United States Patent [19]

Lobb

[11] 3,733,837

[45] May 22, 1973

[54] THERMODYNAMIC RECIPROCATING MACHINE

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[73] Assignee: The British Oxygen Company Limited, London, England

[22] Filed: Nov. 15, 1971

[21] Appl. No.: 198,631

[30] Foreign Application Priority Data

Nov. 18, 1970 Great Britain....................54,880/70
Mar. 24, 1971 Great Britain......................7,746/71

[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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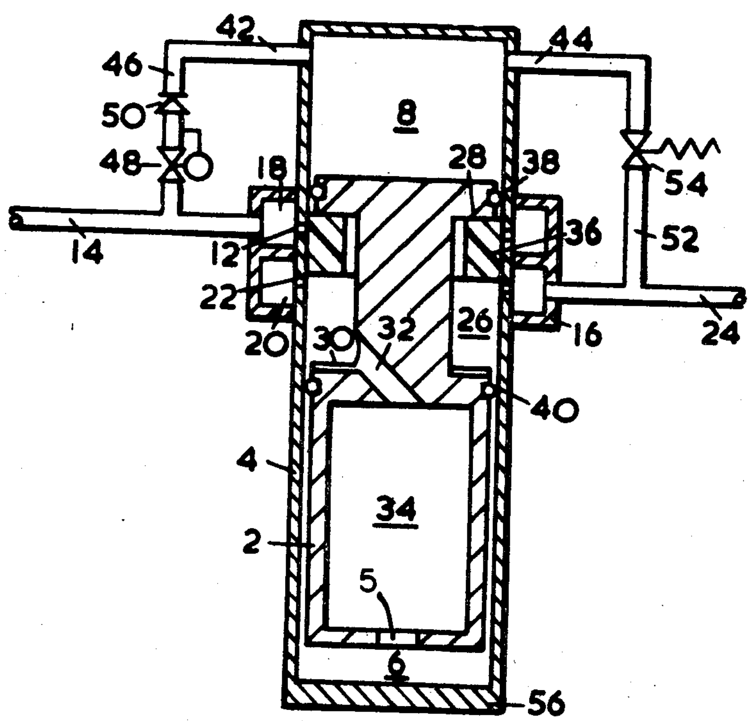
Primary Examiner—William J. Wye
Attorney—Robert I. Dennison et al.

[57] ABSTRACT

A simple form of refrigerator in which gas is cooled by expansion of a gas in an expansion chamber. The refrigerator includes a reciprocable displacer located within the cylinder, the expansion chamber being defined, at least in part, between the end of the displacer and the inner wall of the cylinder. Inlet and outlet of gas to the expansion chamber is controlled by a valve or valves operated by the displacer.

13 Claims, 13 Drawing Figures



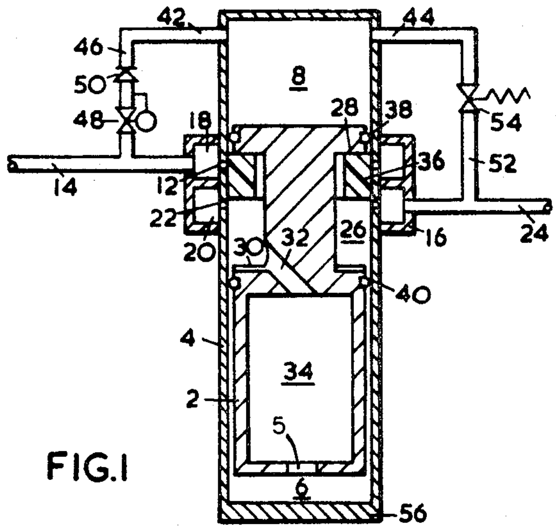

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FIG.1

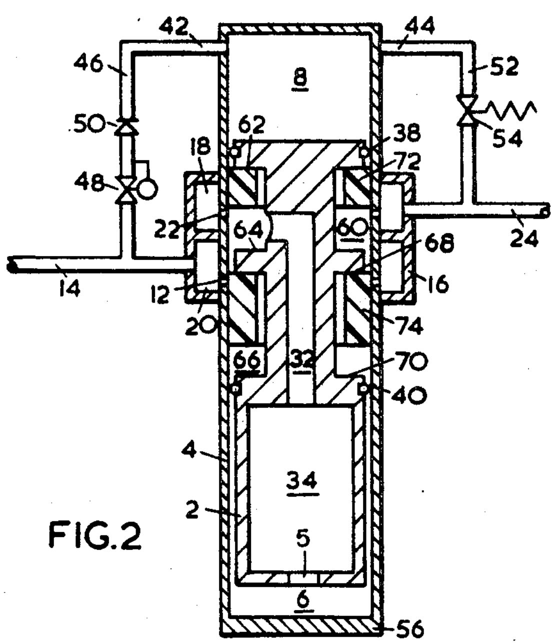
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FIG.2

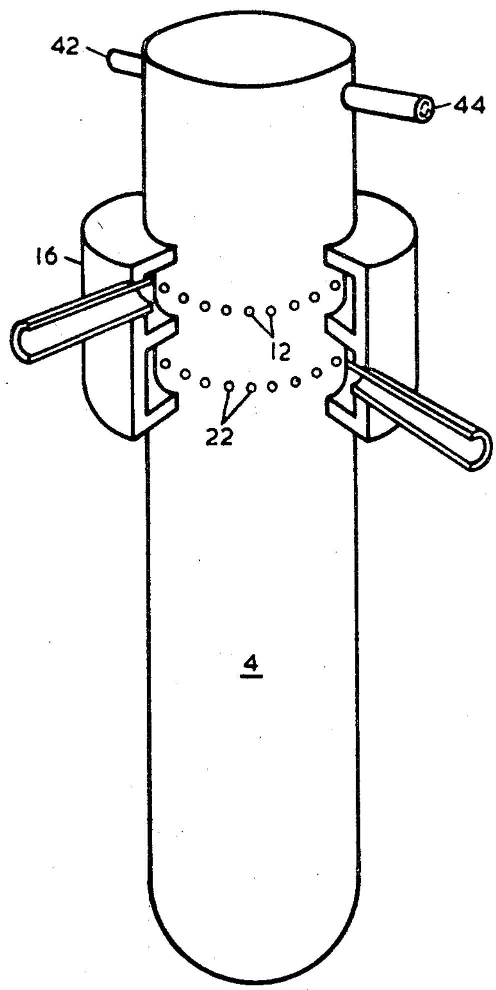
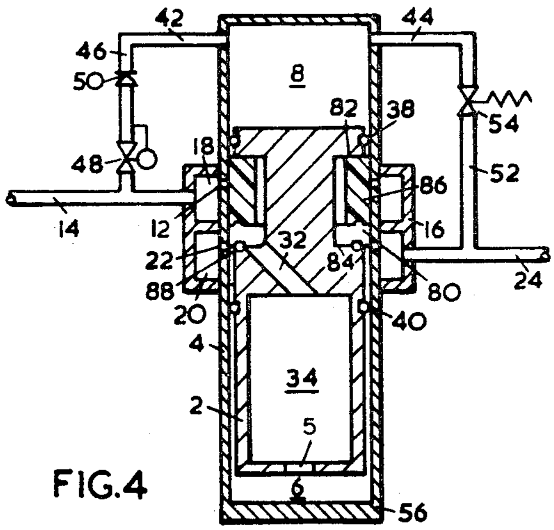


