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(54) **CENTERING SYSTEM FOR FREE PISTON MACHINE**

(75) Inventor: **William T. Beale**, Athens, OH (US)

(73) Assignee: **Sunpower, Inc.**, Athens, OH (US)

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Related U.S. Patent Documents

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Filed: **Dec. 4, 1996**

(51) **Int. Cl.**[7] **F01B 29/10**
(52) **U.S. Cl.** **60/520**
(58) **Field of Search** 60/517, 520

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,404,802 A * 9/1983 Beale 60/520
4,583,364 A * 4/1986 Wood 60/520

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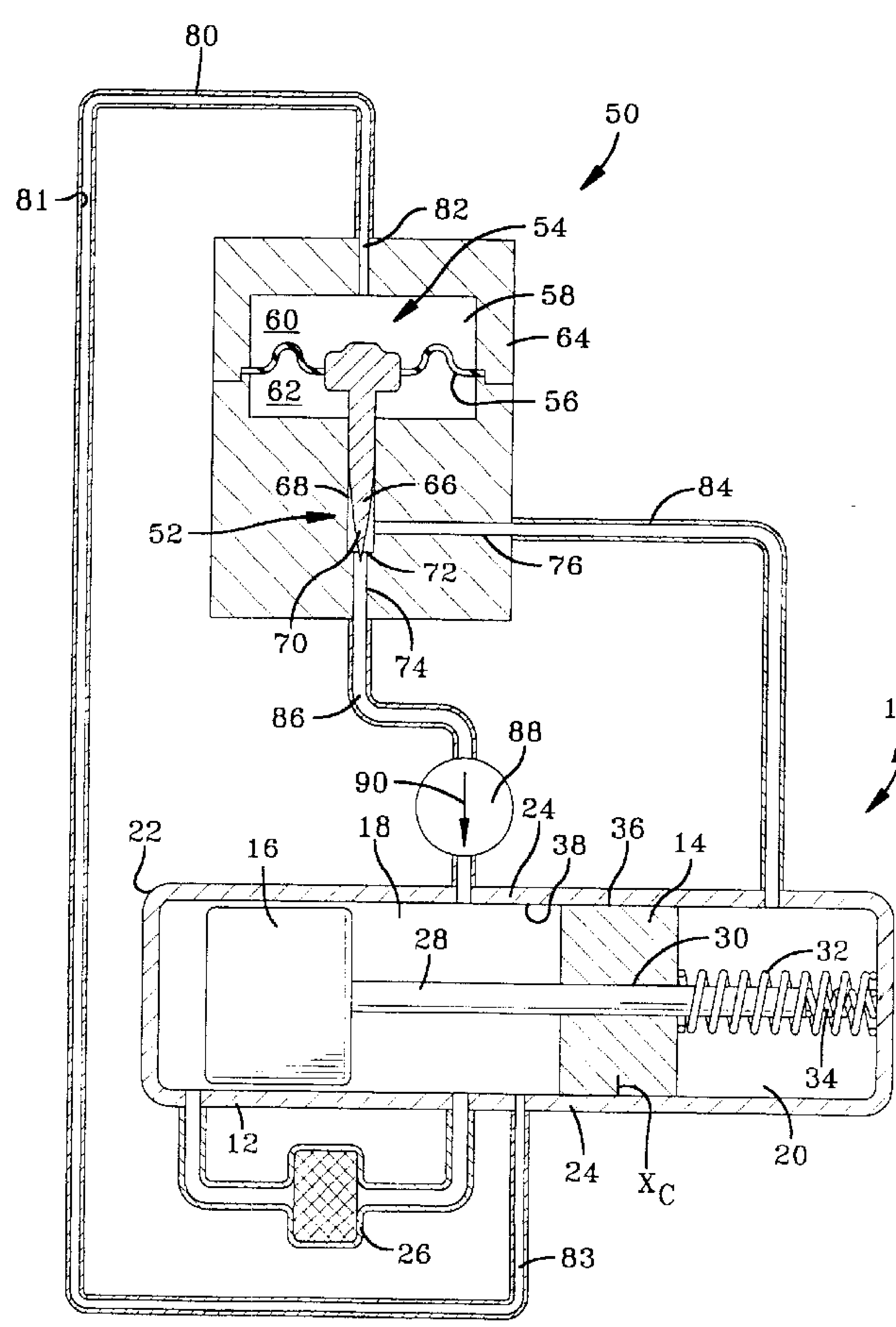
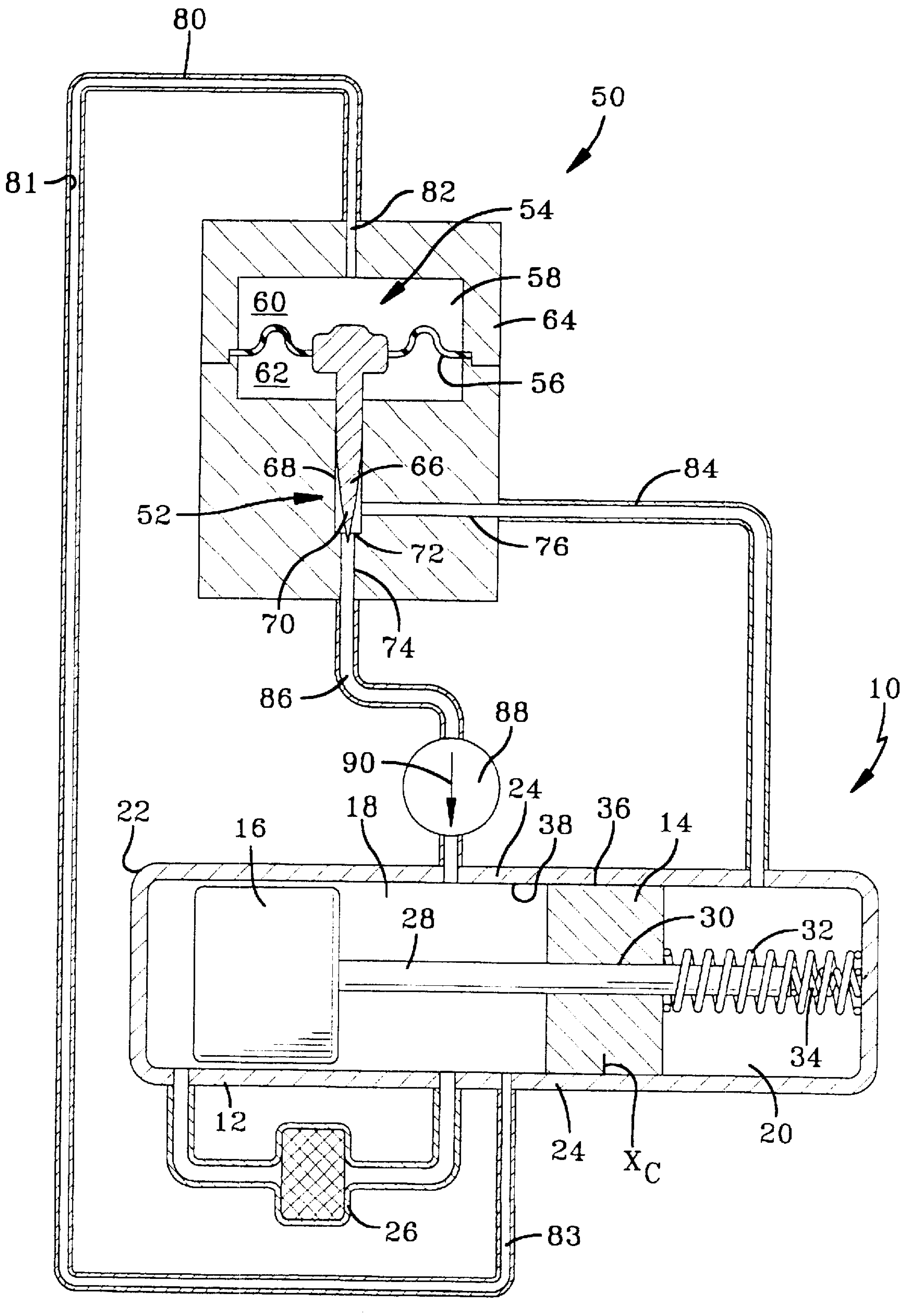
Primary Examiner—Noah P. Kamen
(74) *Attorney, Agent, or Firm*—Jason J. Foster; Kremblas, Foster, Phillips & Pollick

