machined to be integral with the disk and to fit between the lower housing section 88 and tubing 99 thus sealing off the cold end of the apparatus. Fluid communication between refrigeration chamber 105 and regenerator 101 is by way of a plurality of passages 109 drilled in the annular ring section 108 of the heat station and aligned with passages 110 drilled in the tubing 99,

In this apparatus it is, of course, necessary to provide some modified system for introducing the high-pressure fluid into and withdrawing the low-pressure fluid from the upper or warmer regenerator 93. This is done by modifying the upper or solid section 92 of the displacer to provide a passage or groove 111 defined between the outer displacer wall and the inner wall of the upper housing 89. This annular passage or groove 111 is then connected for fluid communication with the regenerator 93 through a single or plurality of radial passages 112 drilled in the displacer. The passage 111 must, of course, be of such a length that it is always open to the external conduit 113 (comparable to conduit 25 of FIG. 1) throughout the full stroke of the displacer.

When the displacer is constructed as shown in FIG. 3 to have an intermediate annular section 98 formed of a material having high thermal conductivity it is possible to derive refrigeration from the fluid in the intermediate-temperature refrigeration chamber 100. This may be done by bonding coils 114 to housing section 88, the coils being suitable for circulating a heat transfer fluid therethrough. Since heat is to be transferred from the cold fluid in refrigeration chamber 100 to the fluid in coils 114 by way of the copper section 98 of the displacer and the wall of housing section 88, the lower sleeve liner 115 of this invention must terminate at its upper end at or somewhat below the upper level of tubing 99. In like manner, the sleeve liner must terminate at its lower end at the upper level of the heat station 106 to eliminate any interference with the heat transfer between the fluid in refrigeration chamber 105 through heat station 106 to an external load. Because of the relatively large temperature gradient which can exist in the housing sections 88 and 89 extending from just above that point where coils 114 make thermal contact to the top of the apparatus, an upper sleeve liner 116 is used. If the annular section 96 of the displacer is formed as a single piece of low-conductivity material, then the sleeve liners 115 and 116 may be combined as a single liner extending from heat station 106 to the top 90. If tubing 99 is formed of metal, then a sleeve liner 117, serving the same function as liner 115 may be used to reduce motional heat leak on the inner wall of the displacer.

FIG. 4 shows the use of the sleeve liner in another embodiment of the apparatus described in U.S. Pat. No. 2,906,101 wherein the regenerator is external of the piston housing. In FIG. 4 like reference numerals are used to identify like components of the apparatus of FIGS. 1 and 3. The cylindrical housing 118 terminates in a heat station 34 and has a sleeve liner 119 extending throughout most of its length. The displacer 120 has sealing means such as one or more o-rings 121 associated with its warm end, and in its motion it defines a single (refrigeration) chamber 122. The fluid flow path is located externally of the housing 118, and includes a regenerator 123 connected directly to the fluid conduit 25 and a fluid line 124 connecting the regenerator to the chamber 122.

In a similar manner, the sleeve liner of this invention may be incorporated into apparatus using indirect heat exchange systems in place of or in addition to regenerators. A combination of these two types of heat exchangers is illustrated in an application Ser. No. 832,752

filed June 12, 1969 in the names of Walter H. Hogan and Robert W. Stuart and assigned to the same assignees as the present application. Sleeve liners such as illustrated in FIGS. 1-4 may be used in the apparatus illustrated in Ser. No. 832,572 and it is intended that that disclosure be incorporated herein.

The Vuilleumier apparatus (see U.S. Pat. No. 1,275,507) of FIG. 5 and the Stirling engine of FIG. 6 differ from the apparatus of FIGS. 1-4 in that they incorporate compressor means within the same housing as the refrigeration temperatures and hence they are completely closed systems.

