

Nov. 8, 1960

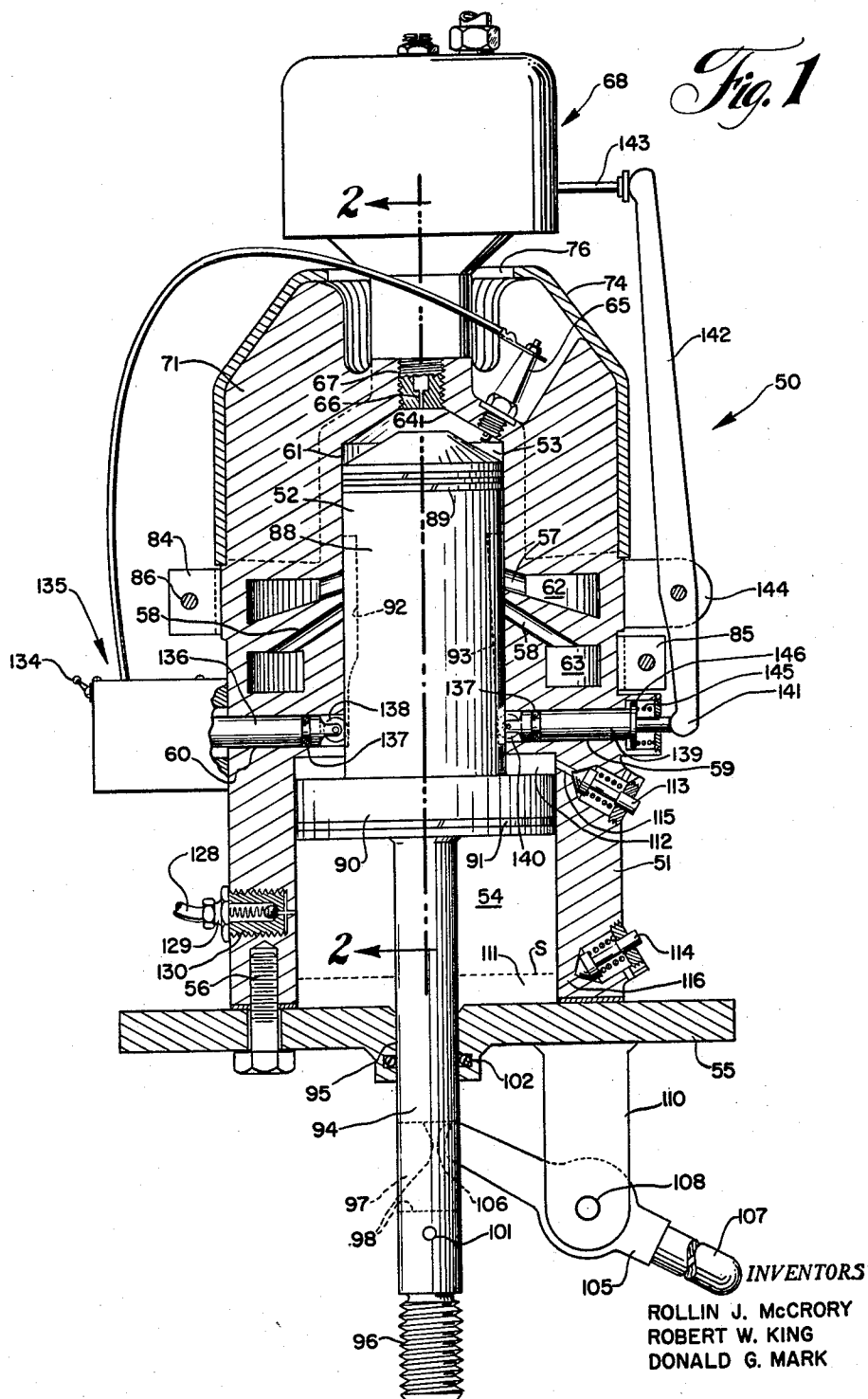
R. J. McCRORY ET AL

2,959,159

FREE-PISTON INTERNAL COMBUSTION APPARATUS

Filed May 16, 1958

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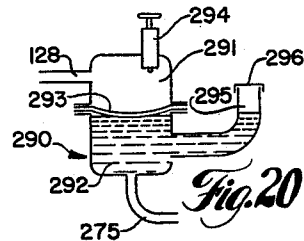
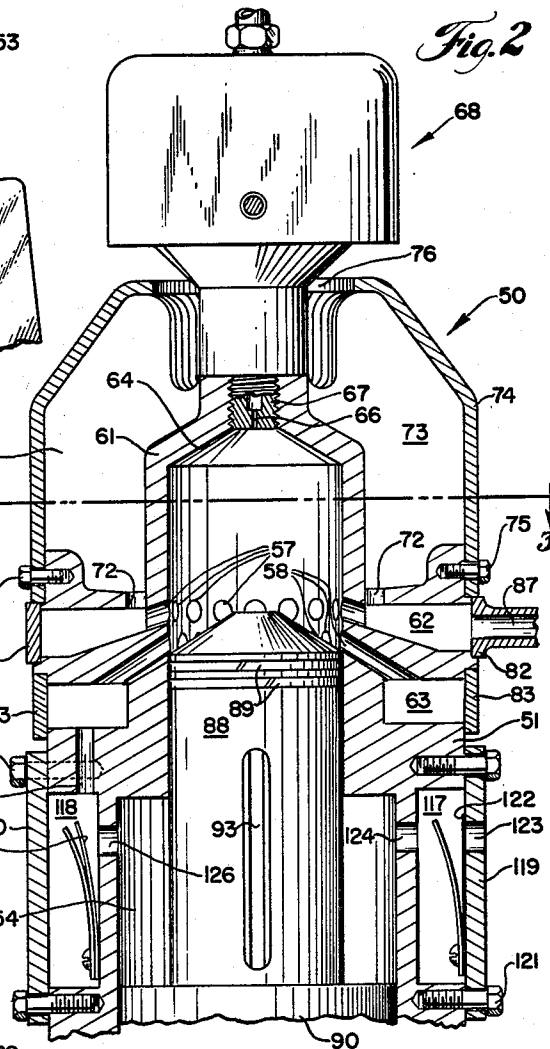
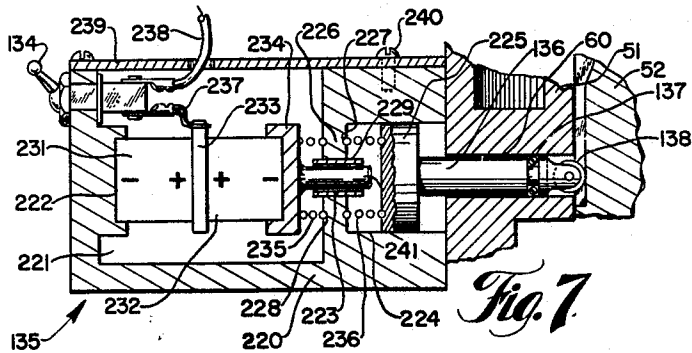
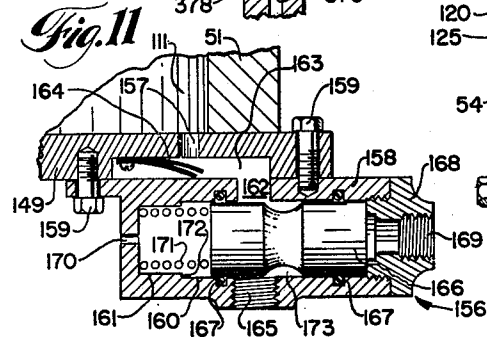
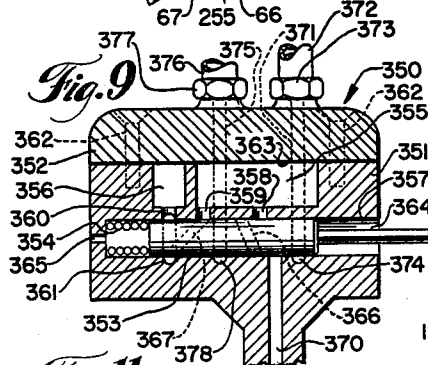
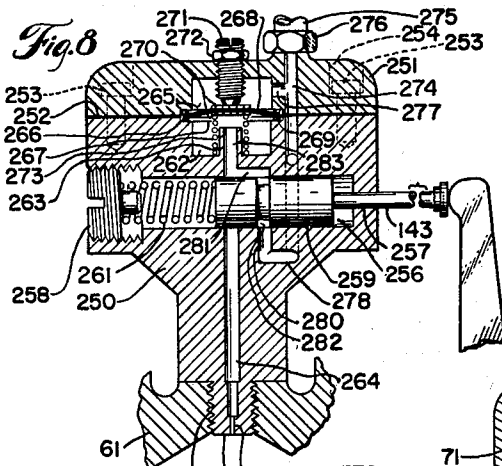
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FREE-PISTON INTERNAL COMBUSTION APPARATUS