(57) **ABSTRACT**

A centering apparatus for a free piston Stirling engine including a pressure regulator valve which connects a passageway between the work space and the back space when both (a) the average pressure in the back space exceeds the average pressure in the work space as a result of the piston deflecting a spring, and simultaneously (b) the instantaneous pressure in the back space exceeds the instantaneous pressure in the work space. A diaphragm spans across an actuator housing cavity, dividing the cavity into an upper chamber and a lower chamber. A connector valve is linked to the diaphragm for opening and closing the valve upon displacement of the diaphragm. When the average back space pressure exceeds the average work space pressure, the diaphragm is displaced to open the valve, connecting the work space and the back space in fluid communication. A check valve permits the flow of gas in only one direction: from the back space to the work space. A similar arrangement can be included to also cause flow from the work space to the back space when the average work space pressure exceeds the average back space pressure, so as to center the piston against leaks in either direction.

9 Claims, 5 Drawing Sheets




80
50
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62
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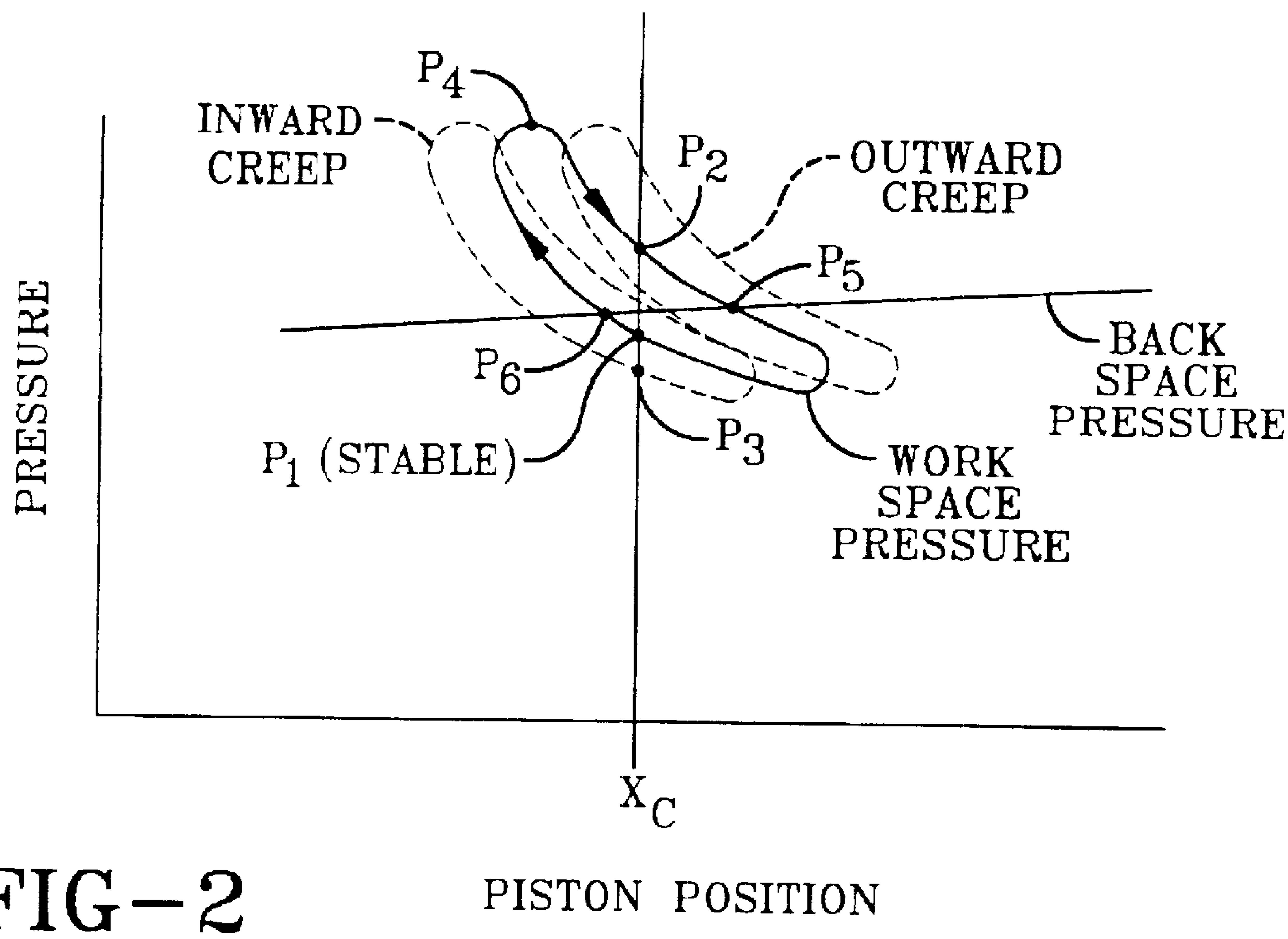
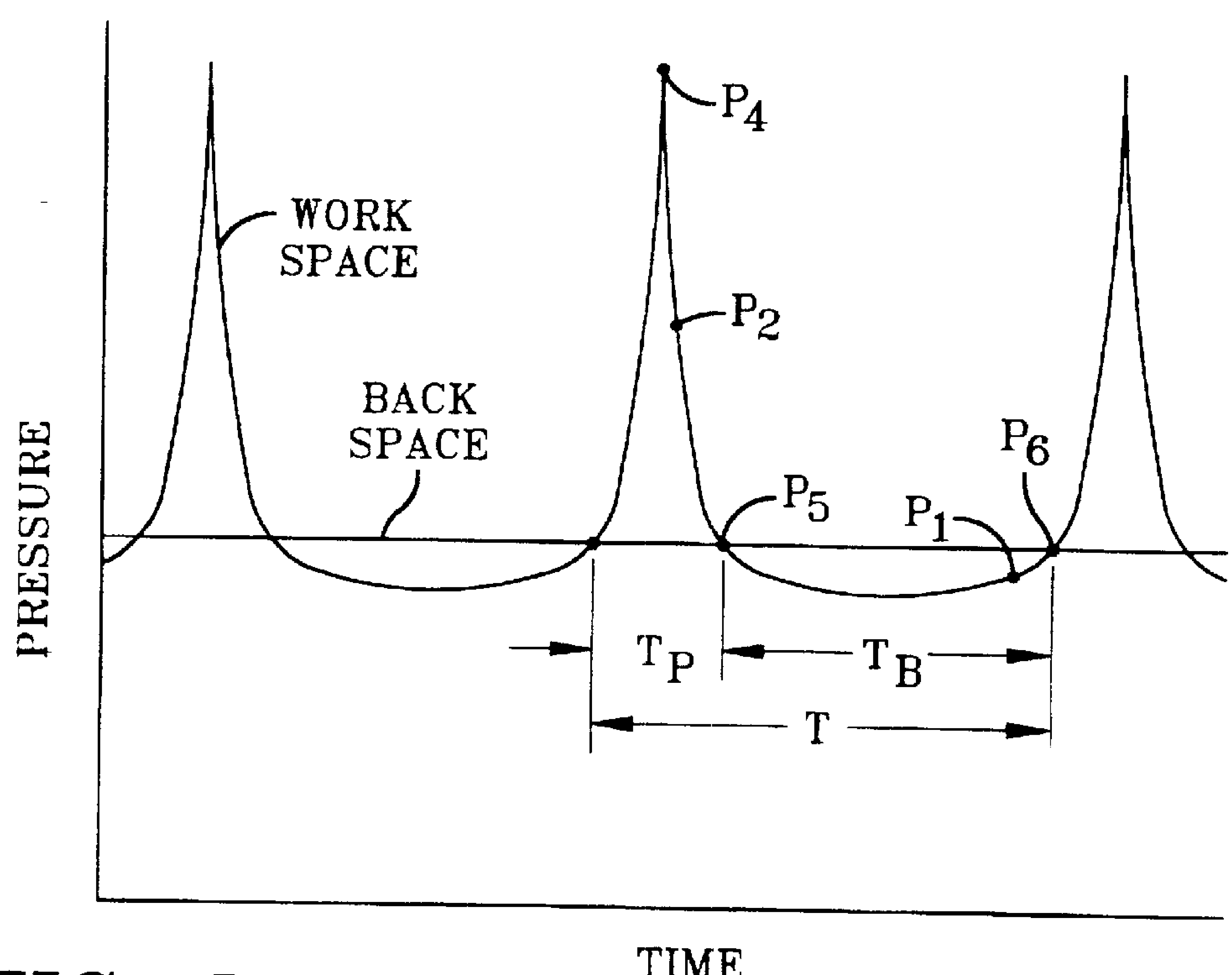
76
72
70
74
86
10
88
90
24
22
18
36
16
38
14
28
30
32
34
12
24
X_C
20
26
83