The compression and expansion means in the apparatus of FIG. 5 are contained within a fluid-tight housing 125. (For simplicity of illustration, fluid seals are not shown since these may be constructed and used in accordance with known art.) The internal volume defined by housing 151 is divided into three chambers of variable volume, conveniently designated as the warm chamber 126, the "intermediate-temperature" chamber 127 and the cold or refrigeration chamber 128. The chambers are defined within the housing and their volume controlled through the movement of two displacers. The first of these is displacer 129 which contains a regenerator 130 having foraminous (or other suitable) ported plates 131 and 132 and which is driven through rod 133 by any suitable mechanical or pneumatic means. The second displacer 134 is likewise formed to have a regenerator 135 and ports 136 and 137 open to chambers 127 and 128. Displacer 134 is driven by any suitable means (not shown) through rod 138. Suitable fluid-tight seals are provided for rods 133 and 138 in accordance with known practice.

Suitable heat exchange means are associated with the chambers-e.g., coils 140 with chamber 126, coils 141 with chamber 127 and coils 142 with chamber 128. The sleeve liners 145 and 146, used to minimize motional heat leak, are located within those sections of housing 125 between the positions of coils 141 and 142 the positions of coils 141 and 140 inasmuch as heat transfer must be accomplished through those sections of housing wall 125 which are in thermal contact with coils 140, 141 and 142. In keeping with the cycle for which the apparatus of FIG. 5 is designed the displacers 129 and 134 will be moved to vary the volumes of chambers 126, 127 and 128. Heat to achieve compression is put into the system through heat transfer with fluid flowing in coils 140 heat is rejected through heat transfer with fluid flowing in coils 141, and refrigeration is delivered through heat transfer to fluid circulated in coils 142. For cryogenic applications a typical temperature sequence would be ambient temperature for fluid in coils 140, liquid nitrogen temperature for fluid in coils 141 and between about 20° and 25° K for fluid in coils 142. Other temperature sequences are of course possible, depending upon the use for the apparatus.

In the operation of the apparatus of FIG. 5 the volume of the fluid system remains constant while the fluid is shuttled among the chambers through the regenerators. The two displacers are phase-separated by about 90° and displacer 134 is subjected to the temperature gradient which is defined between the temperatures of the fluid in chambers 127 and 128, e.g., between about 77° and 20° K.

A Stirling cycle engine is illustrated in FIG. 6. This apparatus operates on a closed system wherein compression is achieved mechanically in contrast to its achievement by the addition of heat as illustrated in the apparatus of FIG. 5. This closed system is contained within an enclosure generally indicated by the numeral 151 which consists of a bottom section 152 housing the drive mechanism, and a main section 153 housing the compressor and the expansion chambers. A compressor piston 154 with suitable sealing rings 155 is driven through rods 156 from drive shaft 157 by motor 158. In the main housing 153 there is a displacer 159 which is driven off shaft 157 through rod 160. In their movement within the enclosure, piston 154 and displacer 159 define a compressor chamber 161 and a refrigeration chamber 162. The displacer 159 has a regenerator 163 located within it which terminates in a foraminous port plate 164. The fluid path between this regenerator and compression chamber 161 comprises an annular passage 165 and a plurality of radial passages 166. A heat station 167 is associated with the refrigeration chamber 162 and it is adapted to deliver refrigeration to a load. A heat station 168 is associated with the compressor chamber 161 and it is adapted through fluid circulating in coils 169 for cooling the compressed fluid prior to its delivery to regenerator 163. The sleeve liner 170 extends between the two heat stations 167 and 168 to minimize motional heat leak normally experienced because of the fact that a large temperature gradient exists between the warm compressed fluid in compressor chamber 161 and the cold fluid in refrigeration chamber 162.