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4 Sheets-Sheet 2



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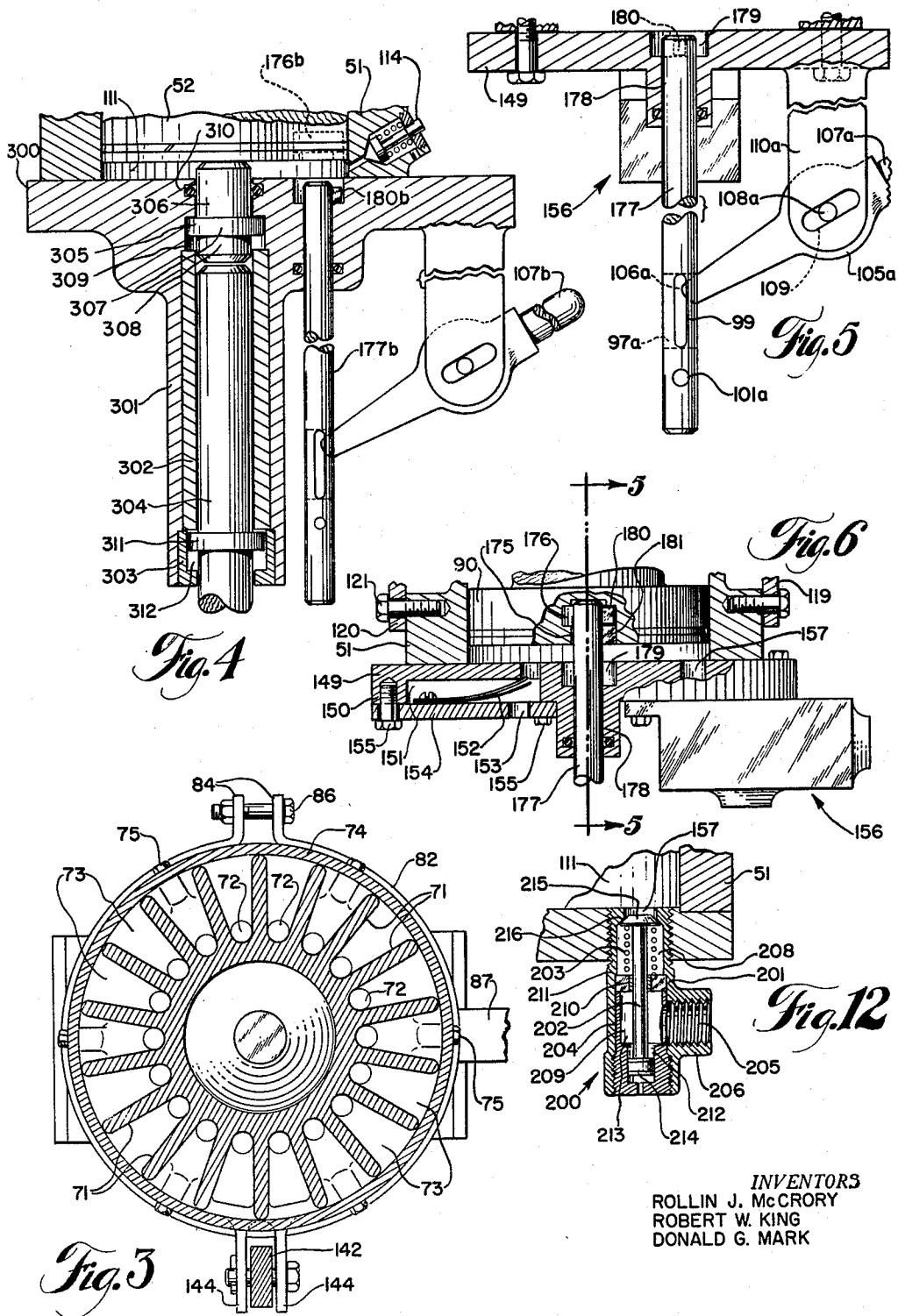
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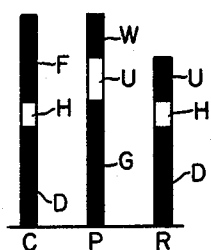


Fig. 13

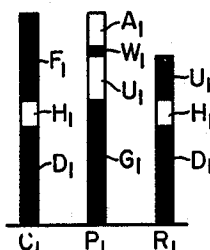


Fig. 14

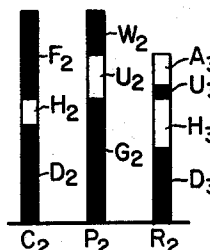


Fig. 15

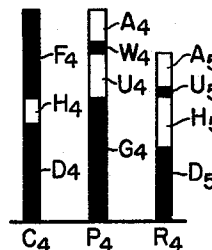


Fig. 16

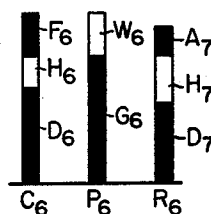


Fig. 17

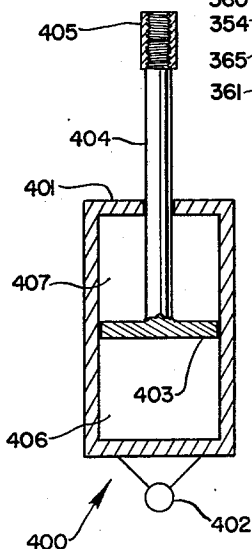


Fig. 21

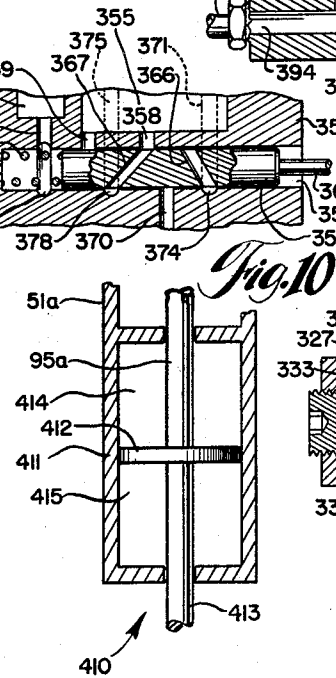


Fig. 22

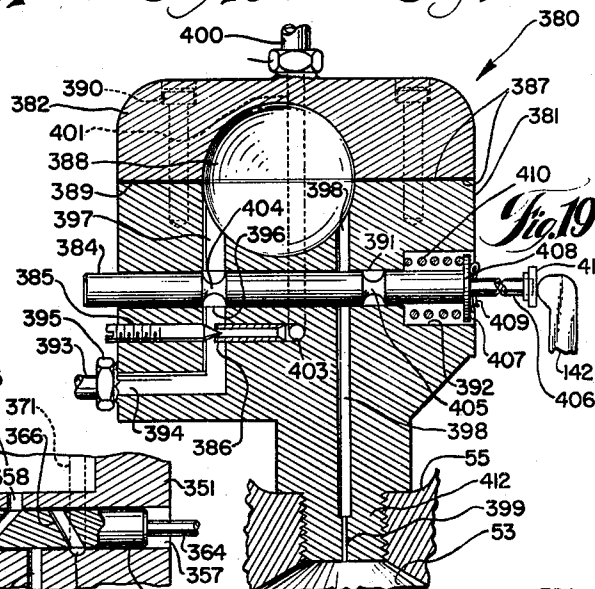


Fig. 19
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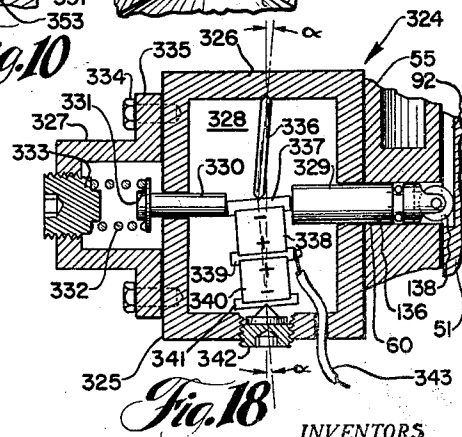


Fig. 18

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FREE-PISTON INTERNAL COMBUSTION APPARATUS

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Filed May 16, 1958, Ser. No. 735,795

15 Claims. (Cl. 123-7)

This invention relates to internal combustion engines of the free-piston type, and, particularly to improvements in the piston bounce and deceleration means associated therewith. This invention also relates to improvements in the ignition, fuel supply, and cooling systems for the free-piston engine, all to the end of providing a thermodynamically balanced free-piston engine capable of sustained operation and provided with maximum construction simplicity.

