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HIGH STABILITY FREE PISTON MACHINE

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2 Sheets-Sheet 1

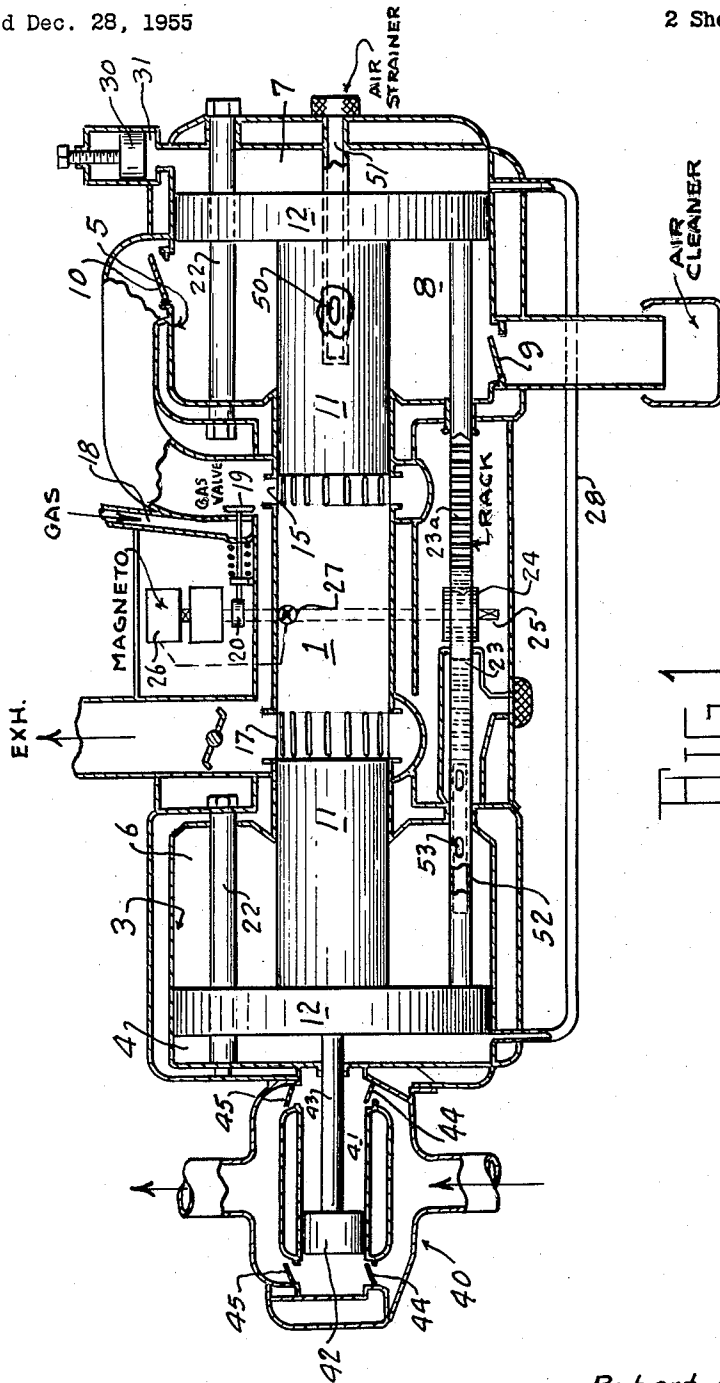


FIG. 1.

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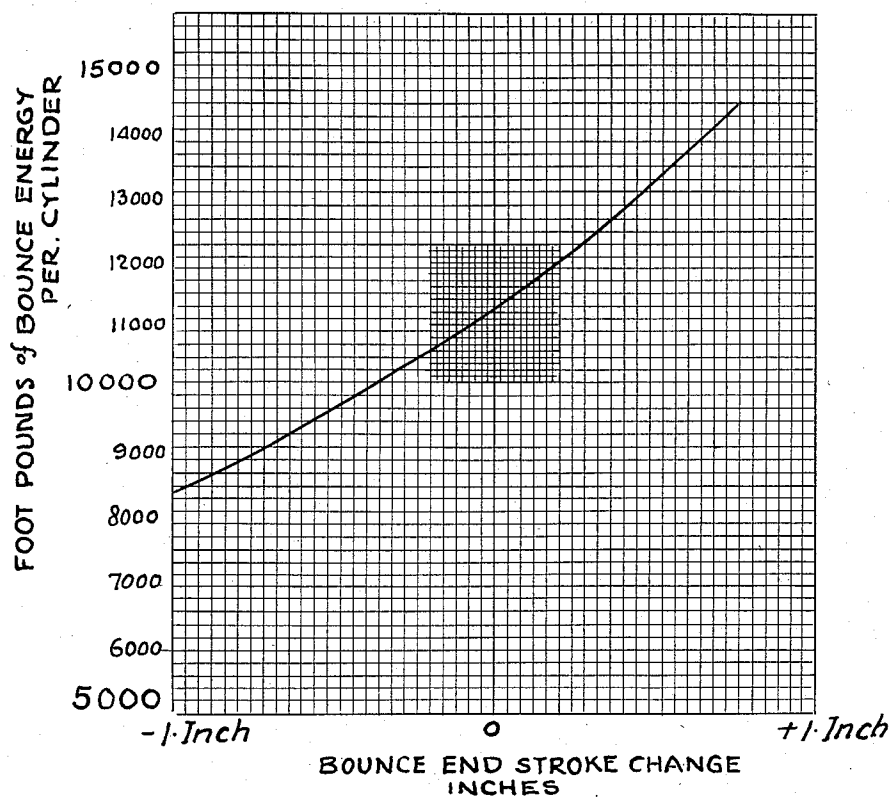
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FIG. 2.