The cycle on which the refrigerator of FIG. 6 operates is not a part of this invention but it may be described briefly as follows. With the displacer in the uppermost position the piston 154 is moved up causing compression of the gas in chamber 161. As the displacer 159 is moved downwardly to displace high-pressure gas from chamber 161 into refrigeration chambers 162 the piston continues to move upwardly to maintain high pressure. When the chamber 162 is at maximum volume by the downward movement of displacer 159, the displacer 159 is moved upwardly to displace the expanded and cooled gas out of volumes 162, while the piston 154 continues to move downwardly to maintain low pressure. The idealized cycle described is in practice modified by the fact that the displacer and piston have a simple sinusoidal motion with a phase separation of about 90° in their motions which closely approximates the cycle described. As the gas is displaced from chamber 165 through regenerator 163 it is cooled. The heat of compression is removed by passage of the gas on displacement from chamber 161 through annular heat exchange path 165 to heat station 168 and cooling fluid in coils 169. It is, of course, well known to use a modification of this Stirling device as a heat engine, and it is within the scope of this invention to incorporate sleeve liners in such modifications.

As noted from the description of the various apparatus embodiments illustrated in the drawings, the sleeve liner preferably extends within the housing over a length which is equivalent to the length of the piston or piston section operating between two different temperature levels plus the length of the stroke of the piston or piston section. It is, however, necessary to ter-

minate the sleeve liner and hence eliminate it along the length of the housing which is defined between those levels corresponding to the position of any heat station associated with the fluid-tight housing. In the case of FIG. 1, this means that the liner 40 preferably extends from the top thin cylindrical section 37 of heat station 34 all the way to the top member 33 as shown. In the case of the apparatus of FIG. 2, the liners 76 and 80 likewise extend from the tops of heat stations 75 and 79 to the top of the housing sections 71 and 72. In the apparatus of FIG. 3, the sleeve liner (115 plus 116) is broken and becomes discontinuous along that length of housing section 88 which is defined between the upper and lower limits of the thermal contact of coils 114, considered as a heat station, with the outer wall of housing section 88. As pointed out previously, if the annular section 96 of the displacer were itself continuous in construction, then the discontinuity of the sleeve liner would not be necessary. In the apparatus of FIG. 5, the length of the sleeve liners must be restricted in the prescribed manner to permit heat transfer through the housing wall to fluid in coils 140, 141 and 142. Essentially the same restrictions apply in the case of the Stirling engine of FIG. 6.

It will be appreciated by those skilled in the art that the apparatus illustrated in FIGS. 1-6 are merely exemplary of the apparatus which may be modified in accordance with the teaching of this invention to reduce thermal losses due to motional heat leak. For example, the apparatus of FIGS. 1 and 2 may be constructed with more than two refrigeration chambers and/or with an inline displacer or displacer section similar to that shown in FIG. 3 or be modified as in U.S. Pat. Nos. 3,188,820, 3,367,121 and 3,421,331. The apparatus of FIGS. 3 and 4 may be constructed as multistaged devices as disclosed in U.S. Pat. No. 2,906,101; while all of the apparatus shown may have external regenerators and additional heat exchangers, or be driven by motors or by pneumatic means such as disclosed in U.S. Pat. Nos. 3,045,436, 3,119,237, 3,188,819 and 3,321,926.

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 carrying out the above method and in the constructions set forth 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 thermodynamic expansion apparatus wherein a piston reciprocates between two different temperature levels to define at least one chamber of variable volume within an integral housing serving as the sole means for enclosing said chamber and wherein heat exchange means are located internal of said piston and are used to isolate at least two temperature levels, the improvement comprising a sleeve liner of a low thermal conductivity, low heat capacity material affixed to and forming a part of the internal wall of said housing and extending between said temperature levels.

2. An apparatus in accordance with claim 1 wherein said sleeve liner is formed of a nonmetallic material.

3. An apparatus in accordance with claim 1 characterized as being an expansion engine.

4. An apparatus in accordance with claim 1 characterized as being a thermal compressor.

5. An apparatus in accordance with claim 1 characterized as being a cryogenic refrigerator or liquefier.

6. In cryogenic apparatus wherein a piston reciprocates between two different temperature levels to define at least one refrigeration chamber of variable volume within an integral housing serving as the sole means for enclosing said chamber and into which high-pressure initially cooled fluid is delivered by way of a heat exchanger, located internal of said piston, for expansion and final cooling, the improvement comprising a sleeve liner of a low thermal conductivity, low heat capacity material affixed to and forming a part of the internal wall of said housing.