Free-piston engines are those in which the reciprocating motion of the piston or pistons are not mechanically restrained by the conventional connecting rod and crankshaft. Although most of the multipiston free-piston engines have mechanical connections between the pistons to maintain the proper phasing between the pistons, the end positions of the piston stroke are not established by the mechanical connections. The end positions of the piston stroke are established each engine cycle by the energy released to the work article or load that is being driven by the engine and the energies of the combustion process and the resilient rebound system.

Two resilient rebound systems are commonly used for free-piston engines. For one type engine, a mechanical resilient system, such as a compression spring, is provided. This compression spring is located at the end of the piston opposite the combustion chamber. Thus, when the piston is accelerated on its combustion stroke by the energy developed in the combustion chamber, the spring is compressed. The energy absorbed by the spring then returns the piston on its compression stroke. This type of rebound system for free-piston engines is considered to be unsatisfactory because of the rapid failure of the compression spring. The second type of rebound system which has been employed is the pneumatic or compressed-gas type. In this second type, a gas, usually air, is trapped and compressed beneath the free piston on its combustion stroke and this compressed gas is utilized to rebound the piston to head-end position on the compression stroke.

Most free-piston engines are used where the load changes only very slightly each cycle. For this type of application, the rebound and combustion energies require a gradual-type control to keep the piston stroke such that continued and reliable operation can be maintained. However, considerable difficulty has been found in providing a free-piston engine capable of sustained operation and reliability when the energy delivered to the work article or load driven by the engine changes radically in one engine cycle. It is the type of free-piston engine with compressed-gas rebound and controls to compensate for radical changes in load in one engine cycle that this invention is particularly directed.

It is apparent that when considering free-piston engines without mechanically restrained end positions for the piston, that sustained and reliable operation depends on balanced energy conditions each cycle on both ends of the piston. The energy conditions on both ends of the piston depends on the combustion energy developed, the amount of energy removed from the engine, and the

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energy stored and released from the rebound system. In looking further, it can be seen that a change in any one of the three energy factors mentioned above will affect the other two. It can be seen then that a radical change in any one will produce a radical change in the operational characteristics of the engine, unless a control system to compensate for the change operates on the very cycle the change occurred. Factors affecting these energy conditions include: combustion cycle control with all of its attendant ramifications, such as proper ignition timing and potential; proper fuel timing, disbursement and quantity; proper combustion cylinder wall temperatures; and rebound energy control when subjected to variations in the load on the engine. Various types of loads or output usages of the engine will produce different and additional problems in the successful, continuous, reliable use of the engine.

As stated above, most free-piston engines are used where load changes occur gradually. With gradual changes in load, the control system can operate slowly to change the combustion and/or the rebound energies to compensate for the load changes. One feature of this invention is apparatus and a method for controlling the energies on each side of the piston during each cycle so that the piston stroke remains essentially constant and the factors affecting combustion are not varied. Another feature is improvements in combustion controls. With this type of control system, the application for free-piston engines will not necessarily be restricted to those with gradually changing loads.

With a control system that allows the combustion energy to remain constant, the variation in load must be compensated by a corresponding change in rebound conditions. The load energy or work from a free-piston engine can be delivered in several different forms. However, when considered on an engine-cycle basis, energy can be delivered in three possible ways: (1) on the expansion stroke, (2) on the compression stroke, and (3) on both the expansion and compression stroke. The following description is directed to a control system for energy being delivered on both the expansion and compression stroke. Therefore, the invention of the control system herein covers all three types of loading for free-piston engines.

Briefly, the part of this invention directed to the rebound and deceleration control system is a method and apparatus for controlling in each cycle, the energy absorption and release within two pneumatic rebound chambers, located on opposite ends of the compression cylinder piston. The pneumatic rebound chamber opposite the combustion chamber will be referred to as the bounce chamber, while the pneumatic rebound chamber acting on the same side of the compression cylinder piston as the combustion chamber will be referred to as the counter chamber. This invention provides the use of pressure-relief valves of low inertia in both the bounce and counter chambers, such that if the pneumatic pressure in either chamber exceeds the pop-off pressure of their respective relief valve, the gas in the chambers will be exhausted either to the atmosphere or to a low-pressure line of the gas system.

In operation, if all of the energy intended for doing useful work on the expansion stroke of the piston is not absorbed by the work article or the load being driven by the engine, the piston will travel further on this stroke. However, as the piston travels further on the expansion stroke, the final volume of the bounce chamber is reduced to a value lower than the normal full-load operating volume. As the volume of the bounce chamber is reduced below normal, the pressure will increase above the normal full-load operating pressure. The pop-off pressure for the relief valve and the volume of this

bounce chamber are so proportioned that, if the load on the expansion stroke falls off to a great enough extent to increase appreciably the energy storage of the chamber, the relief valve will open and exhaust some of the energy in the compressed gas so that the rebound energy from this chamber will not become excessive. By this manner, most of the energy that would normally be delivered to the work article or load being driven by the engine will be exhausted from the bounce chamber.

The same type of compensating control system is provided in the counter chamber to correct the energy balance when the energy normally intended for the useful work on the compression stroke is not absorbed by the work article or load being driven by the engine. Therefore with combustion conditions established to provide greater than predetermined maximum energy use, the engine operates through all load conditions continuously, wasting excess energy when the energy usage on the engine is less than full load.

A feature of this invention is the compact, self-contained engine construction without the usual complex mechanical controls for the combustion energy. Another feature is the adaptability of the free-piston engine to a variety of uses where radical changes in load in either or both the compression and expansion stroke of the piston can occur in the duration of only one engine cycle without radically affecting the operational characteristics of the engine.

A further feature of the present invention is a piezoelectric generator adapted to be operated directly from the reciprocation of the free piston to generate an ignition potential simultaneously with the need therefor and at the proper time therefor. Another feature is the way in which the elements of the piezoelectric generator are positioned with common poles in connection with a common terminal centrally positioned between the elements so that problems of electrical insulation are greatly reduced and that the proper voltage is obtained to fire the ignitor with minimum force being applied to the elements. Still another feature of the electric generator is its construction to provide individual electrical impulses at a precisely timed, rapidly repeating rate required for effective combustion control in a free-piston engine.

A feature of the present invention is a fuel-injection system capable of positively injecting a fuel charge into the combustion chamber under the control of means operated directly and properly timed in connection with the rapid reciprocation of the free piston. Another feature includes the way in which air compressed in either the bounce or counterchambers is directly provided to the combustion chamber for scavenging and combustion purposes, and the way in which air compressed in the bounce chamber is provided to the fuel injection system at sufficient pressure for the fuel-injector operation.

A feature of the engine of this invention is the external construction of the combustion cylinder which provides a plurality of cooling air chambers about the outer surface of the combustion cylinder wall to effectively cool the cylinder wall by removing the excess heat of combustion therefrom.

Another feature is the construction having the engine exhaust ports at a position adjacent to one end of the cooling air chambers and in communication therewith to induce air flow in the chambers.

Yet another feature of the present invention is a free-piston engine starting mechanism by which a free-piston engine having pneumatic rebound is initially put into operation by lever means.

Other features and objects of the invention will be apparent from the attached drawings, and the following description. This invention comprises apparatus and a method of applying the same, the preferred form of which is disclosed in the following description and attached drawings. Although the apparatus, structure, and method described and shown in detail refer with par-

ticularity to a single-cylinder, free-piston engine, it is apparent that this invention should not be limited thereto. Many of the significant features of this invention apply with equal qualification to free-piston engines of all sizes, classes, and types. The invention may be used for other purposes, where its features are advantageous.