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HIGH STABILITY FREE PISTON MACHINE

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1 Claim. (Cl. 123—46)

This invention relates to free piston machinery and has for its primary object the provision of a machine which is inherently stable in its operation.

Free piston machines, particularly those used either to drive gas compressors or incorporating gas compressing cylinders, are generally incapable of continued operation in the event that the power impulse portion of the cycle fails in even a single cycle for any reason. Thus, if the ignition fails to fire a fuel charge where electric ignition is used, or a fuel injection system fails to deliver the proper quantity of fuel at the proper time where compression ignition is used, the machine stalls. In conventional crankshaft machines the fly wheel and rotating system store sufficient energy to keep the machine operating in spite of an occasional misfire, but in free piston units no such energy storage has been available.

Two classes of free piston machines are known at the present time. In one class the entire work developed in the power cylinder is absorbed in bounce chambers and the work of compression of scavenging air and gas for external use is developed on the inward stroke of the pistons. In machines of this class the front faces of the bounce pistons are used to compress air or gas and the work thereof is largely extracted from the system through the power cylinder.

In the second class of machines, only a portion of the power cylinder work is stored in bounce chambers, the remainder being extracted in the form of compressed scavenging air or gas for external use. In a subdivision of this class there are machines in which the bounce energy is made to exceed that required to return the pistons to firing position, so that a portion of the energy is stored in "reverse bounce" chambers, to reenter the cycle on the next outward stroke.

It has been proposed to utilize the inner sides of the compressor pistons as reverse bounce spaces for the purpose of maintaining an outward pressure on the piston system to compensate for changes in stroke resulting from changes in atmospheric pressure. It has also been proposed to utilize this "reverse bounce" space as a means of increasing the cyclic frequency of operation. To our knowledge, however, it has never been proposed to use this space, or any similar space, in a free piston machine in combination with other energy storing chambers in such a manner that the engine will continue to operate in the event of a misfire. To do this requires that the energy contribution of the power cylinder be normally a relatively small part (preferably in the order of 24%) of the energy absorbed and released from the bounce space. This may be done by absorbing bounce chamber energy in a chamber that is in a position to contribute a substantial or major part of the energy required for an outward stroke. If the power cylinder compression work, the scavenging work and friction are only a small fraction of the maximum potential energy stored up in the bounce chambers, an inward stroke of the pistons will be made and normal oscillation under

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only slightly reduced amplitude will continue even after a misfire at full load, since a very substantial part of the potential energy is absorbed in the chamber contributing to the outward piston stroke.

A preferred manner of carrying out the invention has been disclosed in the accompanying drawings, in which:

Fig. 1 is a diagrammatic cross-sectional view of a free piston machine incorporating the present invention; and Fig. 2 is a graph of piston stroke against accumulated

bounce energy.

Referring to the drawings, 1 designates a central power cylinder of the free piston machine. At each side of the power cylinder are larger cylinders 3 and 5, divided into front and rear spaces by the pistons therein. The cylinder 3 is closed at each end and is used solely for the accumulation of energy in chambers 4 and 6, while the cylinder 5 acts not only as an energy accumulator in its rear chamber 7, but also as a scavenging air pumping cylinder 8. To this end the cylinder 5 is fitted with intake valves 9 at one end and discharge valves 10 intermediate the ends, as indicated diagrammatically.