FIG. 3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48
52
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14
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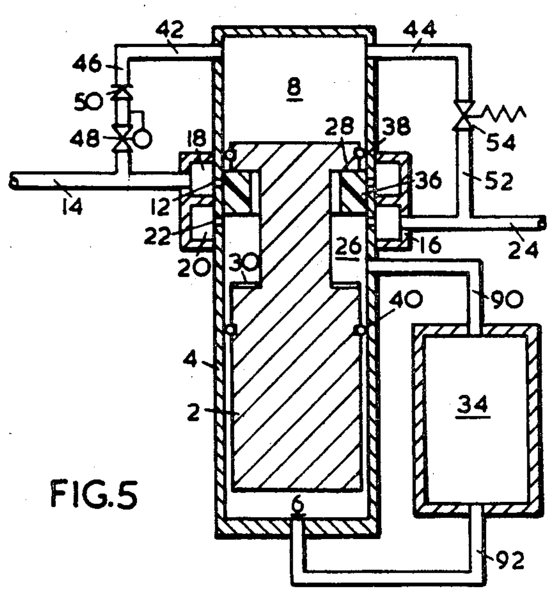
FIG.4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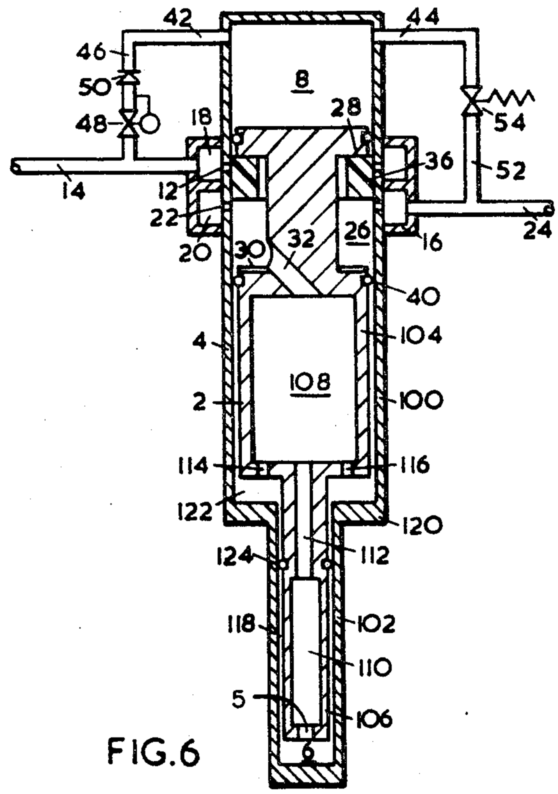
90
4
34
2
6
92

FIG.5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48
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12
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4
104
108
2
100
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116
122
120
124
112
118
102
110
5
106
6

FIG.6

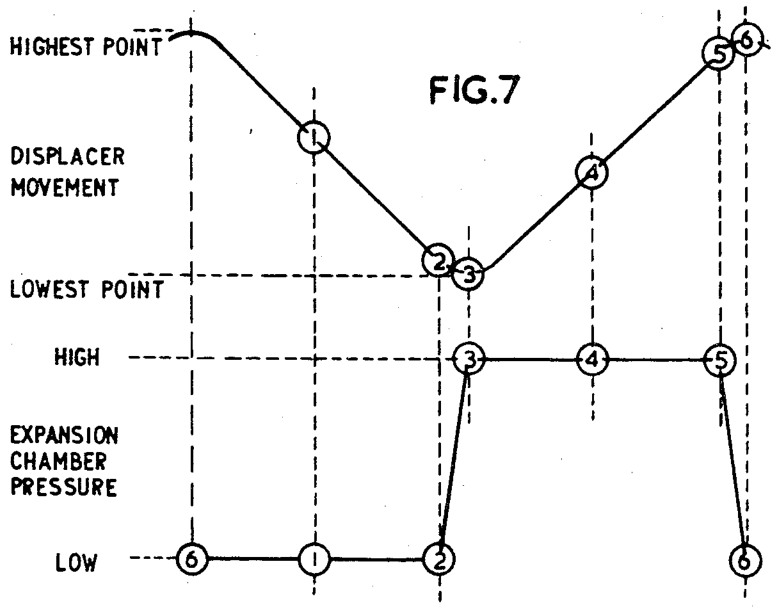
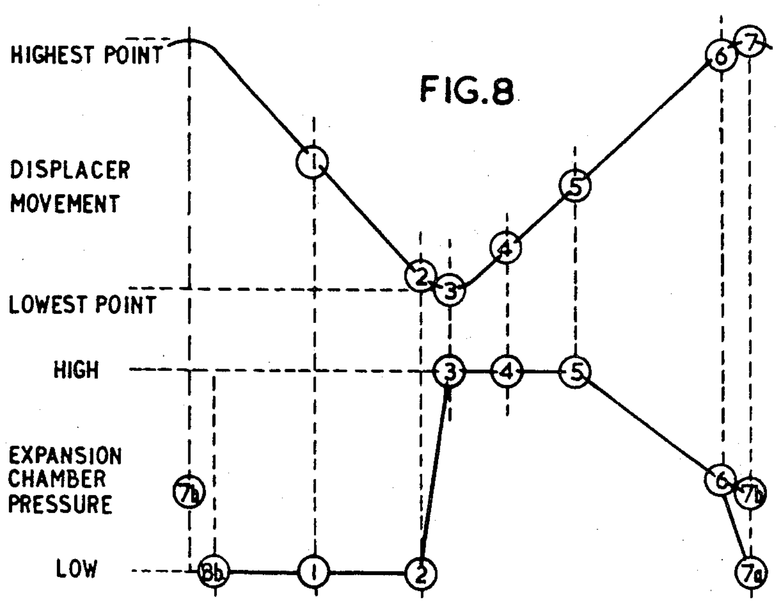

HIGHEST POINT
DISPLACER MOVEMENT
LOWEST POINT
HIGH
EXPANSION CHAMBER PRESSURE
LOW
1
2
3
4
5
6

FIG.7


HIGHEST POINT
DISPLACER MOVEMENT
LOWEST POINT
HIGH
EXPANSION CHAMBER PRESSURE
LOW
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2
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7
7b
7a
8b