In the drawings:

Fig. 1 is an elevational, partially sectioned view of a free-piston engine constructed according to and having the features of this invention;

Fig. 2 is a partially sectioned, elevational view taken along the line 2—2 of Fig. 1;

Fig. 3 is a sectional plan view taken along the line 3—3 of Fig. 2;

Fig. 4 is a sectional, elevational view of a portion of a free-piston engine, according to this invention, showing a form of starting mechanism in connection therewith;

Fig. 5 is a sectional, elevational view of another form of starting mechanism which may be used in connection with the free-piston engine of this invention;

Fig. 6 is a sectional, elevational view of the output end of a free-piston engine, according to this invention, disclosing a different construction;

Fig. 7 is a sectional, elevational view of an ignition generator forming a part of this invention;

Fig. 8 is a sectional, elevational view of a diaphragm-operated fuel injector forming a part of this invention;

Fig. 9 is a sectional, elevational view of an air-blast fuel injector forming a part of this invention;

Fig. 10 is a partial sectional view of the air-blast fuel injector of Fig. 9 with the plunger at a different position;

Fig. 11 is a sectional, elevational view of a pressure-compensating valve forming a part of a compressor which may be formed integrally with the free-piston engine of this invention;

Fig. 12 is a sectional, elevational view of another embodiment of a pressure-compensating valve which may be used with a compressor according to this invention;

Fig. 13 is an energy diagram for the operation of a free-piston engine having the improvements of this invention;

Fig. 14 is an energy diagram for different operating conditions of the engine;

Fig. 15 is an energy diagram for different operating conditions of the engine;

Fig. 16 is an energy diagram for still different operating conditions of the engine;

Fig. 17 is an energy diagram for still different operating conditions of the engine;

Fig. 18 is a sectional elevational view of another form of ignition generator which is a part of this invention;

Fig. 19 is a sectional elevational view of another embodiment of an air-blast fuel injector forming a part of this invention;

Fig. 20 is a schematic elevational view of a fuel tank and accumulator to be used with this invention;

Fig. 21 is a schematic sectional view of an inertia apparatus which may be combined with the free-piston engine of this invention, and

Fig. 22 is a schematic sectional view of another form of an inertia apparatus which may be combined with the free-piston engine of this invention.

The free piston engine in general

It has been considered for many years that it would be desirable to provide a free-piston engine capable of sustained, reliable, efficient operation for radical changes in load occurring in a very short interval of time. Among the reasons for this favorable attitude are the compactness of free-piston engines with respect to power (high horsepower per pound ratio), comparatively quiet operation, few moving parts, and the production of energy in the form of rapid motion of translation directly from the piston without circumvention through a rotary system, such as a crankshaft. These advantages stem, in the most

part, from the elimination of the crankshaft and other forms of rotary-motion mechanisms, through which the output energy of the usual crankshaft engine is transmitted. Friction energy is reduced by the elimination of crankshaft bearings and thrust on the piston skirt. Noise is reduced considerably by the absence of the crankshaft, rod, and piston pin bearings and the clearance of these parts along with valve mechanisms associated with four-cycle engines.

The above-mentioned advantages may be better utilized when the work to be done or energy use requires reciprocal motion. However, these advantages may also be gained when the free-piston engine is used to drive an exhaust gas or compressed air turbine, which ultimately produces rotary motion. Three significant types of applications for a source of reciprocating-motion energy are: as a reciprocation tool such as a saw blade, as an impact tool such as an air hammer, and as a fluid compressor, or pump. In addition to the applications listed above, there is a corollary to the first, which is an application that requires a reciprocating motion capable of providing energy or doing work in both directions of operations. An example of such requirement is a reciprocating electric generator.

The following description discloses how the free-piston engine of this invention, with its control accessories, provides a reliable source of reciprocating-motion energy in all of these instances.

Referring to Figs. 1, 2, and 3, a free-piston engine 50 comprises a block or frame 51 and a free piston 52 reciprocal therein. The frame 51 is provided with an internally bored combustion cylinder 53 and provided in communication therewith is a coaxial greater-diameter compression cylinder 54. Closing the compression cylinder 54 at the end opposite to the combustion cylinder 53 is a base or mounting plate 55 fastened to the block 51 by suitable means, such as screws 56. The combustion cylinder 53 is provided with exhaust ports 57, intake ports 58, and cam-follower bores 59 and 60 at spaced intervals along the cylinder wall 61 thereof. An exhaust manifold 62 encircles the combustion cylinder 53 having an annular form and cast integrally with the frame 51. Communication is provided between the exhaust manifold 62 and the combustion cylinder 53 by means of the exhaust ports 57.

An annular intake manifold 63 is also provided in the frame 51 at a position further removed from the head end of the combustion cylinder. Communication is established between the combustion cylinder 53 and the intake manifold 63 by intake ports 58.

At the head end 64 the combustion cylinder 53 is provided with ignition means 65, such as a spark plug. Centrally positioned on the axis of the combustion cylinder 53, at the head end 64, is the fuel nozzle 66 of a fuel injector, designated generally as 68.

The cylinder wall 61 has formed integrally therewith a plurality of fins 71 disposed radially therefrom and continuing from a position adjacent to the exhaust manifold 62 to a position near and adjacent to the fuel injector 68. At the intersection of the sides of the fins 71 with the external edge of the cylinder wall 61, and at the base, is provided an ejector port 72 establishing communication between the exhaust manifold 62 at each exhaust port 57 and the ejector chambers 73. Forming the third side of each chamber 73 is a portion of an ejector housing 74 which is adapted to enclose the ejector structure housing 74 in the form of an inverted dish-shaped annular member held in position by suitable means, such as screws 75 at the lower end. Ejector housing 74 has an annular opening 76 at the upper end, which is adapted to form, in conjunction with the fuel injector 68, an aperture in communication with the atmosphere.

All but one of the fins 71 continue upward to a position near the fuel injector 68. However, in order to pro-

vide room for the spark plug 65, one fin is relieved at a position removed from the fuel injector 68.

The exhaust manifold 62 and the intake manifold 63 are formed in the frame or block 51, when it is cast, by suitable cores which extend to the outer periphery of the casting on two sides. Thus, the manifolds 62 and 63 are partially within the block 51 as shown in Fig. 1 and extend to the periphery of the block as shown in Fig. 2. Cover bands 82 and 83 are provided to close exhaust manifold 62 and intake manifold 63 from the atmosphere. Each cover band 82 and 83, respectively, is provided with cover-band tabs 84 adapted to receive a clamping bolt 86 which may be tightened to maintain the cover bands 82 or 83 in place.

An exhaust outlet 87 is provided at one position in the cover band 82.

As shown in Figs. 1 and 2, piston 52 is constructed with a minor-diameter portion 88 that is adapted to reciprocate in the combustion cylinder 53, being sealed with the cylinder wall 61 by means of piston rings 89. At the opposite end piston 52 is formed in a greater-diameter portion 90 which is adapted to reciprocate in a compression cylinder 54 and is sealed in connection therewith by means of the piston ring 91. The minor-diameter portion 88 is provided with oppositely disposed longitudinal cam grooves 92 and 93, respectively.

The free-piston engine 50 shown in Figs 1 and 2 is provided with a piston rod 94 fastened to or formed integrally with piston 52 and adapted to protrude through the base plate 55 and reciprocate therein through a bushing 95 with a seal 102. The piston rod 94, shown in Fig. 1, is constructed with a threaded end 96 to receive and hold a reciprocating tool.

Piston rod 94 is also provided with a starting slot 97 passing diametrically therethrough and having oppositely disposed perpendicular ends 98. A key bore 101 is provided through piston rod 94 at a position adjacent to and below the lower edge of slot 97.

To cooperate with the starting slot 97 a starting lever 105 is provided. The lever 105 is formed with a lever tip 106 and a handle 107, and is supported on a pivot 108. Pivot 108 is located in the end of a starting lever trunnion 110.

Compression cylinder 54 is divided by the major-diameter portion or piston flange 90 into a bounce chamber 111 on the one side (lower side in Fig. 1) and a counterchamber 112 on the other side (upper side in Fig. 1). Since, in Fig. 1, the piston 52 is shown at its uppermost head-end position, bounce chamber 111 is at its maximum volume, while counterchamber 112 is at minimum volume. On the other hand, in Fig. 2 the piston is shown at the bottom of its stroke and bounce chamber 111 is of minimum volume and counterchamber 112 is of maximum volume. Near each end of the compression cylinder 54, pressure-relief valves 113 and 114 are provided in the frame 51. Relief valve 113 is in communication with counterchamber 112 by means of a conduit 115. Relief valve 114 is in communication with bounce chamber 111 by means of a conduit 116.

At a position circumferentially removed from the relief valves 114 and 115 is located an inlet air valve chamber 117 and a scavenge air valve chamber 118. Each of chambers 117 and 118 is formed from a recess in the frame 51 and a cover plate 119 and 120, respectively. Cover plates 119 and 120 are held in place by suitable means, such as screws 121.

The inlet air valve chamber 117 is provided with a reed-type inlet air valve 122 adapted to open and close with respect to an inlet air valve port 123. Communication is provided between counterchamber 112 and valve chamber 117 by means of an inlet port 124.

On the opposite side a scavenge valve 125, of the reed type, is adapted to open and close a scavenge air port 126 in communication with counterchamber 112. A conduit

127 is provided in the frame 51 connecting the intake manifold 63 with scavenge air valve chamber 118.