The several cylinders are fitted with opposed piston sets in the usual manner, each comprising a power piston section 11 and an integral larger piston 12. Thus, the large piston 12 working in cylinder 3, which divides the cylinder into front and rear chambers, compresses air on both its inward and outward strokes and the energy stored in the air so compressed is returned to the piston by reexpansion on the next succeeding stroke as hereinafter described. The large piston working in cylinder 5 compresses air during its outward stroke in the outer chamber 7, the energy so accumulated being used to assist in the next succeeding inward stroke. During the outward stroke air is drawn into chamber 8 behind the piston 12 through the intake valves 9 and is discharged during the first portion of the next inward stroke through discharge valves 10. Discharge of the air so compressed in the scavenging cylinder is stopped when piston 12 overruns the discharge valves 10 and thereafter the scavenging cylinder or inner chamber 8 formed in this cylinder also acts to accumulate energy.

The discharge ports 10 in the wall of the scavenging cylinder communicate via a conduit 16 with piston controlled intake ports 15 in the power cylinder 1, and at the opposite end of the power cylinder there are the usual exhaust ports 17, also piston controlled.

The machine is ideally suited to use natural or artificial gas as a fuel, and a gas injection valve 19 of any suitable form is interposed in conduit 16. Gas is supplied to a passage 18 controlled by valve 19 under pressure higher than that existing in conduit 16 so that, when valve 19 is opened, gas will flow into the conduit and will be carried into the power cylinder with the air to form a combustible mixture therein. The gas valve 19 is controlled by a cam 20 driven from the engine synchronizing pinion as hereinafter described.

The large pistons 12 are guided in their reciprocation by guide rods 22 and are synchronized in their movements by conventional racks 23, 23a meshing with a common pinion 24 whose axis is fixed adjacent the center of the machine. The synchronizing pinion 24 is mounted on a shaft 25 which drives (through appropriate mechanical connections not shown) the gas valve 20 and a magneto 26. If magneto ignition is used the energy from this unit is taken to a conventional spark plug indicated diagrammatically at 27.

The bounce chambers or energy accumulating spaces 4 and 7 at the outside of the large pistons 12 are interconnected by a bounce equalizing pipe 28. The effective clearance adjustment in each of the bounce cylinders may be adjusted by any suitable means such as a piston 30

working in a small cylinder 31 which is, in effect, an extension of the respective bounce chamber volume. The adjustment of the small piston in these cylinders may be made manual or automatic, depending on the design of the machine.

Provision is made for all of the energy accumulating chambers 4, 6, 7 and 8 to operate with atmospheric minimum pressure. This may be conveniently accomplished by using "breathing ports." In the case of bounce chamber 7 the port 50 is formed in a tubular member 51 which extends from the outside of the machine through piston 12 and is opened by being overrun by the piston. An appropriate check valve prevents air flowing out through the port 50 from the scavenging cylinder 8. In the case of the bounce cylinder 3, which acts only to accumulate energy on both strokes of its piston, the front chamber 6 is connected to atmosphere through a hollow rod 52 having a breathing port 53 therein which is opened to atmosphere at the normal outermost position of piston 12 and is closed just after the piston begins its inward stroke. The rear bounce chamber 4 is equalized to chamber 7 (which breathes through port 50) through the equalizing line 28. In each instance the breathing ports 50 and 53 are of a longitudinal extent that corresponds with about half the total expected variations in the normal stroke of the pistons. For example, if the normal variation of stroke amounts to $\pm 1''$, the longitudinal dimension of the ports will be 1 inch.

The machine shown in the drawing is connected to operate a reciprocating, double-acting gas compressor which is indicated diagrammatically at the left side of the drawing and is designated generally 40. The compressor comprises a cylinder 41 having a compressor piston 42 operating therein, being directly connected by a tail rod 43 to the large piston 12 on the left side of the machine. Intake valves 44 and discharge valves 45 are provided at each end of the compressor cylinder so that the driven unit is made double-acting and energy is taken from the free piston system at each inward and outward stroke of the machine.

The operation of a machine constructed in accordance with the present invention can best be understood by reference to a specific example. A machine intended to drive a double-acting gas compressor requiring about 75 horsepower was designed. The unit was required to operate flexibly throughout the pressure ranges of: 150 p. s. i. g. to 500 p. s. i. g.; 250 p. s. i. g. to 500 p. s. i. g.; 350 p. s. i. g. to 500 p. s. i. g.