FIG.8

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9 Sheets-Sheet 6

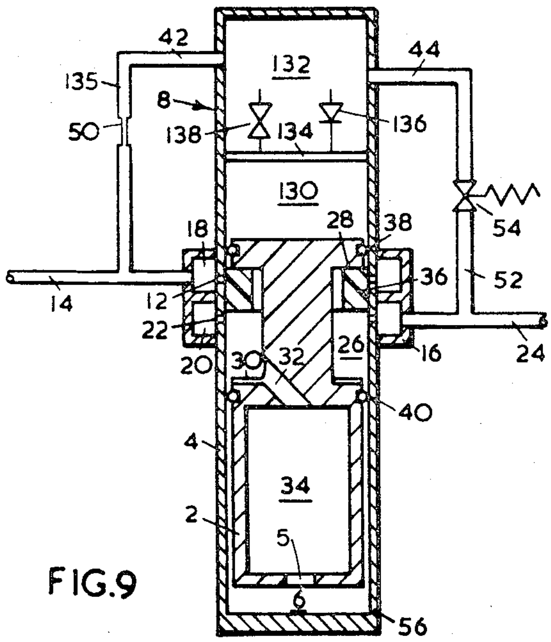

FIG.9

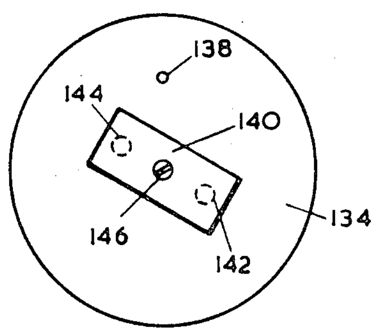

FIG.10

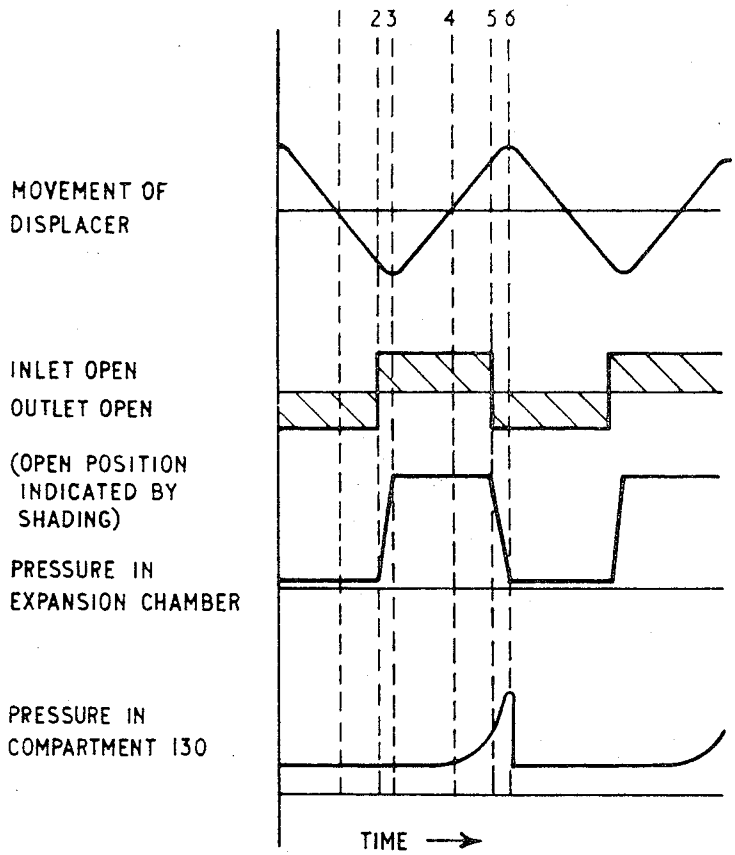
1
2
3
4
5
6
MOVEMENT OF DISPLACER
INLET OPEN
OUTLET OPEN
(OPEN POSITION INDICATED BY SHADING)
PRESSURE IN EXPANSION CHAMBER
PRESSURE IN COMPARTMENT 130
TIME

FIG.11

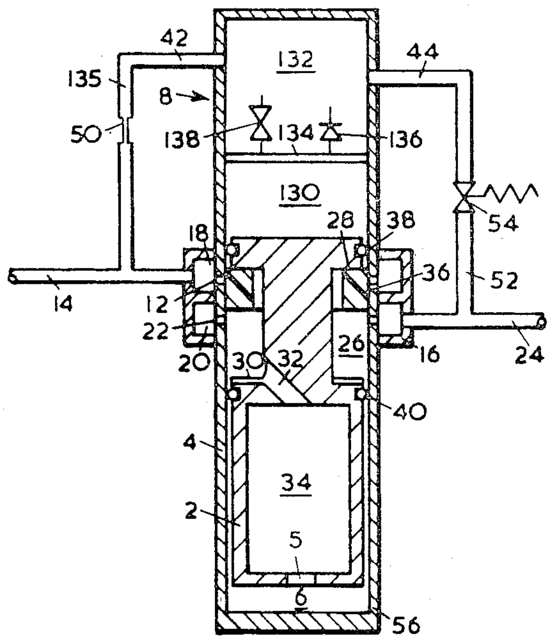
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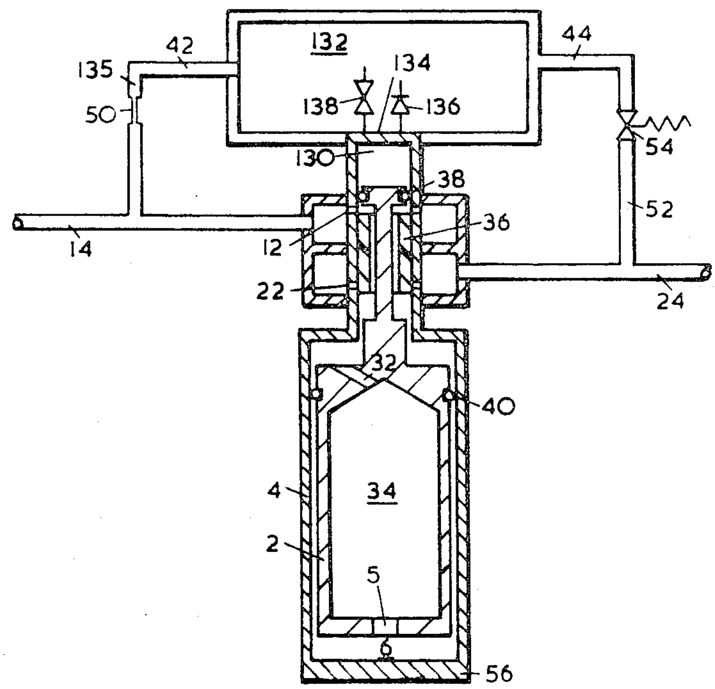
FIG.12


132
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32
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4
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2
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6
56

FIG.13

THERMODYNAMIC RECIPROCATING MACHINE

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a thermodynamic reciprocating machine, particularly the type of machine where a displacer is located inside a cylinder to form an expansion chamber, the displacer being caused to reciprocate within the cylinder by a varying difference in magnitude between the pressure exerted thereupon by gas admitted to the expansion chamber and a driving force exerted thereagainst. Refrigeration can be produced by the gap in the expansion chamber doing work against the displacer. Although in this specification the machine is described for producing refrigeration it may be possible to use as a hot gas engine.

2. Summary of the Prior Art

Known thermodynamic reciprocating machines of the aforementioned type often include a complex mechanical valve system for the inlet and outlet of gas from the expansion chamber.

SUMMARY OF INVENTION

It is an aim of the present invention to provide a simple valve system for a thermodynamic reciprocating machine.

Accordingly the present invention provides a thermodynamic reciprocating machine including a cylinder; a reciprocable displacer located in the cylinder; a gas inlet through the cylinder wall; a gas outlet through the cylinder wall; one or more valve members located between the cylinder wall and the displacer and operated by the displacer to open and close the inlet and the outlet; an expansion chamber which includes the space defined by one end of the displacer and the cylinder, and which is able to receive gas entering through the inlet and to expel gas through the outlet; and a regenerator for exchanging heat between gas entering and leaving the expansion chamber; in which machine the displacer is driven by a varying differential pressure between the gas in the expansion chamber and a restoring pressure.

Expansion of gas may occur in the expansion chamber and alternatively or additionally the machine may be arranged such that gas is expanded on exhausting from the expansion chamber.

The restoring pressure may, for example, be exerted by a spring, by hydraulic liquid or by means of a force transmitted through a mechanical linkage.

Preferably the restoring pressure is exerted by a gas in a driving chamber which includes the space defined by the ends of the displacer and the cylinder opposite the ends thereof defining the expansion chamber. If desired the driving chamber may additionally include the space defined by a separate chamber in communication with the part of the driving chamber located in the cylinder.