Bounce chamber 111 is connected to an accumulator 291 (Fig. 20) by means of an accumulator line 128. This connection may be made at the frame 51 by means of a suitable fitting 129 on a check valve 130 which is threadedly received in the side of the frame 51.

At one side of engine 50 is located a generator 135 having a cam-follower rod 136 adapted to reciprocate in bore 60. Cam-follower rod 136 is provided with sealing means 137 within the bore 60, and carries, for freely rotatable motion, a generator cam follower 138. Cam follower 138 is adapted to roll in cam groove 92 of piston 52.

As the piston 52 reciprocates longitudinally, cam follower 138 is caused to reciprocate radially with respect to the pistons 52 by the depth and contour of cam groove 92. Resilient means is provided to keep cam follower 138 in contact with the bottom of the cam-follower groove 92, as will be described later in detail.

At the opposite side of the frame 51, a cam-follower actuator rod 139, having a suitable seal 137, is positioned in cam-follower bore 59 for radial reciprocation when actuated by a cam follower 140 operating in cam-follower groove 93 in a manner similar to that described for the generator rod 136. Actuator rod 139 engages an end 141 of a rocker arm 142. At the opposite end, rocker arm 142 is in contact with a plunger or stem 143 of the fuel injector 68. A trunnion yoke 144 pivotally supports rocker arm 142. Resilient means, such as a spring 145, acting against a collar 146 urges actuator rod 139 into continuous contact with the cam groove 93.

In the description of the engine 50 and the description of its operation to follow, reference may be made to the power stroke as the down stroke and the compression stroke as the up stroke. This is in conformity with the position of the engine in Figs. 1 and 2. This terminology is employed for descriptive convenience and defines no limitation of the position of the engine, as the engine may be operated at any orientation.

Operation

In order to start the engine 50, the tip 106 of lever 105 is inserted in slot 97. The handle 107 is then drawn upward which draws the piston down to the position shown in Fig. 2, ready for starting. This draw-down operation preparatory to starting is always necessary in a free-piston engine having pneumatic rebound, because the engine always stops with the piston at a position above bottom or lowest piston position. Having been at rest any length of time, combustion conditions in the combustion cylinder 53 will no longer be suitable for ignition, and the engine cannot be started until the piston 52 is brought to near the lowest position.

Once the piston has been drawn to the lower position, as shown in Fig. 2, ignition switch 134 is closed and the handle 107 is pushed briskly downward, impelling the piston upward on the first compression stroke. Sufficient stroke is given to handle 107, when it is pushed downward, to carry the arc of tip 106 beyond the upper surface 98 of slot 97, and therefore free of piston rod 94, so that the first downward combustion stroke takes place free of the starting mechanism.

In the combustion cycle of free-piston engine 50, upward movement of the piston compresses air which has been admitted from the intake manifold 63 through the intake ports 58. Fuel is admitted through the fuel nozzle 66, forming a combustible mixture which is ignited by spark plug 65 at or near the time the piston reaches head-end position shown in Fig. 1. Ignition and burning of the fuel forces the piston 52 downward, making energy available at the connection 96 of piston rod 94. When the piston 52 passes exhaust ports 57 on the downward stroke, products of combustion are exhausted through

these ports into exhaust manifold 62. Continued downward progress of piston 52 opens intake ports 58, permitting the admission of air to scavenge the combustion cylinder 53.

During the downward stroke of the piston 52, air is compressed in bounce chamber 111, storing energy to return the piston 52 for the next upward stroke. At the same time, inlet air valve 122 opens by reason of the less-than-atmospheric pressure created in counterchamber 112 by the downward stroke of piston 52. Opening of inlet valve 123 admits air to the counterchamber 112.

On the down stroke of piston 52, when the pressure in bounce chamber 111 exceeds the pressure in accumulator 291 and line 128 by an amount sufficient to open check valve 130, air is pumped into the accumulator for operation of the fuel injector 68.

The compression energy of the air in bounce chamber 111 forces the piston 52 up on the compression stroke. The air in counterchamber 112 is compressed causing scavenge air valve 125 to open and the air to be expelled through the scavenge air port 126. Compressed air is forced from scavenge air chamber 118 upward through conduit 127 into intake air manifold 63 for operation of the combustion cycle of the engine. After the major-diameter portion 90 of piston 52 closes inlet port 124 and scavenge air port 126 on the upstroke, air is compressed in counterchamber 112, serving to help decelerate the piston to a stop at the head-end position.

In a free-piston engine 50 without mechanical control of the piston stroke, the position of the piston 52 when it stops on the upward stroke is controlled only by the pressures existing in counterchamber 112 and combustion cylinder 53. In the event piston 52 comes up on the compression stroke with more than the energy necessary for proper running balance, piston 52 will over-travel its usual stopping place and pressures would become too high in counterchamber 112 and combustion cylinder 53. However, in the engine of this invention, the pressure-relief valve 113 provides for a predetermined maximum pressure in counterchamber 112, and therefore, a fixed maximum energy return to the system on the combustion stroke. Conduit 115 of pressure-relief valve 113 is located a short distance from the upper end of counterchamber 112, and the remaining short distance provides a completely sealed air cushion for safety purposes. This air cushion prevents the piston from making contact with the ends of counterchamber 112 or combustion cylinder 53.

Pressure-relief valve 114, near the lower end of the bounce chamber 111, is provided for a purpose similar to that of relief valve 113 on counterchamber 112. In the event that the energy possessed or retained by the piston 52 on the power stroke is abnormally high, the piston will proceed downward beyond its ordinary stopping position, shown by the dashed line S in Fig. 1. This would compress the air in bounce chamber 111 to a higher pressure and would store excess energy for the following compression stroke. In this invention the pressure-relief valve 114 is adjusted to open at a predetermined maximum pressure, and therefore, to control the energy storage for the compression stroke to a predetermined maximum amount. In the event that the energy possessed by piston 52 on the power stroke is so abnormally great as to endanger the structure of the engine by causing contact between the bottom of piston 52 and base plate 55, the outlet 116 is positioned a small distance from base plate 55 so that a completely sealed safety cushion will remain below the piston 52.

In this invention the provision of pressure-relief valve 113 and 114 at each end of compression cylinder 54 prevents excess energy storage at each end of the piston stroke in chambers 111 and 112. Therefore, the operation of the engine is under constant cycle-by-cycle control.

Changes in the load of an engine will result in a change

in speed, unless the input to the engine is changed. For engines with a mechanically controlled piston stroke, this change in speed is usually not harmful and the engine can be brought back to the desired operating speed within a reasonable number of cycles by changing the input energy. However, if the load driven must be operated at a constant speed, regardless of load, complex control systems to vary the input energy are required. Even complex control systems cannot vary the input energy to match the load requirements on a cycle-by-cycle basis. If the load characteristics are such that a drastic change can occur during one cycle, a flywheel sufficient to store the energy not absorbed by the load or to deliver the additional energy required by the load without an appreciable change in speed until the control can compensate for the change must be provided.

With free-piston engines without the necessary flywheel effects, the change in load will effect the speed on the very cycle that the change in load occurs. Since even the most complex controls cannot vary the input energy to match the load changes on a cycle-by-cycle basis, existing free-piston engines are not suitable for driving loads that require constant speed and that vary radically during the time of one engine cycle.

Since the change in load will also vary the stroke on the very stroke that the change occurs, it follows that a drastic change in load during the time of one engine cycle will produce a drastic change in stroke. This change in stroke could be sufficient that the piston will impact the ends of the cylinder, either or both on the power or compression stroke in the event that the load is suddenly and drastically reduced; or that the stroke would be shortened sufficiently to cause the engine to stop should the load be drastically increased. This invention discloses a control system for a free-piston engine which maintains the load on the engine essentially constant, at the full-load value during each cycle, no matter how the useful load removed from the engine varies from idle to full load. By means of this control system, the operating frequency and the stroke will remain essentially constant for all loading conditions. With the frequency and stroke remaining essentially constant no matter how the useful load varies, the complex controls for varying the input energy are not required and the free-piston engine can be applied where sudden changes in the useful load will occur.

The operation of the control system of this invention with the relief valves 113 and 114 in the bounce chamber 111 and counterchamber 112 is shown by the energy programs shown in Figs. 13, 14, 15, 16, and 17. As shown in Fig. 13 the amount of energy quantitatively shown in bar C is that delivered to the piston on the power stroke. Fig. 13 represents a normal operating cycle of the engine. The upper portion F of bar C represents the amount of energy produced by fuel combustion. A middle portion H represents energy stored in the combustible mixture when compressed by the piston on the compression stroke. Sufficient energy is produced by the fuel combustion to accomplish work necessary on both the power and compression strokes and supply losses from friction, although the latter are not shown on the bar-diagrams. The lower portion D represents the amount of energy returned to the piston through the compressed air in counterchamber 112. The sum of F, H, and D represents the total potential energy transferred to the piston on the power stroke.