The fuel burned was natural gas, so the free piston machine was subject to the same requirement as to idling conditions that would be expected of a crank-type gas engine; it must have such stability that occasional misfires will not cause it to stall. In a crank-type engine, the kinetic energy stored in a flywheel can be utilized to carry the engine over stalling periods, but in a free piston machine as usually constructed such energy storage is not available. The present invention, therefore, introduces a new concept in the construction of free piston engines which takes into account for the first time the "energy content" or maximum potential energy that is stored in the bounce chambers at the end of an outward stroke which is deliberately made much larger than the energy required to return the pistons to center position plus that required to overcome friction and for compression of scavenging air. If the power cylinder work, the scavenging work, the load on the engine and the work of friction total only a fraction of the potential energy in the bounce chambers, oscillation of the pistons will continue with only slightly reduced amplitude even after a misfire in the power cylinder. In the case described herein by way of example, the free piston machine will not stall even if the power cylinder misses firing on three successive strokes at idle load or once at full load. Every free piston machine with which we are familiar requires faultless ignition of the proper fuel charge at each stroke for continued operation.

Since there is a substantial quantity of energy stored in the bounce chambers over and above that required to return the pistons to center position, overcome friction, and product the scavenging work, a very substantial storage of energy must take place during the inward stroke to assist the power cylinder in making the following outward stroke. Details of the relative quantities of energy thus stored in the various chambers is apparent from the following analysis of a typical machine.

- The dimensions of the machine are as follows:
- Power cylinder: 1
- Bore ----- 8".
 - Stroke ----- 9.5".
 - Scav. port height ----- 2".
 - Exh. port height ----- 3".
 - MEP at full load ----- 67.1 p. s. i.
 - Pressure at beginning of compression ----- 15.2 p. s. i. a.
 - Compression pressure ----- 365 p. s. i. a.
- Scavenging cylinder: 8
- Bore ----- 24".
 - Stroke ----- 9.5".
 - Discharge valve cut-off ratio ----- 2.4.
 - Intake pressure ----- 14.1 p. s. i. a.
 - Discharge pressure ----- 19.7 p. s. i. a.
 - Clearance ----- 31.5% P. D.
- Bounce cylinders: 4 and 7
- Bore ----- 24".
 - Stroke ----- 9.5".
 - Breathing port height ----- 1".
 - Minimum pressure ----- 14.7 p. s. i. a. (const.).
 - Volumetric compression ratio ----- 3.9.
- Idle bounce: 6 (left hand side)
- Bore ----- 24".
 - Stroke ----- 9.5".
 - Breathing port height ----- 1".
 - Minimum pressure ----- 14.7 p. s. i. a. (const.).
 - Volumetric compression ratio ----- 3.
- Gas compressor: 40
- Stroke ----- 6 1/2".
 - Clearance ----- 9.5".
 - Bore ----- % P. D.

	L. H.	R. H.
	Percent	Percent
150 to 500 p. s. i. g.	34.4	32.4
250 to 500 p. s. i. g.	74.4	69.8
350 to 500 p. s. i. g.	114	108.2

Energy balance: (in ft.-lbs.) 250 to 500 p. s. i. g.

	Left Side		Right Side	
	Inward	Outward	Inward	Outward
Power-----	-1,991	4,658	-1,991	4,658
Scav-----			-7,803	7,268
Load-----	-1,140	-2,956		
Idle-----	-9,369	9,369		
Bounce-----	11,323	-11,323	11,323	-11,323

- Friction: --352 ft. lbs. both ways
Energy content: 22,646 ft.-lbs.
150 to 500 p. s. i. g.: energy content 22,869 ft.-lbs.
350 to 500 p. s. i. g.: energy content 22,473 ft.-lbs.
- The effect of the change in energy content of the bounce cylinders can be understood with reference to Fig. 2 in the accompanying drawings. In Fig. 2 the variation in stroke length of the pistons from the nominal 9 1/2 inch average in the above machine is plotted against the potential energy in each bounce chamber. It

will be understood, of course, that if the pistons make a shorter stroke into the bounce chambers 4 and 7 the energy accumulated therein is reduced because the ultimate air pressure is lower. Similarly, if the length of the piston stroke is increased, the air pressure in the energy accumulating bounce chambers 4 and 7 is increased and the potential energy is greater. Fig. 2 shows the relationship between the change in stroke length and "energy content" of the chambers and the "O" line represents "normal" stroke length for operation between 250 p. s. i. g. and 500 p. s. i. g. From Fig. 2 it can be seen that:

(1) Operation at full load between 150 and 500 p. s. i. g. increases the outer stroke length by .02 inch because the energy content increases from 22,646 ft. lbs. to 22,867 ft. lbs.

(2) Operation at full load between 350 and 500 p. s. i. g. decreases the outerstroke length by .02 inch because the energy content decreases from 22,646 ft. lbs. to 22,473 ft. lbs.