FIG-1


P4
INWARD CREEP
P2
OUTWARD CREEP
P5
BACK SPACE PRESSURE
P6
P1 (STABLE)
P3
WORK SPACE PRESSURE
PRESSURE
XC
PISTON POSITION

FIG–2


P4
WORK SPACE
P2
BACK SPACE
P6
P5
P1
PRESSURE
TP
TB
T
TIME

FIG–3

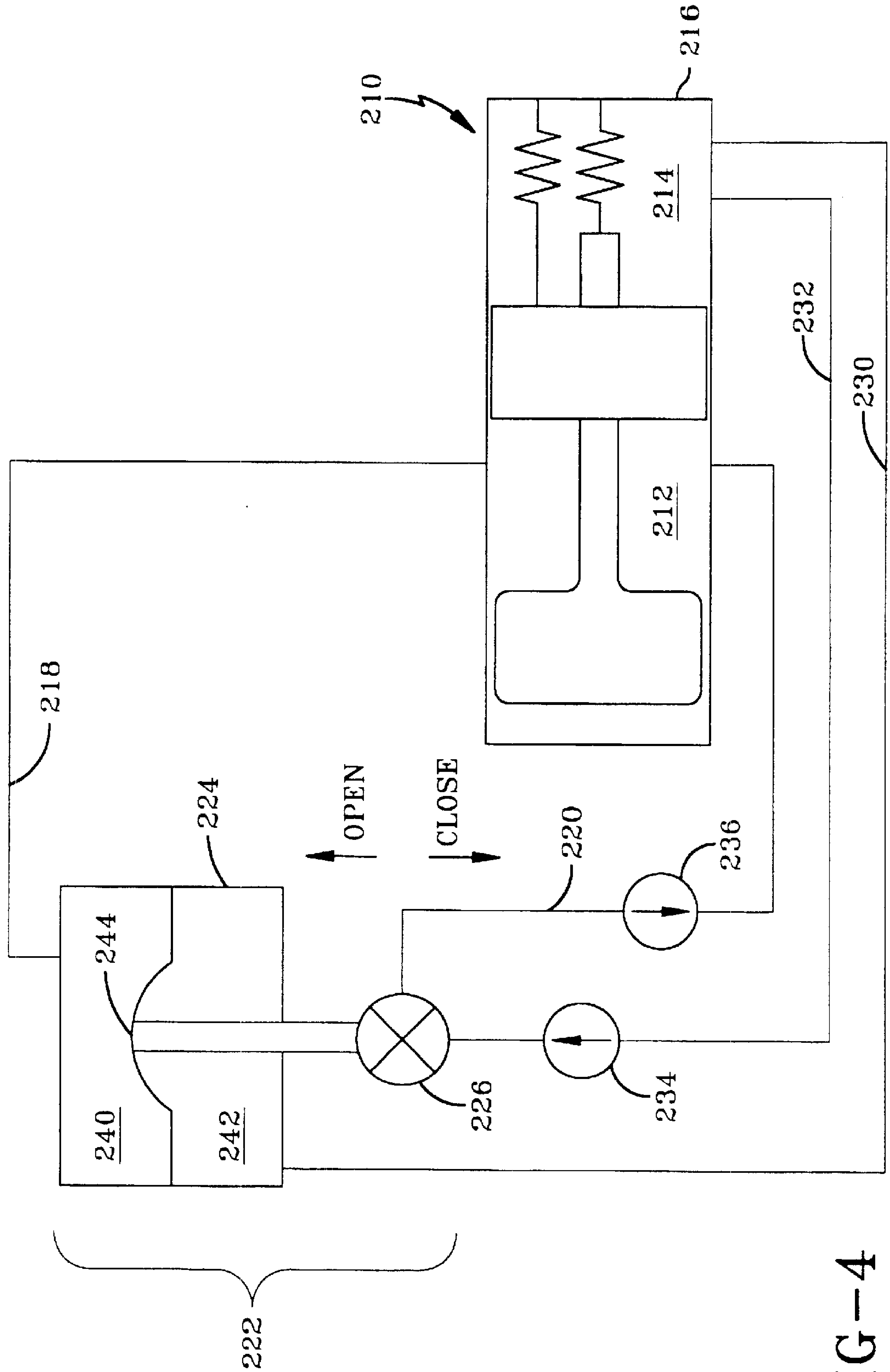
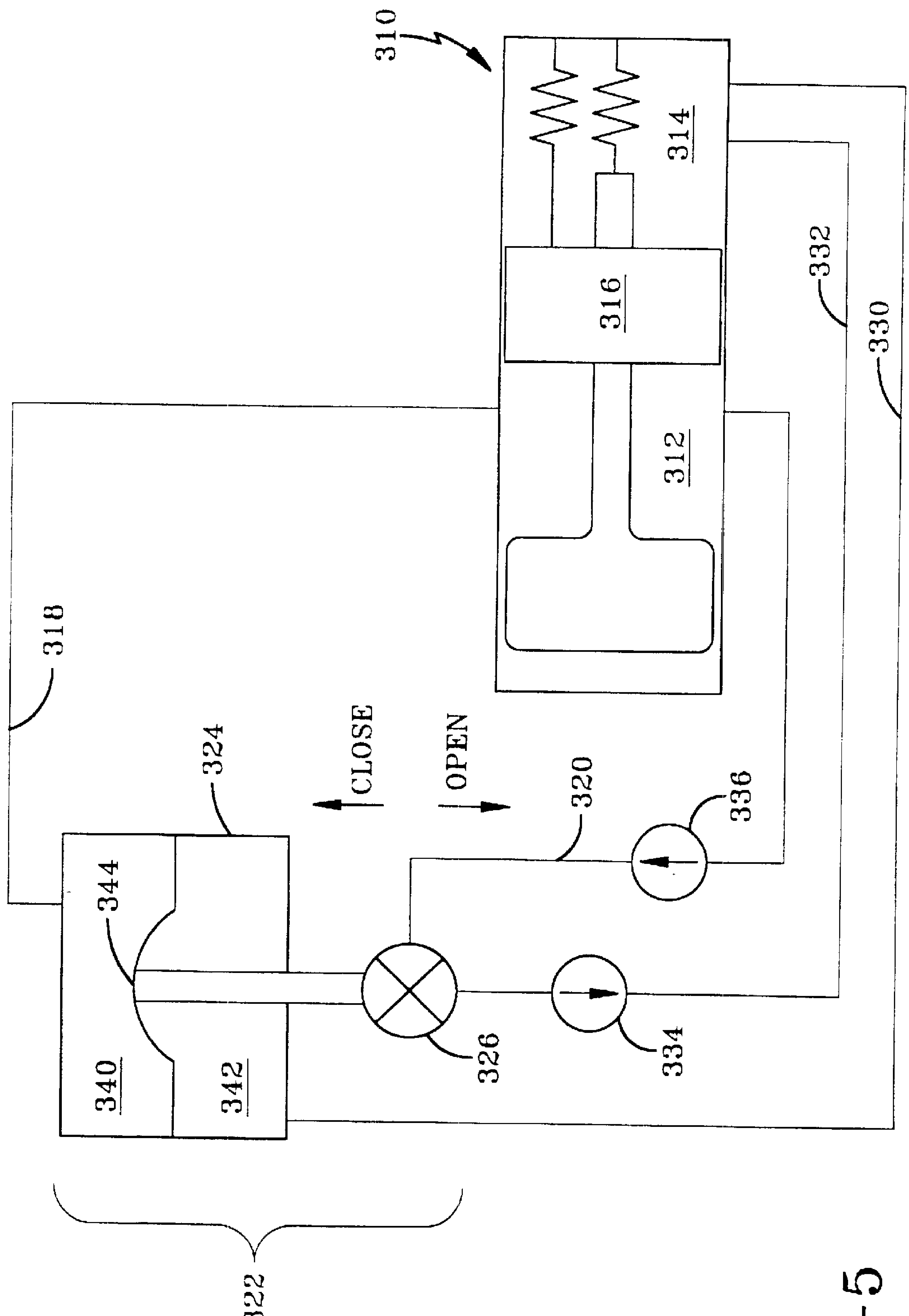