The energy on the power stroke is represented by the bar P as utilized, in work done by the engine represented by upper portion W, and compression of air in the bounce chamber for rebound represented by the lower portion G. A portion of the energy to be delivered to the work, represented by the middle portion U, is unused on the power stroke and is stored in the compressed air in the bounce chamber for delivery to the work on the compression stroke to follow. On the return stroke, repre-

sented by the bar R, the energy expended from the system is the amount stored in bounce chamber, and comprises the energy necessary to compress the fuel and air for combustion, as represented by the center portion H, the energy of compression D in the counterchamber 112 that is necessary for energy control and the energy applied to the work U. On the next power stroke, fuel energy in the amount F is added to the energy in the counterchamber 112 and the compression energy in the combustion chamber 53 so that the amount shown by bar C is again applied to the piston on the power stroke at the beginning of the next cycle.

During operation, if any of the operating characteristics change, the energy program shown in Fig. 13 will not be maintained. The case where only part of the energy intended for useful work on the power stroke is absorbed by the work article or load driven by the engine is shown by the energy program of Fig. 14.

Bar C₁ of Fig. 14 represents the potential energy available to the piston for the power stroke. The lower portion of bar C₁, designated D₁, is the energy available from the compressed air in the countrechamber, the middle portion H₁ is the energy stored in the compressed fuel and air mixture in the combustion chamber while the upper portion F₁ represents the energy added by fuel combustion.

On the power stroke the energy represented by bar C₁ is applied to the piston. If, on the power stroke, the load were partially removed from the piston rod of the engine so that the amount of energy W₁ of Fig. 14 would be delivered to the work, rather than the energy W of Fig. 13, the difference between W and W₁ would be delivered into the air in the bounce chamber. If all the energy delivered to the air in the bounce chamber were available for the compression stroke, an excessive rebound stroke would result on the next piston return. However, by means of the pressure-relief valve 114, the excess energy delivered to the bounce chamber on the power stroke is discharged to the atmosphere while that retained G₁ is used to rebound the piston on the next compression strike. The energy discharged from the bounce chamber on the power stroke is represented by the portion A₁. With only the proper amount of energy G₁ stored for the return stroke, the engine has a normal return stroke as depicted by the bar R₁.

The most severe condition for a reduction in the useful work absorbed on the power stroke would be when W₁ would not appear on Fig. 14. In this case, the bounce chamber would discharge the total amount of energy intended for useful work on the power stroke. The height of A₁ and W₁ in bar P₁ would be equal to W of Fig. 13. However, since the energy A₁ is discharged through valve 114, the normal amount of energy would be stored in the bounce chamber for returning the compression stroke and a normal compression stroke would occur.

The energy program of Fig. 15 will occur if all of the energy intended for the load on the compression stroke is not absorbed by the load. If the energy intended for use on the compression stroke were not dissipated from the counterchamber when the load did not absorb the energy, an abnormal amount of energy would be available for the next power stroke. Bars C₂ and P₂ show the normal energies available for the power stroke and absorbed on the power stroke respectively. The return stroke as represented by bar R₂ shows the control action by discharging energy through the pressure-relief valve 113 in the counterchamber 112. On bar R₂, the portion U₃ is the reduced amount of energy absorbed by the load on the compression stroke. The portion H₃ is the amount of energy delivered to compress the fuel-air mixture in the combustion chamber. The section H₃ represents slightly more energy than the portion H₂ on bar C₂ because the control acts at the end of the compression stroke and a slightly longer piston stroke is produced. The portions D₃ and A₃ represent the energies delivered

to the counterchamber. Of these two energies, A_3 is exhausted from the counterchamber while D_3 is retained for the next power stroke. The pop-off pressure of valve 113 and the volume of chamber 112 are so proportioned with respect to the combustion chamber that the reduction in the amount of energy retained in the counterchamber, as represented by the difference between D_2 and D_3 , is essentially equal to the difference between combustion chamber energies H_3 and H_2 . By this manner, the total energy available for the next power stroke is essentially the same as the energy as shown in Bar C_2 of Fig. 15. On the next power stroke the energy of fuel compression will be the same as H_3 and the counterchamber compression energy will be equivalent to D_3 . The engine will run balanced in this condition so long as the energy absorbed in work on the compression stroke U_3 remains the same.

The most severe condition for a reduction in the energy absorbed by the work on the upstroke would be when the work load is completely removed. The energy value U_3 would be zero and would not appear on Fig. 15. With this condition, the relief valve 113 would discharge the total amount of energy intended for work on the compression stroke. However, the total energy available for the expansion stroke would still be essentially the same because the reduction in the counterchamber energy available for the next power stroke, as represented by D_3 , would compensate for the work load and the increase in the energy of the compressed fuel-air mixture in the combustion chamber.

Fig. 16 shows the balanced-energy program for the control system operation for a reduced load on both the power and compression strokes. In the manner described above, the control system operates within the very cycle that the changes in load occur. With this control system, the actual load on the engine remains essentially constant at full-load value every cycle no matter how the load being driven by the engine varies from no load to idle conditions. The total energy available for the power stroke, C_4 , the energy stored in the bounce chamber G_4 , and the energy stored on the compression stroke H_5 plus D_5 have remained essentially constant at their respective levels no matter how the load driven by the engine has varied. On the power stroke P_4 , the excess energy A_4 is released to the atmosphere by relief valve 113. On the compression stroke R_4 , the excess energy A_5 is released to the atmosphere by relief valve 114.

Another application of the free-piston engine where control at both ends of the stroke is required is when the free-piston engine is used as an impact tool where the free-piston impacts against a resilient work article near or at the end of its expansion stroke. Fig. 17 shows the effect of valve 113 on counterchamber 112 to control for elastic rebound from the work article. On Fig. 17, the power stroke P_6 is normal in that W_6 , the energy intended for useful work, is delivered to the work article. However, the energy available for the compression stroke is high because of the elastic-rebound energy returned by the work article. Bar R_6 on Fig. 17 shows how the control system discharges the extra energy. The rebound energy is absorbed by compressing the fuel-air mixture in the combustion chamber and by the compression and discharge of air in the counterchamber. Because the control in the counterchamber acts at the end of the compression stroke, a slightly longer piston stroke is obtained. Therefore, the energy H_7 absorbed by the combustion chamber is slightly greater than the energy absorbed on a normal compression with negligible elastic rebound. The pop-off pressure of valve 113 and the volumes of counterchamber 112 are so proportioned to the combustion chamber compression energy that the energy of elastic rebound A_7 is discharged to the atmosphere while the increase in the energy required to compress the fuel-air mixture in the combustion chamber, as represented by the portion H_7 , is offset by a reduction in

energy retention in the counter chamber as represented by D_7 . By this manner, the energy available for the next power stroke is essentially the same no matter how great the elastic rebound becomes. This control operates on a cycle-by-cycle basis and allows the engine to run smoothly and continuously no matter how the impact load or elastic rebound varies.

The preceding description shows how a control system with compensation on both the power and compression strokes operates to allow the engine to operate a full-load no matter how the load on the power stroke or compression stroke varies or, in the case of the impact tool, how the energy delivered to or returned from the work varies.

Ejector cooling on free-piston engine

A significant feature of this free-piston-engine invention is the cooling method employed and the construction that is integral with the engine for this method.

As previously described, on the power stroke of the engine the upper surface of piston 52 passes exhaust ports 57 allowing the products of combustion to escape into the exhaust manifold 62. Because of the blow-down pressure of exhaust in a two-cycle engine of this type, the exhaust gases and products of combustion are expelled at high velocity through the exhaust ports 57 passing beneath ejector ports 72. Passage of the exhaust stream at high velocity beneath each ejector port 72 causes a reduction of pressure in the throat of the port 72, and consequently induces flow downward in ejector chambers 73. Downward air flow in ejector chambers 73 draws additional air from the atmosphere into the ejector chamber 73 through ejector inlet 76. Passage of the relatively cooler air downward through the chambers 73 removes heat from the fins 71 which conduct heat from the wall 61 of combustion cylinder 53.

In the ejector cooling apparatus shown, the ejector ports 72 and the exhaust manifold are constructed to have a progressively larger cross section along the path of outward flow of the gases to produce a nozzle affect, and increase the efficiency of the ejector ports in downwardly inducing air flow. The exhaust gas and cooling air mixture passes from the exhaust manifold 62 outward to the atmosphere through exhaust pipe 87.