(3) When operating at full load between 250 and 500 p. s. i. g. one misfire decreases the outer stroke length by .45" because the energy imparted by the power piston drops from 4,658 ft. lbs. to 1,991 ft. lbs. which represents only the recovery of the energy of compression in the power cylinder, so that the total energy content is reduced from 22,646 ft. lbs. to 19,781 ft. lbs.

(4) A sudden loss of load during an outward stroke which would seriously damage most free piston machines results only in an increase in the outer stroke length of .4" because the energy absorbed by the load from the left compressor cylinder during the outward stroke is only 2,956 ft. lbs.

(5) The power cylinder output at each side of the machine is only 11.8% of the energy content of the machine.

(6) Idling conditions result in a reduction in the outer stroke of about .4" while four successive misfires at idling reduces the outer stroke length by .85". The "normal" contribution of energy by the burning of fuel during idling is 550 ft. lbs.

(7) The change in the inner position of the pistons is of an order similar to the change in the outer positions given above, and so long as the scavenging air and exhaust ports are uncovered in a normal manner during the outstroke the engine pistons will continue to reciprocate and the engine will continue to fire.

It can be seen from the above energy balance that even at full load the power cylinder output to each side of the machine is only 11.8% of the "energy content" of the machine or the maximum potential energy stored in the bounce chambers 4 and 7. The power cylinder absorbs 1991×2 ft. lbs., as the work of compression and contributes 4658×2 ft. lbs. as expansion energy during normal firing at full load operation between a suction pressure of 250 p. s. i. g. of the compressor 40 and a discharge pressure of 500 p. s. i. g. of the compressor. It will also be seen that the scavenging cylinder 8 absorbs 7803 ft. lbs. of energy during the inward stroke and contributes 7268 ft. lbs. during the outward stroke to assist in driving the pistons into the bounce chambers 4 and 7. The difference between the energy contained in the inward and outward strokes of the scavenging piston in cylinder 8 is taken as the energy required to compress the air used for scavenging purposes. The compressor, being double-acting, absorbs 1140 ft. lbs. of energy during the inward stroke and 2956 ft. lbs. of energy during the outward

stroke. It will be seen that the quantity of gas displaced by the compressor during the inward stroke of the pistons of the free piston machines is less than the quantity of gas displaced during the outward stroke due to the presence of the piston rod in the compressor cylinder on the right hand side. The bounce cylinder 6 formed on the inward side of the large piston in the left hand cylinder absorbs 9369 ft. lbs. of energy during the inward stroke and, since the cylinder is closed, contributes this same quantity of energy during the outward stroke. Totaling the energy balance during the inward stroke of the left hand piston it will be seen that a total of 12500 ft. lbs. is absorbed during the inward stroke and that 11323 ft. lbs. of this energy is derivable from the bounce cylinder alone. The deficit in energy is made up by transfer from the right hand piston through the racks 23 and 23a. Totaling the energy in the right hand piston it will be seen that 9794 ft. lbs. of energy is required to force the pistons into the proper center position and that there are 11323 ft. lbs. available for this purpose. There is thus an excess of energy in the right hand piston which can be transferred to the left hand piston and which can also be used for overcoming friction in the machine during the inward stroke.

Similarly, it will be seen that there is an excess of energy during the outward stroke in the right hand piston and that this is absorbed in the left hand piston which has a deficit during the outward stroke, the difference between the two representing the element of friction. There is thus energy transferred back and forth in the racks which become energy transmitting elements in addition to functioning for the usual purpose of synchronizing the motion of the pistons.

It will be seen that the present invention provides, for the first time, a free piston machine that has essentially the stability of a crank-type engine and can operate satisfactorily on gaseous fuels which are subject to occasional misfiring. While the invention has been disclosed in conjunction with a specific example it should be appreciated that such example is by way of illustration only and that various modifications and changes in the invention can be made without departing from the scope of the appended claim.

We claim:

The method of controlling the operation of a free piston machine having piston controlled exhaust and scavenging ports which comprises, storing and releasing energy in bounce cylinders on an outward stroke in a quantity at least two times the net quantity of energy derived from the power cylinder by combustion, and storing and releasing energy in other cylinder spaces in a quantity in excess of that imparted to the pistons by combustion in the power cylinder, the quantity of energy available to cause an outward stroke of the pistons being at least enough to cause more than one stroke of the pistons of a length sufficient to uncover said piston controlled ports on the outward stroke and to compress a charge to an ignitable point on an inward stroke in the absence of any energy imparted by combustion.

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