If a gas provides a restoring pressure, them that end of the displacer on which the pressure is exerted is in effect a piston which compresses the driving gas when the displacer moves to increase the volume of the expansion chamber. In this specification such a combined displacer-piston will be referred to, for convenience as a "displacer".

The pressure in the driving chamber is maintained within such limits that the reciprocating action of the displacer is facilitated. This may be achieved by supplying pressurized gas to the driving chamber, and having a pressure relief device in communication with the driving chamber being set to exhaust gas at a pressure between the maximum and minimum pressures which are created in the expansion chamber by the reciprocating displacer. This arrangement has the disadvantage that a considerable amount of pressurized gas may be wasted in operating the machine.

The gas consumption of the machine may be reduced if the driving chamber is divided into first and second compartments which communicate through a constriction, the first compartment being, in part, bounded by the end of the displacer. Preferably this form of machine further includes a one-way valve between the compartments. The function of the second compartment is act as a reservoir to the first compartment.

Conveniently the driving chamber is divided into compartments either by a plate located within the cylinder, or by the end of the cylinder itself.

Preferably the one-way valve permits gas flow only from the first compartment to the second compartment, the constriction regulating gas flow in the opposite direction when the one-way valve is closed. This arrangement offers the advantage that the speed at which the displacer moves to reduce the volume of the expansion chamber can be lessened, whereby disadvantageous compression of the gas in the expansion chamber can be minimized. Good results however, may be achieved if the one-way valve permits gas flow in the opposite direction only.

In a preferable form of the one-way valve the partition separating the compartments has a diaphragm attached at one or more points to the face thereof facing the compartments to which the one-way valve leads, and at least one aperture is formed in the partition and may be sealed by the diaphragm when the pressure in the compartment in which the diaphragm is located is greater than in the other compartment. The pressure difference between the two compartments required to open the one-way valve depends on the size of the aperture or apertures covered by the diaphragm and the thickness and flexibility of the material from which the diaphragm is formed.

Desirably the diaphragm has a smaller area than that of the partition so that it does not constrict the flow of gas when the diaphragm is lifted from the aperture or apertures.

Conveniently the constriction is provided by a small aperture in the partition between the compartments. The size of the aperture is preferably such that there is only a slow rate of flow therethrough when the displacer is moving to increase the volume of the expansion chamber. Alternatively the constriction may be provided through a pressure-relief valve (one-way valve) leading in the opposite direction to the other one-way valve.

Preferably one of the compartments of the driving chamber is supplied at a low rate with pressurized gas to compensate for gas leaking from the driving chamber.

Preferably the volume of the second compartment is at least twice that of the first compartment. This prevents excessive pressure fluctuation in the second compartment and maintains the first compartment at substantially constant pressure when its volume is being increased.

Desirably two sealing rings are located between the displacer and the inner surface of the cylinder wall one sealing ring being located on one side of the inlet and the outlet of the expansion chamber, the other sealing ring being located on the other side of the inlet and the outlet. This enables the expansion chamber to be sealed from the driving chamber. However some gas leaks from the driving chamber past the sealing ring located nearest to the driving chamber when the pressure therein is greater that in the expansion chamber. Thus in order to regulate the pressure in the driving chamber a small amount of gas is required to replace that leaking past the sealing ring located nearer to the driving chamber. In practice the gas may be supplied to the driving chamber by a restricted passage which leads to the driving chamber from a passage leading to the inlet of the expansion chamber. The restricted passage may, for example, be provided by a narrow bleed conduit, or by means of a conduit having a needle valve. It is found that the driving chamber may be supplied at a rate of less than 1% of the rate at which gas is supplied to the expansion chamber.

In a particularly simple form of machine according to this invention there is a single valve member including a single ring in frictional engagement with the inner surface of the cylinder wall. In order to prevent the inlet and the outlet of the expansion chamber being simultaneously open the length of the ring measured along the axis of the cylinder is desirably greater than the distance between the inlet and the outlet measured along the same axis. Preferably the ring is located between the end walls of a recess formed in the displacer and is operated by being contacted by one or both in sequence, of the end walls.

In order that the machine can produce the most efficient refrigeration it is desirable that the outlet remains open when the volume of the expansion chamber is being reduced in order to minimize the amount of compression occurring in the expansion chamber. In addition when the volume of the expansion chamber is being increased it is desirable that both the inlet and the outlet are closed in order to permit the gas in the expansion chamber to expand and cool considerably.

With the form of valve including a single ring it is found that improved cooling can be achieved if the length of the recess measured along the axis of the cylinder is sufficiently greater than the length of the valve ring measured along the same axis to enable the inlet to be closed and the outlet to be open for the greater part of the period during which the displacer is moving to reduce the volume of the expansion chamber, and to enable the inlet to be open and the outlet closed for the greater part of the period during which the displacer is moving to increase the volume of the expansion chamber.

In a more efficient form of machine including a single valve ring, the end face of the ring nearer to the expansion chamber is able to make a seal with the end wall of the recess facing said end of the face. Preferably one of the end face and the end wall accomodates a sealing ring, and the other cooperates therewith to effect the seal therewith. By using this form of valve, for the greater part of the period when the displacer is moving to increase the volume of the expansion chamber, the seal between the end face of the valve ring and the end wall of the recess closes the outlet and the valve ring closes the inlet. In order for the seal between the end face of the valve ring and the end wall of the recess to be maintained for a sufficiently long period it is generally required that the valve ring be made longer than when no seal between the end face of the recess and the valve ring is employed.

In another form of machine giving a good thermodynamic performance there is a valve member for the inlet, and a separate valve member for the outlet, each valve member including a ring in frictional engagement with the inner surface of the cylinder wall. Preferably each valve ring in located between the end walls of a recess formed in the displacer, and is operated by being contacted and displaced by the end walls of the recess in which it is located. Preferably the difference in length between the outlet ring and the recess in which it is located is greater than the difference between the inlet ring and the recess in which it is located, whereby both the inlet and the outlet are able to be closed for the greater part of the period during which the displacer is moving to increase the volume of the expansion chamber.

Preferably each of the end faces of the or each ring, or each of the surfaces of the end walls of the or each recess has a passage formed therealong to enable gas to pass between the or each ring and each recess wall it contacts during the operation of the machine.

It is desirable that the mass of the or each valve ring, the coefficient of friction between the ring and the inner surface of the cylinder wall, and the velocity of the displacer are such that the ring does not move relatively to the displacer upon initial contact by the displacer.

It should be appreciated that a small leakage of gas past a valve ring when it closes the inlet or the outlet is tolerable and will facilitate the starting of the machine. If difficulty does arise in starting the machine, however, it is found that opening the pressure relief device for exhausting gas from the driving chamber will provide an impulse sufficient to start the machine.

Preferably the regenerator is located within the displacer for simplicity of construction. Alternatively the regenerator may be housed in a separate chamber or is located between the walls of the displacer and the cylinder.

The warmer end of the cylinder — i.e. the end where the driving chamber is located — may be cooled by leading exhaust gas from the regenerator around the outer surface of the cylinder at the warmer end. This may be achieved by providing a jacket and forming annular grooves around the outer surface of the cylinder so that the exhausted gas from the expansion chamber is constrained to flow around the grooves.

Preferably the inlet and the outlet each comprises a plurality of small apertures formed through the cylinder wall, and communicates with a passage in an annular collar which is located around the cylinder wall and which has an inlet and an outlet port.

If desired the displacer and the cylinder may be moulded from a plastics material.