By means of the ejector cooling arrangement of this invention the energy of the exhaust gases which are normally wasted are utilized to increase the cooling rate of the combustion cylinder of the engine and therefore to enhance the efficiency of the engine. In addition, the exhaust gases are cooled by mixing with the cooling air passing down through the ejector ports 72. This makes a cooler final exhaust temperature which is an advantage because there is less possibility that persons close to the engine will be harmed. In the use of a small engine, provided in a portable impact tool, this is particularly significant as the person operating the tool must be close to the engine.

The ejector cooling arrangement of this invention is particularly advantageous in combining with the free-piston engine because forced cooling is provided with a readily available source of energy; i.e., the kinetic energy of the exhaust gas. Conventional fans and blowers require a source of energy in the form of rotary motion, which is unavailable on the engine of this invention.

Free-piston engine compressor

The adaptability of the free-piston engine 50 as a compressor is an advantage and feature of this invention. Referring to Fig. 6, the lower output end of free-piston engine 50 is shown integrally constructed with a reciprocating compressor. In this compressor construction, the bounce chamber 112 is also used as the reciprocating compressor chamber.

While the fluid suitable for compression in the compressor under consideration could be any which has, a

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compressibility comparable to that of gas and air, for descriptive purposes it will be considered that the engine disclosed in Fig. 6 is an air compressor.

The engine base plate 149 is provided with a formed substructure housing 150. A recess 151 is formed in housing 150. Recess 151 receives a reed-type compressor intake valve 152 operatively opening and closing a compressor intake port 153. A cover 154 supports compressor intake valve 152 and is retained in position by suitable means, such as screws 155. A pressure-compensating compressor discharge valve 156 (most clearly shown in Fig. 11) is supported beneath the base plate 149 in communication with a compressor outlet 157 from bounce chamber 111.

Referring to Fig. 11, a pressure-compensating valve 156 is assembled in a valve housing 158 fastened to base plate 149 by suitable means, such as screws 159. Pressure compensating valve 156 is constructed with a longitudinal bore 160 terminating at one end in a portion of smaller diameter 161. A compensator inlet 162 is provided at one side of housing 158 in communication with a recess 163 formed in base plate 149 and bore 160. Recess 163 is formed as a chamber for the support of compressor outlet valve 164 which controls flow through compressor outlet 157. A compensator outlet 165 is provided in valve housing 158 in communication with bore 160. A compensator 166 in the form of a piston is disposed in the bore 160 and adapted to reciprocate therein, suitable seals 167 being provided between compensator 166 and bore 160 within the minimum limits of travel of the ends of the compensator 166. An annular groove 173 is disposed intermediate to the ends of compensator 166. Closure means, such as a cover 168, threadably engages one end of the bore 160 and is provided with a threaded aperture 169 in communication with bore 160 and an air storage tank, not shown. At the opposite end, housing 158 is provided with an aperture 170 in communication with bore 160 and the atmosphere. Portion 161 of reduced diameter guides resilient means 171, such as a compression spring. The shoulder 172 formed at the meeting of the bore 160 with the minor diameter portion 161 serves as a stop for the compensator 166.

Referring to Fig. 6, when free-piston engine 50 is constructed as an air compressor, the major diameter portion 90 is provided with a bore 175 having an annular recess 176. An axially disposed starting rod 177 is positioned for reciprocation in a bushing 178 in the base plate 149. Base plate 149 is counterbored on its longitudinal axis to provide an annular recess 179 which receives a lug 180 that radially projects from the side of the starting rod 177 at the upper end. A longitudinal groove 181 connects the bottom surface of piston 90 with recess 176 of a width and depth necessary to conveniently pass lug 180. As seen in Fig. 5, the remainder of the starting mechanism, which is in many respects the same as that for the reciprocating tool shown in Fig. 1, is supported from the base plate 149.

In addition to the slot 97a, a second slot 99 is provided in starting rod 177 disposed perpendicular to the first slot 97a. The trunnion 110a is constructed with a slot 109 for longitudinal movement of a pivot 108a. A lever 105a having a handle 107a at one end and tip 106a at the opposite end is supported on pivot 108a.

Operation

As previously described for the operation of free-piston engine 50 as a reciprocating tool, it is necessary for piston 52 to be drawn to its lower position, shown in Fig. 6, preparatory to engine starting. To accomplish this, the starting rod 177 is raised into bore 175 by manipulation of handle 107a. In order to align the lug 180 for passage through slot 181, starting lever 177 is rotated by means of key-bore 101a ninety degrees. This aligns extractor slot 99 with lever 105a and permits the entrance of tip

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106a therein. With pivot 108a at the lower position in slot 109, starting rod 177 may be controlled and inserted in bore 175. With starting rod 177 positioned within bore 175, as shown in Fig. 6, tip 106a is removed from slot 99, permitting rotation of starting lever 177 ninety degrees. This operation of rotation moves lug 180 circumferentially in recess 176, securing the starting rod 177. With tip 106a engaged in slot 97, handle 107 may be manipulated to draw the piston down to position ready for the first upward compression stroke. With piston 52 at its lower position, starting rod 177 is rotated until lug 180 aligns with slot 181 and tip 106a of lever 105a is positioned in groove 99.

To start the engine, handle 107a is pushed briskly downward, forcing piston 52 upward on the first compression stroke. Handle 107a is pushed downward in rotation about pivot 108a through an angle great enough for tip 106a to pass out of groove 99a, so that lever 105a is free of starting rod 177 on the first power stroke. On the immediately following first power stroke, the upper end of starting rod 177 is thrown into counterbore 179 and is restrained from further downward movement by lug 180.

Once engine 50 is running, air is drawn into bounce chamber 111 through compressor intake port 153, past compressor intake valve 152, on the compression or up stroke of piston 52. On the power or down stroke, intake valve 152 closes and air is compressed in bounce chamber 111 until a pressure is obtained that will open valve 164. The continued downward movement of piston 52 forces air through pressure-compensating valve 156 to a storage tank or other use (not shown). At the end of the power stroke sufficient energy is available in the compressed air in bounce chamber 111 to rebound the piston 52 on the compression stroke of the engine cycle.

In the beginning when the storage tank is at atmospheric pressure, a connection from the tank to aperture 169 allows atmospheric tank pressure to press against one end of compensator 166. At the other end, compensator 166 is urged by atmospheric pressure and by spring 171. The force of spring 171 makes the balance of forces to the right greater than to the left (as seen in Fig. 11), and compensator 166 is forced to the position shown.

In its right-hand position shown, groove 173 of compensator 166 is aligned to provide only a small opening at inlet 162 and outlet 165. The area of the opening is established so that the pressure rise in chamber 111 exceeds the rate of pressure fall by reason of flow to the tank through outlet 165. On each down stroke a small amount of air is passed to the tank and at the same time the pressure rises to the proper bounce pressure. At any time during the pressure build-up in the tank, if the pressure in bounce chamber 111 exceeds the predetermined setting of pressure-relief valve 114, air will be vented to the atmosphere.

Continued operation of the engine will increase tank pressure to the point at which the pressure on the end of compensator 166 at aperture 169 will be greater than the force of spring 171 in its extended position. At this time, compensator 166 will move to the left, enlarging the opening at the ends of groove 173. At the time that compensator 166 begins to move to the left, valve 164 will not open until bounce chamber pressure 111 exceeds the pressure in the tank, groove 173, and recess 163.

When the predetermined maximum, tank pressure is reached, a relief valve on the tank, or relief valve 114 may be set to open, allowing the engine to run, and discharge to the atmosphere until such time as tank pressure falls. In the event that there should be a valve 164 failure and the production of more than the required bounce energy, the valve 115 will operate to discharge the excess and control the engine.

Another type of pressure-compensator valve that may be used in the engine-compressor combination is shown

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in Fig. 12. Compensator valve 200 comprises a housing 201, compensator 202, and resilient means 203, such as a compression spring. Housing 201 is formed with an internal chamber 204 that is provided with an opening 205 having a boss 206. Boss 206 is adapted to receive a conduit which is in communication with an air storage tank (not shown). Chamber 204 is divided into an upper spring compartment 208 and a lower cylinder compartment 209. Compartment 208 and compartment 209 are separated by a web-compensator guide 210 which also serves as a base for spring 203. Compensator guide 210 is positioned against a shoulder 211 and held in place by cylinder shell 212. Shell 212 is provided, for a portion of its length with a cylindrical bore 213 which is adapted to receive a piston 214 at one end of compensator 202. The opposite end of compensator 202 is provided with a frusto-conical plug 215 that is adapted to contact a mating valve seat 216 of compressor outlet 157. The internal area of piston 214 is made equal to the internal area of the plug 215.