210
216
214
212
232
230
218
224
OPEN
CLOSE
220
236
244
226
234
240
242
222

FIG-4


310
314
316
312
332
330
318
324
CLOSE
OPEN
320
336
344
326
334
340
342
322

FIG—5

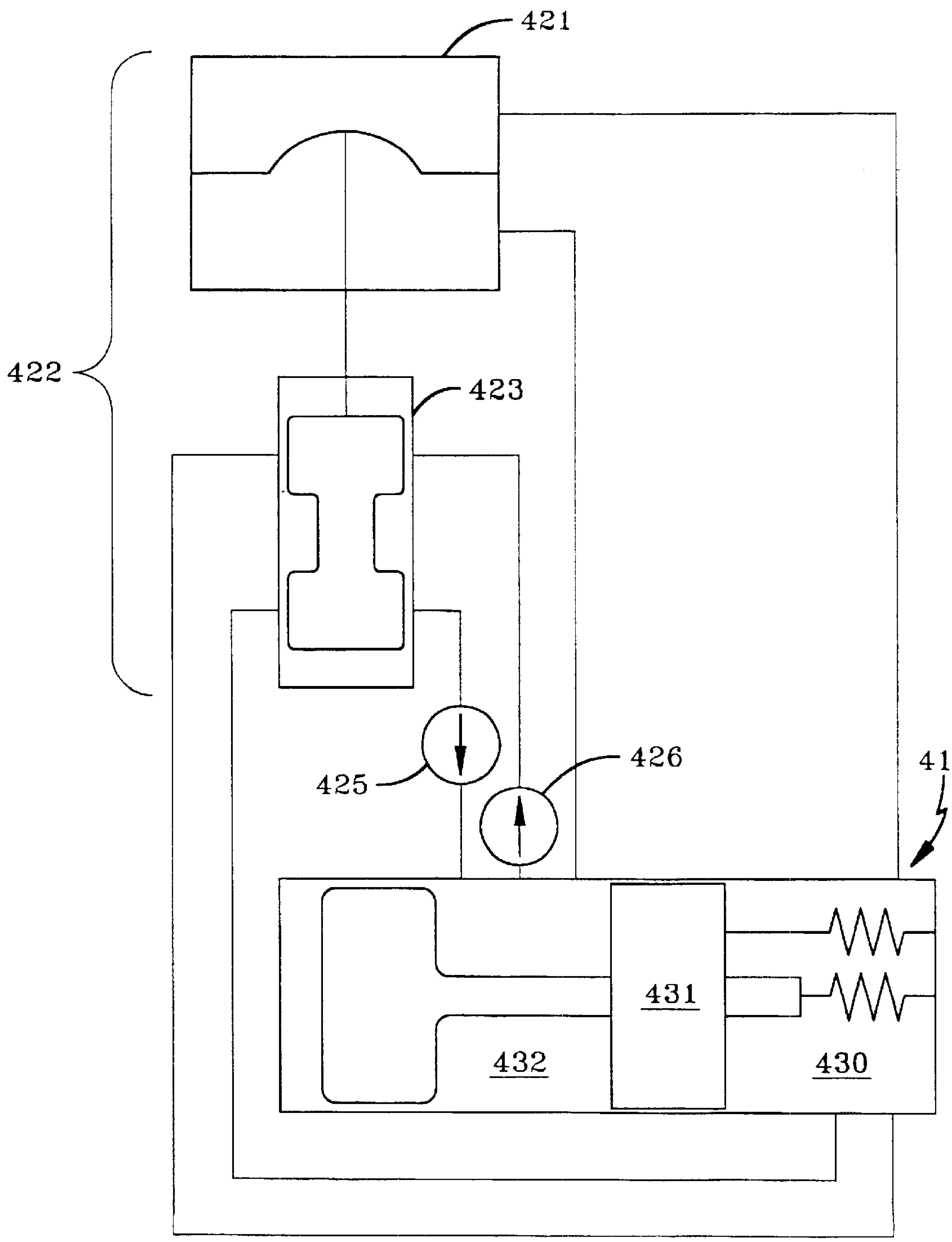


FIG-6

CENTERING SYSTEM FOR FREE PISTON MACHINE

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

TECHNICAL FIELD

The present invention relates to an apparatus for centering the piston of a free piston machine, such as a Stirling cycle engine or heat pump, at a desired mean operating position. It relates specifically to a centering system which vents gas from the space at a first end of the piston to the space at the second end of the piston when the average piston position creeps away from its design center position toward the second end.

BACKGROUND ART

A free piston Stirling machine typically comprises a housing having a cylinder containing a linearly reciprocating power piston and a linearly reciprocating displacer. The piston divides the interior of the housing into two gas spaces. One space is a work space bounded by the piston on the displacer side of the piston, and the other is a back space or bounce space bounded by the other side of the piston. Heat is supplied to the gas in the work space and together with the piston and displacer cooperates to cyclically compress and expand the gas to convert a portion of the supplied heat into mechanical work. The piston and displacer reciprocate in periodic, although out of phase, relation. Heat is removed from the gas in the work space in an amount equal to the difference in the heat supplied and the work produced as required by the first and second laws of thermodynamics. A regenerator device is employed for regenerating some of the heat supplied from one cycle to the next. The working gas in the engine may be air, hydrogen, helium, other gases, vapors or liquids, or the like.

While reference is made to a Stirling engine, the invention is applicable to other free piston machines such as heat pumps and refrigerators and to other free piston machines such as a free piston compressor. In such heat pumping Stirling applications, the direction of the heat and work energy interactions are reversed. The term Stirling machine is intended to refer to Stirling cycle engines, heat pumps, and refrigerators.

Sealing means are provided between the power piston and the inner wall of the housing for substantially sealing the work space from the back space. The sealing means may be in the form of rings or simply a precision fit. In either case, since the piston must be free to reciprocate in the housing, taking into account effects such as thermal expansion, a small annular gap unavoidably exists between the piston and the housing. The working gas may flow between the work and back spaces through the interposed annular gap with the direction of flow being from high to low pressure. The working gas, therefore, will leak from the work space to the back space when the work space pressure is higher than the back space pressure and in the reverse direction when the pressure difference is reversed.