A preferable material for forming the displacer is a fiber-based phenolic resin. Other suitable synthetic resins include polyamide, polyimide, acrylic, epoxy, acetal and polyester resins.

The or each valve ring may, for example, be formed in part, of a polytetrafluoroethylene. Preferably the polytetrafluoroethylene is glass-filled. Alternatively the polytetrafluoroethylene may be reinforced with other fibers or carbon.

The regenerator is provided by a material having a high specific heat. Such material, for example, phosphor-bronze screens are well known in the art.

If desired the region of the cylinder wherein the inlet and the outlet of the expansion chamber are located may be of smaller cross-sectional area than the region of the cylinder that, in part, bounds the expansion chamber. This offers the advantage of reducing the volume between the expansion chamber and the driving chamber wherein the gas does not perform a useful function, and thus adds to the efficiency of the machine. A machine according to this invention may be used to cool a gas to a deep low temperature. This may be achieved by including more than one regenerative stage in the machine.

Such a machine may conveniently include a stepped displacer incorporating separate regenerators and located in a stepped cylinder.

To enable refrigeration to be obtained from the machine, at least part of the region of the cylinder that, in part, bounds the expansion chamber may be made of a heat conductive material to facilitate heat transfer between the load being cooled and the gas in expansion chamber. For instance the cylinder may have a copper cap provided at the base of the expansion chamber.

A thermodynamic reciprocating machine according to this invention may also be used to cool a gas, for example in a stage of liquefaction process.

The machine is particularly suitable for cooling the walls of a vapor trap of a vacuum system, or used as a cryopump.

It is an advantage of the machine according to this invention that it has few moving parts, in preferred forms only the displacer and the or each valve member. Thus the machine is simple and cheap to manufacture.

Another advantage of preferred forms of the machine according to this invention is that frictional wear of a valve ring does not seriously impair the operation of the machine as a small leakage of gas past the ring has little if any detrimental effect.

The invention includes within its scope a refrigeration process employing the thermodynamic reciprocating machine of this invention.

The invention is now described by way of example with reference to the accompanying drawings, of which

FIG. 1 is a diagrammatic representation, partly in section, of one form of thermodynamic reciprocating machine which includes a valve member provided by a single ring;

FIG. 2 is a diagrammatic representation, partly in section, of a second form of thermodynamic reciprocating machine which includes two rings serving as valve members;

FIG. 3 is a perspective view of the outer surface of a cylinder which forms part of the machine shown in FIGS. 1, 2, 4, 9 and 12.

FIG. 4 is a diagrammatic representation, partly in section, of a third form of thermodynamic reciprocating machine which includes a single valve ring which is able to close the outlet to the expansion chamber by forming a seal with the wall of a recess in the displacer;

FIG. 5 is a diagrammatic representation partly in section of a form of thermodynamic reciprocating machine in which the regenerator is located outside the displacer.

FIG. 6 is a diagrammatic representation, partly in section, of a thermodynamic reciprocating machine including two regenerative stages;

FIG. 7 is a diagram showing how the pressure in the expansion chamber varies from the position of the displacer during the operation of the machine shown in FIG. 1,

FIG. 8 is a diagram showing how the pressure in the expansion chamber varies with the position of the displacer during the operation of the machine shown in FIG. 2, or of the machine shown in FIG. 4;

FIG. 9 is a diagrammatic representation, partly in section, of another form of thermodynamic reciprocating machine incorporating a driving chamber including two compartments;

FIG. 10 is a plan view of a portion of the form of machine shown in FIG. 9;

FIG. 11 is a diagram showing the variation of the pressure in the expansion chamber, the first compartment, and the position of the valve member with the position of the displacer as it reciprocates during the operation of the machine shown in FIGS. 9, 12, or 13;

FIG. 12 is a diagrammatic representation, partly in section, of another form of thermodynamic reciprocating machine including a driving chamber having two compartments; and

FIG. 13 is a diagrammatic representation, partly in section, of a form of thermodynamic reciprocating machine having a small "dead" volume between the expansion chamber and the driving chamber.

In the following description like parts are denoted in each figure by the same reference numerals and the operation of each machine is described as if the machine is in a vertical attitude with its driving chamber above its expansion chamber although it may, of course, be used in other attitudes.

In the form of machine shown in FIGS. 1 and 3 a displacer 2 is located inside a stainless steel cylinder 4 to define therein an expansion chamber 6 and a driving chamber 8.

An inlet in the expansion chamber 6 is provided by a plurality of small, circumferentially located apertures 12 formed through the wall of the cylinder 4 and an outlet from the expansion chamber 6 is provided by a plurality of small, circumferentially located apertures 22 formed through the wall of the cylinder 4 and located below the apertures 12. Around the region of the outer surface of the wall of the cylinder 4 wherein the apertures 12 and 22 are disposed a collar 16 is located, which collar, with the wall of the cylinder 4 forms annular compartments 18 and 20 for the passage of gas flowing into the apertures 12 and out of the apertures 22. An inlet port 14 leading from a source of high pressure gas (not shown) communicates with the compartment 18. An outlet port 24 for the venting of gas exhausting from the expansion chamber 6 leads from the compartment 20.

Gas at high pressure enters the inlet port 14 and passes around the annular compartment 18, through the inlet apertures 12, into the cylinder 4 where it passes around a recess 26 having mutually facing walls 28 and 30 and formed in the displacer 2, passes through a passage 32 and a phosphor-bronze regenerator 34 located in the interior of the displacer 2 and passes through a port 5 into the expansion chamber 6. Gas exhausting from the expansion chamber 6 passes through port 5 into the regenerator 34 through the passage 32, around the recess **26** and out of the cylinder **4** through the outlet apertures **22** and into the annular compartment **20** wherefrom it exhausts through the outlet port **24**.

Whether the outlet apertures **22** or the inlet apertures **12** of the expansion chamber **6** are open depends on the relative positions of a ring **36** and the apertures **22** and **12**. The ring **36** is located in the annular recess **26** and is in frictional engagement with the inside wall of the cylinder **4** such that according to its position it seals the apertures **22** or **12** from the recess **26**. The ring **26** is of such a size that it is capable of just sealing the orifices **22** and **12** from the recess **26** simultaneously. On one side of the recess **26** is located a circumferential seal **38** which minimizes passage of gas from the driving chamber **8** to the annular recess **26**. On the other side of the recess **26** is located a circumferential seal **40** which minimizes the passage of gas to or from the expansion chamber **6** by-passing the regenerator **34** by flowing along the annular clearance formed between the outside wall of the displacer **2** and the inside wall of the cylinder **4**.

Ports **42** and **44** are located at the upper end of the cylinder **4** for inlet and outlet respectively of gas from the driving chamber **8**. A conduit **46** leads from the inlet port **14** of the expansion chamber **6** to the port **42**. A regulator (pressure reducing valve) **48** and a one-way valve **50** for permitting a gas flow in the direction only of the port **42** are located along the conduit **46**, the valve **50** being located between the regulator **48** and the port **42**. A conduit **52** leads from the port **44** to the outlet port **24** and has located therealong a pressure relief valve **54**.

The function of the regulator **48** is to regulate a minimum pressure within the driving chamber **8**, the regulator **48** being supplied with high pressure gas from the source via the conduit **46**.

The function of the one-way valve **50** is to protect the regulator **48** from pressure fluctuations created in the driving chamber **8** by the reciprocation of the displacer **2**.