7. An apparatus in accordance with claim 6 wherein said sleeve liner extends within said housing over a length no greater than that which is substantially equivalent to the length of said piston plus the length of the stroke of said piston but is discontinuous throughout those sections of said housing corresponding to the position of any heat stations associated therewith.

8. An apparatus in accordance with claim 6 wherein said sleeve liner ranges from about 0.002 to 0.100 inch in thickness.

9. An apparatus in accordance with claim 6 wherein said low thermal conductivity, low heat capacity material is a non-metallic material.

10. An apparatus in accordance with claim 9 wherein said nonmetallic material comprises polytetrafluoroethylene.

11. An apparatus in accordance with claim 9 wherein said nonmetallic material is Micarta.

12. An apparatus in accordance with claim 9 wherein said nonmetallic material is a ceramic or refractory.

13. A cryogenic apparatus, comprising in combination

- a. an integral fluid-tight housing serving as the sole means for defining an enclosure therein;
- b. piston means movable between two different temperature levels within said enclosure defined by said housing to define at least one refrigeration chamber of variable volume;
- c. a fluid flow path including heat exchange means located internally of said piston means adapted to deliver initially cooled high-pressure fluid into said refrigeration chamber;
- d. heat station means external of said housing adapted to effect indirect heat exchange between the fluid in said refrigeration chamber and a load; and
- e. a sleeve liner of a low thermal conductivity, low heat capacity material affixed to the internal wall of said housing and defining therewith a continuously smooth surface, said sleeve liner extending within said housing over a length no greater than that which is substantially equivalent to the length of said piston plus the length of the stroke of said piston but being discontinuous through those sections of said housing corresponding to the position of said heat station means.

14. A cryogenic apparatus in accordance with claim 13 wherein said piston also defines a warm chamber of variable volume and said fluid flow path provides fluid communication between said refrigeration chamber and said warm chamber.

15. A cryogenic apparatus in accordance with claim 13 wherein said piston means comprises multiple sections each of which is movable between two different temperature levels thereby defining multiple refrigeration chambers.

16. A cryogenic apparatus in accordance with claim 13 including external high-pressure fluid supply means and external low-pressure fluid reservoir means in fluid communication with said fluid flow path.

17. A cryogenic apparatus in accordance with claim 13 including additional piston means independently movable within said housing to define a compressor chamber of variable volume.

18. A cryogenic apparatus in accordance with claim 17 including an additional sleeve liner of a low thermal conductivity low heat capacity material affixed to the internal wall of said housing extending within said housing over a length no greater than that which is substantially equivalent to the length of said additional piston means plus the length of the stroke of said additional piston means but being discontinuous through those sections of said housing corresponding to the position of said heat station means.

19. A cryogenic apparatus in accordance with claim 13 including additional piston means independently movable within said housing to define a compressor

chamber of variable volume and with said piston means which defines said refrigeration chamber to define a chamber of variable volume maintained at a temperature intermediate between said compressor chamber and said refrigeration chamber, and wherein heat station means are associated with each of said chambers.

20. In a method for developing refrigeration which includes the steps of introducing an initially cooled high-pressure fluid into a refrigeration chamber, the volume of which is varied by the motion of a movable body, having heat exchange means internal thereof, within an integral fluid-tight housing serving as the sole means for enclosing said chamber, and subsequently expanding said initially cooled fluid in said chamber by motion of said movable body between two different temperature levels to increase the volume of said chamber, the improvement comprising interposing between said piston wall and said fluid-tight housing wall a thin continuous layer of a low heat capacity, low thermal conductivity in the form of a sleeve liner for said housing, whereby said body in its motion is exposed to a minimum temperature gradient and the thermal losses due to motional heat leak are maintained at a relatively low level.

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