The back space in Stirling machines is generally designed to have a relatively large volume and, consequently, the pressure of the gas in the back space remains approximately constant during operation. The pressure in the work space, however, undergoes large amplitude changes over the cycle. The work space pressure, when viewed as a function of time, appears as a pressure wave having a series of peaks which rise rapidly above the back space pressure. The peaks are followed by a longer interval of time wherein the work space pressure is slightly below the back space pressure until the next peak occurs. The pressure wave increases and decreases in asymmetric relation to the back space pressure. Although the peaks in the pressure wave last for only a short period of time in relation to the overall period of the cycle, there is a strong tendency for net gas leakage from the work space to the back space (outward) due to the nonlinearity of the pressure and flow rate relationship. For the interval of time following the peak where the back space pressure is higher than the work space, the flow will be in the opposite direction (inward). However, due to the nonlinear flow, the gas flow during this interval will be substantially less than during the peak. Over the period of the cycle some of the flow is inward and some of the flow is outward. However, the usual effect of the nonlinearity of the flow is a net transfer of gas from the work space to the back space. This or any other cause of asymmetric leak increases the volume of gas in the back space and decreases the volume of gas in the work space which causes the piston to creep inward from its design mean position.

Imperfections in the piston and housing fit may cause the piston to creep outwardly. However, in a precisely formed engine the nonlinear relation between pressure and flow generally gives rise to an inward creep. Creep in either direction makes it difficult to control the piston position and may degrade engine performance. In other free piston machines a different asymmetrical pressure wave in the work space can also cause inward or outward creep.

Most approaches for automatically centering the piston of a free piston Stirling machine have involved a gas porting system for periodically returning the asymmetrically leaked gas from the back space to the work space. For example, U.S. Pat. No. 4,583,364 teaches a method and apparatus comprising a center port and a passageway which is periodically opened by the power piston, thereby permitting a corrective inward flow of gas to balance the outward asymmetric leak. That patent further teaches the use of a displacer having a sealing surface which periodically registers with a port along the passageway to block the outward flow of gas on the piston return (outward) stroke. Prohibiting the flow of gas during the outward stroke improves power output since there will be no gas transfer from the work space to the back space as would otherwise occur.

U.S. Pat. No. 4,404,802 teaches the use of a centering port system which is opened and closed by the ports of a spool valve coming into registry. The work space and back space are brought into fluid communication during both the inward and outward strokes of the piston so that there is gas flow through the centering port system in both directions. In this mode, both inward and outward creep are balanced. That patent does not contemplate a one way centering port. Centering port systems of the type described are generally formed in a portion of the cylinder part of housing and may also include passageways and ports in the piston. They also include a valve linked to the piston which opens at or near the design mean piston operating position. Typically, the valve is formed to interrupt flow in the centering passageway and is a spool valve arrangement in which the piston functions as the spool which covers and uncovers one or more ports in the cylinder or central post to connect the work space and the second space in communication when the piston is near its center position.