The function of the relief valve **54** is to control the maximum pressure in the driving chamber **8** such that gas is exhausted through the conduit **52** when the pressure in the driving chamber **8** exceeds the chosen relief pressure.

In operation the displacer **2** reciprocates under the action thereacross of a differential pressure created between the gas in the expansion chamber **6** and the gas in the driving chamber **8**. Thus pressurized gas is supplied to the inlet port **14**, at, say 100 psi (6.9×10^5 N m^{-2}), the regulator **48** being designed to reduce the pressure of the gas flowing therethrough to, say, 40 psi (2.76×10^5 N m^{-2}) the relief valve **54** designed to open at a pressure of, say, 60 psi (4.1×10^5 N m^{-2}) and the machine designed such that gas exhausts from the expansion chamber **6** at a low pressure of, say, 5 psi (3.4×10^4 N m^{-2}) or less.

With the ring **36** located such that the inlet apertures **12** are closed and the outlet apertures **22** open and with the pressure in the driving chamber **8** greater than the pressure in the expansion chamber **6** the displacer **2** is decending (passing through the position 1 in FIG. 7). Thus gas is displaced from the expansion chamber **6** and passes through the port **5** the regenerator **34** and the passage **32**, around the recess **26** through the outlet apertures **22** in the cylinder wall, into the compartment **20** and vents through the port **24**.

During the descent of the displacer **2** the wall **28** of the recess **26** contacts the ring **36**. This position is shown in FIG. 1.

The displacer **2** continues to descend, displacing the ring **36** so that the exhaust apertures **22** are closed and simultaneously the inlet apertures **12** are opened (position 2 in FIG. 7), thereby allowing a gas at pressure of 100 psi (6.9×10^5 N m^{-2}) to enter the cylinder **4** through the inlet apertures **12**.

The gas passes around the recess **26** through the passage **32** and the regenerator **34** and then through the port **5** into the expansion chamber **6**. Unless the machine has just been started the gas is cooled in passing through the regenerator **34** which has been cooled by cold exhaust gas from the previous cycles. As the gas flows into the expansion chamber **6** the pressure therein is increased with the result that the differential pressure across the displacer falls and is reversed so that the displacer **2** is decelerated, halted, and returned without striking the end of the cylinder **4**. (Position 3 in FIG. 7).

It can be seen that the exact position of the displacer **2** at which the inlet apertures **12** are opened and the outlet apertures **22** are closed can be chosen by suitably positioning the apertures **12** and the apertures **22**.

The ring **36** is left in the position reached when the displacer **2** was halted and is not moved again on the upward stroke until it contacted by the wall **30** of the recess **26**. As the volume of the expansion chamber **6** is increased through the upward movement of the displacer **2** (which in its ascent passes through position 4 as shown in FIG. 7) more gas enters from the inlet apertures **12**, the passage **32** the regenerator **34** and the port **5** and thus the expansion chamber **6** is maintained at 100 psi (6.9×10^5 N m^{-2}).

After the ring **36** is contacted by the wall **30** of the recess **26**, the displacer **2** in its ascent pushes the ring **36** into a position where the inlet apertures **12** are closed, and the outlet apertures **22** open (Position 5 as shown in FIG. 7). Gas then exhausts from the expansion chamber and cools the regenerator **34** in its passage to the outlet orifice **22**. During the ascent of the displacer **2** the gas in the driving chamber **8** has been compressed to its maximum pressure of **60** psi and some gas has been exhausted through the relief valve **54**.

On opening of the outlet apertures **22** gas exhausted from the expansion chamber **6** and thus the pressure therein begins to fall with the result the displacer **2** is decelerated, halted (Position 6 as shown in FIG. 7) and returned downwards without striking the end of cylinder **4**.

The timing of the displacement of the ring **36** depends on the length of the path travelled by the displacer **2** from the beginning of the upward stroke to contacting the ring **36**. This length is equal to the difference between the depth of the ring **36** and the depth of the recess **26**.

Using this form of machine a surface may be cooled by heat exchange with the end surface **56** of the colder (expansion chamber) end of the cylinder **4**.

The construction of the machine shown in FIG. 12 is generally similar to that of the machine shown in FIG. 1 except for the driving chamber and the arrangements for maintaining the pressure therein. The form of driving chamber shown in FIG. 12 enables a varying differential pressure to be exerted across the ends of the displacer, whilst gas is supplied to the driving chamber at a far slower rate than is required for the form of driving chamber shown in FIG. 1.

In the form of machine shown in FIG. 12 the driving chamber 8 is divided by a plate 134 into two compartments, the lower indicated by the reference numeral 130 and the upper by the reference numeral 132.

Ports 42 and 44 ar located at the upper end of the cylinder 4 for the inlet and outlet respectively of gas from the driving chamber 8. A narrow constricted conduit 135 leads from the inlet port 14 of the expansion chamber 6 to the port 42. The conduit 135, in effect, provides a small bleed of gas to the compartment 132 of the driving chamber 8.

A one way valve 136 permits gas from the compartment 130 to the compartment 132 when the pressure in the compartment 130 exceeds that in the compartment 132. An orifice 138, shown schematically in FIG. 12, is provided to permit expansion of gas from the compartment 132 to the compartment 130 when the pressure in the compartment 132 exceeds that in the compartment 130. A conduit 52 leads from the port 44 to the outlet port 24 and has located therein a pressure relief valve 54.

The construction of the orifice 138 and the one-way valve 136 is shown in FIG. 10. A flexible diaphragm 140 is held against the plate 134 by a screw 146 leading through the center of the diaphragm 140 and the plate 134. The plate 134 has holes 142 and 144 formed through it and which cooperate with the diaphragm 140 to provide the one way valve shown in FIG. 12. When the pressure in the compartment 132 is greater than in the compartment 130 the diaphragm 140 is forced against the plate 134 to cover the holes 142 and 144. On the other hand when the pressure in the compartment 130 is greater than that in the compartment 132 the diaphragm 140 is lifted from the plate 140 with the result that gas flows substantially unrestricted from the compartment 132 into the compartment 130. The orifice 138 is in the form of a small hole through the plate 134.

The operation of the machine at its expansion chamber end is generally similar to that of FIG. 1. The cycle performed by the gas in the expansion chamber is shown in FIG. 11. In the driving chamber 8 gas is freely displaced from compartment 130 to compartment 132 so that the pressure opposing the ascent of the displacer is lessened. Thus a fast displacer ascent is facilitated. As the displacer 2 ascends so the volume of compartment 130 is reduced and the pressure therein increased. This increase in pressure is shown in FIG. 11 (see positions 3 to 6). The pressure in compartment 130 becomes sufficient to halt and reverse the displacer 2 before it strikes the end of the cylinder 4.

During the descent of the displacer 2 gas is bled from compartment 132 to compartment 130 via the orifice 138 at a slow rate in comparison with the rate of passage in the opposite direction when the displacer 2 is ascending. This enables a slower descent than ascent, and hence tends to minimize compression of the gas in the expansion chamber 6. A slow descent of the displacer 2 is also facilitated by setting the pressure-relief valve 54 to open if the pressure in the compartment 132 becomes excessive in comparison to that in compartment 130. If desired, the speed of the displacer ascent and descent may be controlled by adjusting the setting of the pressure-relief valve 54.

The form of machine shown in FIG. 9 is identical to that shown in FIG. 12 except that the one-way valve 136 leads from the compartment 132 to the compartment 130. This form of machine enables a faster descent of the displacer than that shown in FIG. 12.

In the form of machine shown accomodates FIG. 13, the cylinder 4 is stepped and has an upper portion of narrower cross-section than the lower. Furthermore the partition 134 is provided by the upper end of the cylinder 4, and the upper compartment 132 is a chamber having a diameter greater than the cylinder 4. The displacer 2 above its regenerator 34 is formed with a step to be of a shape complementary to that of the cylinder 4. The narrower portion of the cylinder 4 accommodates the inlet and outlet to the expansion chamber 6. The arrangement whereby the region of the cylinder 4 wherein the inlet and outlet of the expansion chamber are located is of smaller cross-sectional area than the region of the cylinder in which the expansion chamber is located, is advantageous since the space between the seals 38 and 40 in which gas is not usefully employed is reduced in comparison to the forms of machine shown in FIGS. 1, 9 and 12.

In the form of machines shown in FIGS. 2 and 3, two recesses 60 and 66 are formed in the displacer 2, the recess 60 having mutually facing walls 62 and 64, and the recess 66 having mutually facing walls 68 and 70. Rings 72 and 74 are located in the recesses 60 and 66 respectively, each ring being in frictional engagement with the inside wall of the cylinder 4. The ring 72 acts as the valve member for the outlet apertures 22 and the ring 74 acts as a valve member for the inlet apertures 12. The machine is designed such that the difference between the depth of the ring 72 and its recess 60 is greater than the difference between the depth of ring 74 and its recess 66.

In FIG. 2 the ring 72 is shown in such a position that the outlet apertures 22 are open and the ring 74 in such a position that the inlet apertures 12 are closed.

Consequently the gas in the expansion chamber 6 is at low pressure and there is a downward force on the displacer 2 exerted by the pressure difference between the driving chamber 8 and the expansion chamber 6, which force causes the displacer 2 to descend (and pass through the position 1 shown in FIG. 7). In descending the displacer 2 displaces gas from the expansion chamber 6 which gas flows through the regenerator 34 to exhaust through the outlet apertures 22. With the displacer 2 descending, the wall 68 of the recess 66 abuts the ring 74 with the result that the ring 74 is pushed downwards. As the displacer 2 continues to descend the wall 62 of the recess 60 abuts the ring 72 and pushes it downwards. The abutment of the wall 62 of the recess 60 and the ring 72 occurs before the ring 74 is displaced sufficiently to close the outlet apertures 22. Indeed the ring 72 covers the outlet apertures 22 simultaneously with the ring 74 uncovering the inlet apertures 12. (This is position 2 as shown in FIG. 7). With the inlet apertures 12 now open gas at a higher pressure flows into the expansion chamber 6 being precooled in passing through the regenerator 34 (except in the first cycle). Consequently the pressure in the expansion chamber 6 increases and thus the differential pressure between the driving chamber 8 and the expansion chamber 6 decreases and reverses thereby opposing the movement of the displacer **2** and becomes sufficient to halt (position **3** as shown In FIG. **8**) and return the displacer **2** upwardly without it striking the end of the cylinder **4**.

On the upward stroke (the displacer **2** passing through position **4** as shown in FIG. **7**) owing to the difference in depth between each ring and the recess in which it is located, the wall **70** of the recess **66** contacts and displaces the ring **74** before the wall **64** of the recess **60** contacts and displaces the ring **72**. Consequently the inlet apertures **12** are closed (position **5** as shown in FIG. **7**) before the outlet apertures **22** are opened (position **6** as shown in FIG. **8**) and there is a period during the upward stroke of the displacer **2** when no gas enters or exhausts from the expansion chamber **6** (i.e. the period taken for the displacer **2** to travel from position **5** to position **6** as shown in FIG. **7**). The gas in the expansion chamber is expanded during the upward stroke to provide particularly efficient cooling. The feature of the design of the machine which enables both the inlet apertures **12** and the outlet apertures **22** to be closed simultaneously during the upward stroke of the displacer **2** is that the difference between the depths of the ring **72** and the recess **60** is much greater than the difference between the depth of the ring **74** and the recess **66**. Further, in order to enable in the inlet apertures **12** to be closed by the displacement of the ring **74** relatively early in the stroke of the displacer **2** the difference in depth between the recess **66** and the ring **74** is small. It is also desirable to make the ring **74** of sufficient depth that the inlet apertures **12** are not reopened during the ascent of the ring **74** on the upward stroke of the displacer **2**.

As the inlet apertures **12** are closed relatively early during the upward stroke in comparison with the machine shown in FIG. **1**, the pressure-relief valve **54** is set to open at a lower pressure than in the machine shown in FIG. **1** to ensure that the movement of the displacer **2** is not prematurely arrested by the decaying differential pressure across the displacer **2** which is caused by the expansion of gas in the expansion chamber **6**.

When the exhaust apertures **22** are opened by the displacement of the ring **74**, the exhaust of the gas from the expansion chamber **6** reduces and then reverses the differential pressure across the displacer **2** and the resultant downward force halts (Position **7***a* as shown in FIG. **8**) and returns the displacer **2** to the position shown in FIG. **2**.

In the form of machine shown in FIG. **4** a single recess **80** having mutually facing walls **82** and **84** is formed in the displacer **2** and a ring **86** is in frictional engagement with the inside wall of the cylinder **4** which ring is capable of sealing the apertures **12** and **22** from the recess **80**. A sealing ring **88** is accomodated in the lower wall **84** of the recess **80** and is co-operable with the ring **86** to seal the outlet orifices **22** from the recess **80**. The ring **86** has a depth just sufficient for it to be able to close both the inlet and the outlet orifices **12** and **22** simultaneously.

In FIG. **4** the ring is shown in such a position that the outlet apertures **22** are open and the inlet apertures **12** are closed. With the displacer **2** descending (and passing through position **1** as shown in FIG. **8**) gas is being exhausted from the expansion chamber **6** and the ring **86** in contact with the wall **82** of the recess **80** and is being pushed in the direction of the motion of displacer **2**.

After having been displaced by the appropriate distance the ring **86** uncovers the inlet apertures **12** of the expansion chamber **6** and covers the outlet apertures **22** (Position **2** as shown in FIG. **8**). Now with the inlet apertures **12** open the gas flows into the expansion chamber **6**, being cooled in passing through the regenerator **34** (except on the first cycle). Consequently the pressure in the expansion chamber **6** increases and becomes sufficient to decelerate, halt (position **3** as shown in FIG. **8**) and reverse the displacer **2** without it contacting the end of the cylinder **4**.

During the upward stroke of the displacer **2** (during which the displacer **2** passes through position **4** as shown in FIG. **8**) the seal **88** completes a seal with the ring **86** to prevent gas leaving cylinder **4** through the orifices **22** when they become uncovered by the ring **86**. As the displacer **2** continues ascending the ring **86** is driven upwards and covers the inlet apertures **12** with the result that the flow of gas into and out of the expansion chamber **6** is prevented (position **5** as shown in FIG. **8**). The inlet apertures **12** remain closed and the seal is maintained between the ring **86** and the seal **88** during the remaining part of the stroke. It is advantageous to ensure that the apertures **12** are closed relatively early in the stroke as the most efficient cooling of the gas is provided when both the apertures **12** and the apertures **22** are closed, and the gas at an initially high pressure in the expansion volume **6** is allowed to expand to a low pressure. The relatively early closing of the apertures **12** and **22** is achieved by making the difference in depth between the ring **86** and the recess **80** small.