Therefore, in summary, in a free piston Stirling cycle machine, an asymmetric pressure wave in the work space causes a problem of keeping the piston centered as a result of a preferential leak from the work space to the back space behind the piston. This results in a creep of the average piston position away from its desired center position as a result of a migration of some fluid mass from one space to the other. A conventional method to prevent this inward creep is to allow a communication between work and back spaces through ports in the equivalent of a spool valve mounted on or connected to the piston which come into coincidence at the center of the stroke, so that a flow of fluid can result between the two spaces and allow the average mass in the two spaces to remain fixed and thus the piston to remain centered. This is the accepted way to keep the piston centered, however a power loss penalty accrues from the fact that gas flows both in and out at each passage of the piston both on its in and out passage by the center port.

BRIEF DISCLOSURE OF INVENTION

The invention is an improved piston centering apparatus for a free piston machine having a housing. The housing includes a cylinder, and a piston is sealingly reciprocatable in the cylinder. The free piston machine includes a spring connected between the piston and the housing, said spring being relaxed and exerting substantially no force on the piston when the piston is in a centered position. The housing encloses a first machine space bounded by a first end of the piston, and encloses a second machine space bounded by the opposite, second end of the piston. The second machine space has a working fluid with an average fluid pressure, and the first machine space has a working fluid with a fluid pressure varying periodically in opposite directions from said average pressure. The pressure variation causes a net leakage flow of working fluid from the first machine space to the second machine space. The improvement comprises a connector valve through which the first and second machine spaces are connected. A valve actuator is linked to the connector valve and the actuator has a first actuator chamber and a second actuator chamber for opening the connector valve in response to the pressure of the second actuator chamber exceeding the pressure of the first actuator chamber. The first actuator chamber is connected in communication with the first machine space, through a restriction for maintaining a pressure in the first actuator chamber equal to the average pressure in the first machine space. The second actuator chamber is connected in communication with the second machine space. A check valve is directed to permit a flow of working fluid from the first machine space to the second machine space when the connector valve is open.

The invention preferably contemplates that the free piston machine is a free piston Stirling cycle machine, the first machine space is the work space of the Stirling cycle machine, and the second machine space is the back space of the Stirling cycle machine.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a side view in section illustrating a free piston Stirling cycle engine with the preferred centering system attached thereto.

FIG. **2** is a graphical illustration of the variation of the work space and back space pressure as a function of piston position.

FIG. **3** is a graphical illustration of the work space and back space pressures as a function of time.

FIG. **4** is a schematic view in section illustrating an embodiment of the present invention.

FIG. **5** is a schematic view in section illustrating an alternative embodiment of the present invention.

FIG. **6** is a schematic view illustrating an alternative embodiment of the present invention.

In describing the preferred embodiment of the invention which is illustrated in the drawings, specific terminology will be resorted to for the sake of clarity. However, it is not intended that the invention be limited to the specific terms so selected and it is to be understood that each specific term includes all technical equivalents which operate in a similar manner to accomplish a similar purpose. For example, the word connected or terms similar thereto are often used. They are not limited to direct connection but include connection through other elements where such connection is recognized as being equivalent by those skilled in the art.

DETAILED DESCRIPTION

Referring to FIG. **1**, a free piston Stirling engine **10** comprises a housing **12**, a reciprocating power piston **14**, and a reciprocating displacer **16**. The piston **14** bounds and, in combination with the interior of the housing **12**, defines a work space **18** on the displacer side of the piston **14**. The opposite end of the piston **14** similarly bounds the back space **20**. The work space **18** and back space **20** contain the same working gas.

For driving the engine, heat is supplied to the hot end **22** of the work space **18** and removed from the cool end **24**. The flow of heat combined with the reciprocation of the displacer **16** induces the gas in the work space **18** to cyclically expand and contract. The piston **14** and the displacer **16** are thereby driven to reciprocate in the housing **12** for producing mechanical work according to well known thermodynamic principles of the prior art.

As is also well known in the art, the engine **10** is provided with a regenerator **26** which acts to regenerate heat in the engine **10** from one cycle to the next. The motion of the power piston **14** towards the work space **18** is referred to as inward motion, while piston motion toward the back space **20** is referred to as outward motion. In one possible mode, the piston **14** is mechanically coupled to a magnet (not shown) which is reciprocated in an electrical alternator apparatus for converting the mechanical work produced by the piston **14** into electrical energy.

A displacer rod **28** passes slidingly through the piston **14** through a central hole **30** in the piston **14**. The piston **14** and displacer **16** are provided with mechanical springs **32** and **34**, respectively, for resonating the piston **14** at the desired frequency of reciprocation. Other equivalent devices, such as gas or magnetic springs, could substitute for the springs **32** and **34**. As is well known to those familiar with free piston Stirling machines there are a variety of different structural alternative morphologies for arranging the basic components of a Stirling machine to which the present invention is applicable. The designed mean position of the piston **14** is labeled X_C.

An exterior wall **36** of the reciprocating piston **14** is sized to have a precision fit within the cylinder defined by the interior wall **38** of the housing **12**. The precision fit which also permits relative sliding reciprocation requires an annular gap therebetween. Although not shown, the piston **14** may be provided with a gas bearing means which provides a thin layer of pressurized gas in the annular gap for lubrication. While the dimensions will vary from one size machine to another, for a 5 kW rated engine, the gap width is preferably between 20 and 30 microns. Similarly, the displacer **16** may be provided with a gas bearing means for lubricating the displacer motion in the housing, as well as a gas bearing means between the displacer rod **28** and a piston hole **30**. Alternative lubrication means are possible as is known to those of skill in the art.

FIG. **2** illustrates graphically the variation in the work space and back space pressures as a function of piston position during the engine cycle. The back space **20** is typically designed to have a volume significantly larger than the work space **18**, although this is not apparent from FIG. **1**. Therefore, the back space pressure remains approximately constant over the cycle. The work space pressure, however, is seen to undergo large variations over the cycle with the peak pressure occurring at point P_4. Points P_5 and P_6 represent the points in the cycle where the work space pressure and back space pressure are equal. As described with reference to FIG. **1**, the desired mean piston operating position is labeled as X_C.

FIG. **3** shows the work and back space pressures as a function of time, and it is seen that the work space pressure comprises a peak-type waveform having a period T. The pressure wave further comprises subintervals T_P having peak P_4, and subinterval T_B wherein the work space pressure is slightly lower than the back space pressure, the interval T_P being shorter in duration than T_B.

During interval T_P the working gas will flow from the work space **18** to the back space **20** (outward) through the annular gap between the piston **14** and the wall **38**. However, during interval T_B the flow direction will be reversed (inward) according to the well known principle of a gas tending to flow from high to low pressure. As described above, there is a net leakage flow resulting from the asymmetry of the leakage which increases the mass of gas in the back space and decreases the mass of gas in the work space, which together cause the piston to creep inwardly. The inward creep is represented on the cycle diagram of FIG. **2** by a broken line. It is a principal object of the present invention to provide a one way valve which causes low power loss while permitting the centering system to automatically and more precisely maintain the mean position of piston **12** at X_C, thereby giving precise control of the piston position.