If the apertures **12** and **22** are closed for the greater part of the upward stroke the pressure relief valve **54** is set to open at a relatively low pressure to ensure that the movement of the displacer is not prematurely arrested owing to the decaying differential pressure across the displacer **2** caused by the expansion of gas in the expansion chamber **6**.

The momentum of the displacer **2** during its upward stroke ensures that the pressure in the driving chamber **8** exceeds the pressure in the expansion chamber **6** after both the inlet and the outlet apertures **12** and **22** have been closed. Thus the pressure difference across the displacer **2** decreases and is reversed so that the displacer **2** is decelerated, (passing through position **6** as shown in FIG. **8**), halted, (position **7***b* as shown in FIG. **8**), thereby breaking the seal formed between the ring **8** and the seal **88** (position **8***b* as shown in FIG. **8**). The displacer then continues its descent to the position shown in FIG. **4**.

It is preferable that the distance between the inlet apertures **12** and the outlet apertures **22** is such that the inlet apertures **12** are not reopened during the upward movement of the displacer **2**.

In the form of machine shown in FIG. **5** the regenerator **34** is located externally from the displacer **2**. It communicates with the recess **26** and the space defined between the seals **38** and **40** by means of a conduit **90** and with the expansion chamber **6** by means of a conduit **92**. The operation of the machine is similar to that shown in FIG. **1**.

FIG. **6** illustrates a machine with the form of valve for the inlet and outlet of the expansion chamber shown in FIG. **1**, but having two regenerative stages. Similarly an additional regenerative stage may be added to the embodiments described with respect to the other Figures.

Multi-stage versions operate in a similar manner to their respective single stage counterparts previously described.

In FIG. 6, the cylinder **4** comprises stepped wider and narrower cylindrical portions **100** and **102**, and the displacer **2** is formed in similar shape having stepped portions **104** and **106**. An upper regenerator **108** is located in the portion **105** of the displacer **2** and a lower regenerator **110** is located in he portion **106** of the displacer **2**. The regenerators **108** and **110** are connected by a conduit **112** formed in the displacer **2**. An upper expansion chamber **122** defined by the cylinder **4**, a step **120** formed in the cylinder **4** and the displacer **2**, communicates with the upper regenerator **108** through passages **114** and **116**. A sealing ring **124** is located between the portion **106** of the displacer **2** and the portion **102** of the cylinder **4**. The ring **124** prevents flow of gas bypassing the lower regenerator **110** through the annular passage **118** formed between the portion **102** of the cylinder **4** and the portion **106** of the displacer **2**. In the operation of the machine shown in FIG. **6** gas entering the lower regenerator **110** is precooled in the upper regenerator **108** so that the temperature in the lower expansion chamber **6** is considerably lower than in the expansion chamber **122**.

In the forms of machine shown in FIG. **2, 4, 5** and **6** the form of driving chamber shown in FIGS. **9, 12** or **13** may be employed instead of the form of driving chamber shown in FIG. **1**.

I claim:

1. A thermodynamic reciprocating machine including a cylinder, a reciprocable displacer located in the cylinder, a gas inlet through the cylinder wall, a gas outlet through the cylinder wall, valve means located between the cylinder wall and the displacer and operated by the displacer to open and to close the inlet and the outlet, an expansion chamber which includes the space defined by one end of the displacer and the cylinder, and which is able to receive gas entering the inlet and to expel gas through the outlet, and a regenerator for exchanging heat between gas entering and leaving the expansion chamber, in which machine the displacer is reciprocated by a varying differential pressure between the gas in the expansion chamber and a restoring pressure.

2. A thermodynamic reciprocating machine according to claim **1**, in which the restoring pressure is exerted by a gas in a driving chamber which includes the space defined by the ends of the displacer and the cylinder opposite to the ends thereof defining the expansion chamber, in which the driving chamber has a pressure-relief device set to exhaust gas at a pressure between the maximum and minimum pressures that are created in the expansion chamber by the reciprocating displacer, in which the driving chamber is divided into first and second compartments, the first compartment being in part bounded by the end of the displacer, in which passage of gas from one compartment to the other is permitted by a one-way valve when the pressure in said one compartment is greater than in said other compartment, and in which passage of gas from said other compartment to said one compartment is through a constriction between the compartments when the pressure in said other compartment is greater than in said one compartment.

3. A thermodynamic reciprocating machine according to claim **2**, in which the one-way valve permits gas flow only from the first compartment to the second compartment.

4. A thermodynamic reciprocating machine according to claim **1**, in which a restricted passage leads to the driving chamber from a passage leading to the inlet of the expansion chamber.

5. A thermodynamic reciprocating machine according to claim **1**, in which two sealing rings are located between the displacer and the inner surface of the cylinder wall, one sealing ring being located on one side of the inlet and outlet of the expansion chamber, the other sealing ring being located on the other side of the inlet and the outlet.

6. A thermodynamic reciprocating machine, according to claim **1**, in which the valve member includes at least one ring in frictional engagement with the inner surface of the cylinder wall, in which the ring is located between the end walls of a recess formed in the displacer.

7. A thermodynamic reciprocating machine, according to claim **6**, in which the end face of the ring nearer to the expansion chamber is able to make a seal with the end wall of the recess facing said end face, whereby for the greater part of the period when the displacer is moving to increase the volume of the expansion chamber, the valve ring directly closes the inlet to the expansion chamber and makes the said seal to close the outlet to the expansion chamber.

8. A thermodynamic reciprocating machine according to claim **6**, in which there is a valve member for the inlet provided by a ring in frictional engagement with the inner surface of the cylinder wall and located between the walls of a first recess in the displacer, in which there is a valve member for the outlet provided by a ring in frictional engagement with the inner surface of the cylinder wall and located between the walls of a second recess in the displacer wall, in which both rings are operated by being contacted and displaced by the end walls of the recesses in which they are located, and in which the difference in length between the outlet ring and the recess in which it is located is greater than the difference in length between the inlet ring and the recess in which it is located, whereby both the inlet and the outlet are able to be closed for the greater part of the period during which the displacer is moving to increase the volume of the expansion chamber.

9. A thermodynamic reciprocating machine according to claim **1**, in which the region of the cylinder wherein the inlet and outlet of the expansion chamber are located is of smaller cross-sectional area than the region of the cylinder that bounds the driving chamber.

10. A thermodynamic reciprocating machine according to claim **1**, and further including more than one regenerative stage.

11. A thermodynamic reciprocating machine according to claim **1**, in which at least part of the region of the cylinder that, in part, bounds the expansion chamber is made of a heat-conductive material to facilitate heat transfer between a load being cooled and the gas in the expansion chamber.

12. A thermodynamic reciprocating machine including a cylinder, a reciprocable displacer located within the cylinder, an expansion chamber which includes the space defined by one end of the displacer and the cylinder, a driving chamber which includes the space defined by the other end of the displacer and the cylinder, an inlet through the cylinder wall leading from the expansion chamber, an outlet through the cylinder wall leading from the expansion chamber, a regenerator located between the inlet and outlet and the expansion chamber for exchanging heat between gas entering and leaving the expansion chamber, and at least one valve member which is in frictional engagement with the inner wall of the cylinder, and which is located between the walls of a recess in the displacer, said at least one valve member being operated by the displacer to open and to close the inlet and the outlet, in which machine the displacer is caused to reciprocate by a varying differential pressure exerted against the displacer by the gas in the expansion chamber and the gas in the driving chamber.

13. The thermodynamic machine defined by claim **6** in which a single ring is employed and the length of said ring measured along the axis of the cylinder is greater than the distance between the inlet and outlet measured along the same axis.

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