Referring again to FIG. **1**, a pressure regulator **50** is shown attached to the free piston Stirling engine **10**. The pressure regulator **50** consists of a connector valve **52** and a valve actuator **54**. The valve actuator **54** includes a diaphragm **56** which extends across a cavity **58**, dividing the cavity **58** into a first actuator chamber **60** and a second actuator chamber **62**. The periphery of the diaphragm **56** is clamped in place between separate portions of the pressure regulator housing **64**.

A needle **66** extends downwardly from, and is drivingly linked to, the diaphragm **56**. The needle **66** is longitudinally, slidably mounted in an aperture, preferably the cylindrical bore **68** formed in the pressure regulator housing **64**. A pointed needle tip **70** can be moved into and out of registration with the shoulder **72**, thereby closing and opening the valve **52**, respectively. The shoulder **72** is the circumferential edge of the end of a passageway **74** formed in the pressure regulator housing **64**. The diaphragm **56** can be displaced upwardly and downwardly in the embodiment shown in FIG. **1**, thereby displacing the needle **66** within the cylindrical bore **68**. At its lowest extreme, the pointed end **70** seats against and registers with the shoulder **72**, thereby closing the end of the passageway **74**. This is the relaxed, normally closed position which exists when there is no pressure differential across the diaphragm. A second passageway **76** extends from the cylindrical bore **68**, and is in fluid communication with the passageway **74** when the valve

52 is open (i.e. when the pointed end **70** is unseated from against the shoulder **72**). A fluid conveying tube **84** connects the passageway **76** with the back space **20**, permitting relatively unrestricted fluid communication between the back space **20** and the passageway **76**.

The diaphragm **56** is forced upwardly, which raises the needle **66**, when the pressure in the chamber **62** exceeds the pressure in the chamber **60**. The diaphragm **56** is displaced in the opposite direction, which lowers the needle **66**, when the pressure in the chamber **60** equals or exceeds the pressure in the chamber **62**. The chamber **60** is in fluid communication with the work space **18** through a passageway formed in a fluid conveying tube **80**. The tube **80** connects to the pressure regulator housing **64** and a passageway **82** is interposed between the chamber **60** and the passageway **81** formed in the tube **80**, connecting them. The pressure in the actuator chamber **60** is substantially equal to the average pressure in the work space **18**, because only a slow rate of fluid flow is permitted through the passageway **83** which filters the high frequency cycling of pressure. This rate of fluid flow can be caused by any suitable restriction, such as the passageway **83** having a restrictive orifice, or the passageway **83** being a restrictive capillary passageway.

Because the pressure in the back space **20** is essentially constant, the chamber **62** can be in unrestricted communication with the back space **20** via a duct extending from the passageway **76**. The duct, which is the gap between the needle **66** and cylindrical bore **68**, does not need to be restrictive if the back space pressure varies only slightly from its average pressure. However, if there are significant variations in the back space pressure, the flow path between the chamber **62** and the back space **20** must be suitably restrictive in order to provide the average pressure of the back space **20** in the chamber **62**. A suitable restriction is a capillary tube (not shown in FIG. **1**) connecting the passageway **76** with the chamber **62**, or a restrictive orifice (not shown in FIG. **1**) in a duct connecting the passageway **76** with the chamber **62**.

A tube **86** connects the passageway **74** with a check valve **88** interposed along the length of the tube **86**, and connects the passageway **74** in relatively unrestricted fluid communication with the work space **18**. The check valve **88**, however, permits gas to flow in an unrestricted manner only in the direction of the arrow **90**, not in the opposite direction. Higher pressure in the passageway **74** than in the work space **18** causes the check valve **88** to open, thereby permitting gas to flow from higher to lower pressure. The check valve **88** closes, however, to prevent gas flow in the opposite direction. The check valve **88** is conventional in its operation and could be substituted by one of many well known equivalents.

Working gas within the free piston Stirling engine **10** can flow without significant restriction through the tube **84**, and can flow without significant restriction toward the work space **18** in the tube **86**, but as explained above, not in the opposite direction. Therefore, when the needle **66** is displaced upwardly out of its contact with the shoulder **72**, the valve **52** is open, and working gas in the back space **20** is able to flow to the work space **18**. However, in order for the working gas to flow in this direction, the instantaneous pressure (i.e. the actual pressure at a given moment as contrasted with the average pressure) of the working gas in the back space **20** must exceed the instantaneous pressure of the working gas in the work space **18**.

In summary, working gas only flows from the back space **20** to the work space **18** when two conditions are met simultaneously. First, the average pressure in the back space **20** must exceed the average pressure in the work space **18** to cause the connector valve **52** to open. Secondly, the instantaneous pressure in the backspace **20** must exceed the instantaneous pressure in the work space **18** for gas to flow in the permitted direction. It is only when both of these conditions are met simultaneously that the present invention operates to permit the flow of gas from the back space **20** to the work space **18**. When the first condition exists, the diaphragm **56** is displaced upwardly due to the pressure in the chamber **62** exceeding the pressure in the chamber **60**. This upward displacement raises the needle **66**, opening the valve **52**, which connects the back space **20** with the work space **18**. If the second condition is met (i.e. the pressure in the back space **20** exceeds the pressure in the work space **18**) at the same time as the first, then the check valve **88** is forced open to permit a flow of gas from the back space **20** to the work space **18**. This flow of gas stops when either or both of the two conditions cease to be met.

The operation of the embodiment shown in FIG. **1** can be discussed in view of the pressures in the work space **18** and the back space **20** as illustrated in FIG. **3**. The back space pressure is illustrated as an essentially flat line, since the high volume back space **20** usually has essentially constant pressure. The instantaneous pressure in the work space is represented by the work space curve, which has regular peaks. When the piston is centered the average work space pressure equals the back space pressure.

However, the average work space pressure can vary due to the asymmetric leakage discussed above. The average work space pressure decreases below the back space pressure if the piston **14** creeps away from its centered position described above. The back space pressure increases because the spring **32** is elongated away from its relaxed design center position by the volume increase, causing the piston **14** to exert an average force on the increased volume of gas in the back space **20**. When the average work space pressure falls below the back space pressure (indicating creep) the needle valve opens. Then, during any part of the cycle during which the work space pressure falls beneath the back space pressure, working gas flows through the check valve **88** from the back space **20** into the work space **18**.

Although the preferred application of the present invention is with a free piston Stirling engine, it can also be applied to a free piston machine having a piston which creeps in an opposite direction. In order to illustrate how this is done, a schematic diagram of first the preferred and then a possible alternative embodiment of the invention will be described.

FIG. **4** shows a schematic diagram of an alternative embodiment which illustrates principles of the invention and in which a Stirling engine **210** has a work space **212** and a back space **214** within a housing **216**. Tubes **218** and **220** extend from the work space **212** to a regulator valve **222**. The regulator valve includes an actuator **224** and a connector valve **226** as in the preferred embodiment. A pair of tubes **230** and **232** connect the back space **214** with the regulator valve **222**. Check valves **234** and **236** are shown attached to the tubes **232** and **220**, respectively. Only one of the check valves needs to be present in a given system, but both check valves are shown to illustrate two possible alternative locations of the check valve. The tubes **218** and **230** connect the work space **212** and the back space **214**, respectively, with the actuator chambers **240** and **242**, respectively. The tubes **218** and **230** have restrictions in them, if necessary, to provide the chambers **240** and **242** with the average pressure of the gas in the portion of the Stirling engine **210** to which they are connected.

When a diaphragm **244** is displaced upwardly by the pressure in the chamber **242** exceeding the pressure in the chamber **240**, the connector valve **226** is opened permitting a flow of gas from the back space **214** to the work space **212**. This is similar in effect to the preferred embodiment.

A schematic diagram of a device very similar to that shown in FIG. **4** is shown in FIG. **5**, including a Stirling engine **310** having a work space **312** and a back space **314**. However, in the case of the Stirling engine **310**, the piston **316** tends to creep toward the back space **314**, rather than the work space as in the Stirling cycle engine used with the preferred embodiment.

Tubes **318** and **320** connect the work space **312** with the pressure regulator **322**. A connector valve **326** is drivingly linked to a diaphragm **344** which separates the cavity of an actuator **324** into first and second chambers **340** and **342**. The tubes **330** and **332** connect the back space **314** with the actuator **324** and the connector valve **326**, respectively.

The orientation of the check valves **334** and **336** is reversed from the embodiment of FIG. **4**, because the flow of gas in a Stirling engine having a piston which creeps toward the back space should be directed from the work space **312** toward the back space **314**. Additionally, the connector valve **326** opens when the diaphragm **344** is displaced downwardly due to the pressure in the chamber **340** exceeding the pressure in the chamber **342**. This is the opposite of the actuator **224** shown in FIG. **4**.

The comparison of the embodiment shown in FIG. **4** and that shown in FIG. **5** is to illustrate that the principle of attaching a pressure regulator valve including an actuator and a connector valve to a free piston machine according to the invention applies to more than merely free piston Stirling engines. Virtually any free piston machine having a piston which creeps in one direction due to asymmetric pressure variations can be restrained with low energy losses using the present invention.

The energy losses of the present invention are lower than conventional centering devices because working gas flows to re-center the piston only once the piston becomes off-center. In the conventional centering devices, gas flows through passageways on each stroke, using significant amounts of power merely to drive the gas through the passageways.

In addition to low energy consumption, the invention can be altered to the application of a particular machine because the invention consists essentially of multiple inputs. There are two inputs to the valve actuator which transmit to the chambers of the valve actuator the average pressures of the work space and the back space. The inputs to the valve actuator determine whether the connector valve will be opened. If the direction in which the piston creeps from center is reversed for a different machine, reversal of the inputs to the valve actuator, and reversal of the check valve, is all that is necessary.

In addition to machines having piston creep in only one direction, it is possible to connect a pressure regulator to a machine having a potential for piston creep in either direction. A schematic diagram of such a device is shown in FIG. **6**. The machine **410** is connected to the pressure regulator **422** which consists of a diaphragm valve actuator **421** and a double acting spool valve **423**. With the apparatus of FIG. **6**, the piston **431** creeps toward the back space when the asymmetric gas flow causes a net transfer of gas to the work space. When the average pressure of the work space **432** exceeds the average pressure of the back space **430**, and the instantaneous pressure of the work space **432** exceeds the instantaneous pressure of the back space **430**, the pressure regulator **422** will cause the spool valve **423** to open a passageway connecting the spaces, permitting gas to flow from the work space to the back space through check valve **426**. When the piston **431** creeps in the opposite direction, the spool valve **423** is opened, connecting the spaces, but with check valve **425** permitting gas flow only from the back space to the work space.

While certain preferred embodiments of the present invention have been disclosed in detail, it is to be understood that various modifications may be adopted without departing from the spirit of the invention or scope of the following claims.

I claim:

1. An improved piston centering apparatus for a free piston machine having a housing, including a cylinder and a piston sealingly reciprocatable in the cylinder, and a spring connected between the piston and the housing, said spring being relaxed and exerting substantially no force on the piston when the piston is in a centered position, said housing enclosing a first machine space bounded by a first end of the piston and also enclosing a second machine space bounded by the opposite, second end of the piston, the second machine space having a working fluid with an average fluid pressure and the first machine space having a working fluid with a fluid pressure varying periodically in opposite directions from said average pressure, said pressure variation causing a net leakage flow of working fluid from the first machine space to the second machine space, wherein the improvement comprises:

(a) a connector valve through which the first and second machine spaces are connected;

(b) a valve actuator linked to the connector valve, the actuator having a first actuator chamber and a second actuator chamber for opening the connector valve in response to the pressure of the second actuator chamber exceeding the pressure of the first actuator chamber, the first actuator chamber connected in communication with the first machine space through a restriction for maintaining a pressure in the first actuator chamber substantially equal to the average pressure in the first machine space, and the second actuator chamber connected in communication with the second machine space; and

(c) a check valve directed to permit a flow of working fluid from the **[**first**]** *second* machine space to the **[**second**]** *first* machine space when the connector valve is open.

2. An apparatus in accordance with claim **1**, wherein the free piston machine is a free piston Stirling cycle machine, the first machine space is a work space and the second machine space is a back space.

3. An apparatus in accordance with claim **2**, wherein the first chamber of the actuator is connected in fluid communication with the work space of the machine, and the second chamber of the actuator is connected in fluid communication with the back space of the machine.

4. An apparatus in accordance with claim **1**, wherein the actuator includes a housing having a cavity formed within the actuator housing, and a diaphragm divides the cavity into the first and second actuator chambers.

5. An apparatus in accordance with claim **4**, wherein the connector valve comprises a needle drivingly linked to the diaphragm and movably mounted in an aperture formed in the actuator housing, for being displaced in response to displacement of the diaphragm, thereby opening and closing the connector valve.

6. An apparatus in accordance with claim **1**, wherein the restriction is an orifice of predetermined size.

7. An apparatus in accordance with claim **1**, wherein the restriction is a capillary tube of predetermined size.

8. An apparatus in accordance with claim **1**, wherein the free piston machine is a free piston Stirling cycle machine, the first machine space is a back space and the second machine space is a work space.

9. An apparatus in accordance with claim **1**, wherein the invention further comprises a second connector valve through which the first and second machine spaces are connected, a second check valve directed to permit a flow of working fluid from the second machine space to the first machine space when the second connector valve is open, and wherein the valve actuator is linked to the second connector valve for opening the second connector valve in response to the pressure of the first actuator chamber exceeding the pressure of the second actuator chamber.

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