In operation, pressure compensator valve 200 operates to admit air from bounce chamber 111 to the tank through opening 205. On the power stroke of piston 52, plug 215 and compensator 202 are forced downward when the pressure in bounce chamber 111 produces a force on plug 215 in excess of the force exerted by spring 203. Since the internal area of piston 214 is equal to the internal area of the plug 215, there is no effect on compensator 202 from the force exerted by tank pressure in the compensator valve 200. Therefore, on each downward stroke of piston 52, compensator valve 200 opens and air is forced to the tank as soon as the pressure in bounce chamber 111 exceeds the spring 203 force. The force of spring 203 is established so that compensator valve 200 opens as soon as the proper rebound pressure is attained in the bounce chamber 111.

Compensator valve 200 gives maximum output from a free piston engine compressor by allowing maximum discharge volume irrespective of the tank or discharge pressure. The construction which provides for cancellation of the discharge-pressure-effect in the valve, gives this advantage.

Each of compensator valves 156 and 200 provide for an important function in the operation of a free-piston engine as an air compressor with pneumatic rebound.

Each valve provides that the bounce pressure shall be constant for stable operation of the engine, and that the increase in tank pressure will not have sufficient effect to prevent the timely opening of the valve and cause a different bounce pressure in the bounce chamber on successive cycles.

Without such a compensation in the combination of a free-piston engine having pneumatic rebound with an air compressor, stable operating conditions would not be maintained.

Free piston engine impact tool

The free piston of free-piston engine 50 is readily adaptable as the driving end for an impact tool. Referring to Fig. 4, the lower output end of a free-piston engine 50 is shown integrally constructed with an impact tool.

In this construction, engine frame 51 is fastened to a base plate 300, which forms in association with piston 52, the bounce chamber 111. Base 300 is constructed with a downwardly projecting cylindrical tool holder housing 301. A tool holder 302 and a retainer 303 support and retain a tool 304 within the tool holder housing 301.

Tool 304 is provided with a flange 311 which controls reciprocation by means of its operation in a recess 312 of retainer 303. The tool 304 is positioned contiguous to and below an anvil 305 comprising a striker portion 306, a flange portion 307 of larger diameter, and a hammer portion 308. Flange portion 307 is constructed to

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control the reciprocation of anvil 305 within the confines of an annular recess 309 which is formed in base 300. Suitable sealing means 310 is provided between the anvil and base 300 to seal chamber 111 from the atmosphere.

Starting apparatus is provided, which is constructed with a starting handle 107b, and which is operated in the same manner as that disclosed in Figs. 5 and 6 for the free-piston engine compressor, with the exception that the axis of starting rod 177b is offset from the longitudinal axis of the engine 50.

In the operation of the impact tool engine, starting is obtained by manipulation of handle 107b in cooperation with starting rod 177b to engage lug 180b in recess 176b and to draw the piston down to the bottom of the stroke as shown. At this time starting rod 177b is rotated to free lug 180b from the recess 176b and handle 107b is manipulated to throw piston 52 upward on the first compression stroke. Operation commences and continues consecutively without further attention to the starting mechanism.

Each time the piston 52 reaches the lower position (shown in Fig. 4) the lower side strikes hammer 306 of anvil 305 delivering impact energy to the tool 304. This is transmitted to a work article, such as a piece of pavement to be broken.

When the engine and tool is lifted away from the work article, tool 304 and anvil 305 drop by action of gravity and pressure in chamber 111 to the lowest position in recesses 312 and 309, respectively. This lowers the top of anvil 305 to a position near, or at the level of, base 300. Piston 52 is stopped in its downward travel by compression in bounce chamber 111 before it makes contact with anvil 305. Under these circumstances the engine runs steadily and freely without impact between the piston and the anvil or tool and the excess energy is wasted through pressure relief valve 114 as previously described.

In the event the work upon which tool 304 impacts is resilient, energy is returned to piston for the upstroke. This energy is an excess and is wasted through pressure relief valve 113 allowing the engine to run steadily, as previously described.

Ignition generator

In the operation of free-piston engine 50, since there is no flywheel effect to keep the piston 52 reciprocating in the event that there is a combustion failure, i.e., misfire for one or two strokes, it is essential that the combustion system be reliable and closely controlled. Critical elements in the combustion cycle are the provision of an adequate ignition potential and the proper coordination of the timing of this potential with fuel and pressure conditions in the combustion cylinder 53.

A piezoelectric generator is provided in this invention, which is conceived and constructed to provide these necessary elements.

Referring to Fig. 7, a generator, designated generally as 135, is constructed in a housing 220 that is attached to the frame 51 by suitable means (not shown). Housing 220 is formed with an open chamber 221 having at one end a socket 222 and at the other end an aperture 223. The aperture 223 communicates with a bore 224. A hammer 225 is constructed to reciprocate in bore 224, being guided thereby. Hammer 225 is provided with an integral projecting generator rod 136 which is constructed to reciprocate in cam follower bore 60 of frame 51.

Chamber 221 and bore 224 are separated by an annular flange 226 which is provided at opposite sides with annular grooves 227 and 228, respectively, and which support at the central aperture 223 thereof, a bushing or guide 229.

A plurality of piezoelectric elements 231 and 232 are disposed within chamber 221 and are assembled with an end of common polarity to a terminal 233. Element 231 is supported at the end of opposite polarity in socket 222.

On the other side of the terminal 233 element 232 is fitted at the end of opposite polarity into an anvil member 234. Anvil 234 is provided with a projecting striker pin 241, which is disposed in bushing 229 and adapted to reciprocate therein. Resilient means, such as a compression spring 235, is disposed between anvil 234 and flange 226 to assist in supporting anvil 234 and the elements 231 and 232. Another resilient means, such as a compression spring 236, is provided between flange 226 and the end of hammer 225 to urge hammer 225 toward piston 52, and to keep follower 138 in contact with the bottom of groove 92. Terminal 233 is electrically connected at one end, by a wire lead 237, to a pole of switch 134. The other pole of switch 134 is connected by a lead 238 to the ignitor 65, as shown in Fig. 1.

Generator 135 is provided with a cover 239 which is held in place by suitable means such as screws 240.

In the operation of the piezoelectric generator, upon each power or down stroke of piston 52, cam follower 138 drops into the deeper portion of groove 92 urged by spring 236 which presses against hammer 225. With switch 134 turned on to connect lead 237 with lead 238, upward movement of piston 52 forces generator rod 136 radially outward when cam follower 138 reaches the slope in groove 92. The speed of piston 52 is such that when follower 138 strikes the slope in groove 92, the follower 138, generator rod 136, and hammer 225 are projected radially outward beyond the position shown in Fig. 7. Their travel is sufficient to strike and impact striker pin 241 and anvil 234. The force of impact upon anvil 234 momentarily subjects elements 231 and 232 to high compressive stress, thereby generating an electrical potential between housing 220 (frame 51, etc.) and lead 238.

After impact, spring 236 moves hammer 225 with generator rod 136 and follower 138 radially inward to the position shown in Fig. 7. On the next downward stroke of piston 52 the cam follower 138 again drops into the deeper portion of groove 92. The generator cycle is repeated as above described once for each reciprocation of piston 52.

Among the advantages and features of generator 135 over similar units of the past is the single polarity construction. In connection with a free-piston engine, generator 135 provides the notable advantage of precise timing of ignition electrical impulses which is so necessary in operation of engines of this class.

In the generator 135 construction shown, the necessity for elaborate precautions to insure electrical insulation between the two sides of the line has been removed. With elements 231 and 232 positioned in contact with terminal 233 at their ends of common polarity and supporting terminal 233 there between, there is no need for electrical insulation at either end of either element. There is therefore a notable advantage in manufacture of parts and assembly of units in the generator construction process. In addition, reliable trouble-free operation is provided.

The cam and follower operation of the generator 135 directly from the piston not only provides precise ignition timing but also provides for the utilization of a portion of the engine output that is directly for auxiliary functions. Generator 135 produces an electrical potential as a direct result of reciprocating motion. This is particularly advantageous when used in conjunction with the free-piston engine 50 because reciprocating motion is the only type of motion provided by this engine. A rotary generator would require a complicated means of deriving rotary motion from the action of the free piston.

A feature of the generator 135 is its compactness in comparison with conventional ignition generators for internal combustion engines. This is a particular advantage when the engine is embodied in a portable hand

tool as it provides increased ease of handling from both a maneuverability and a weight standpoint.

Another embodiment of a piezoelectric generator forming a part of the free-piston engine 50 of this invention is shown in Fig. 18. The generator 324 of this embodiment comprises a housing 325 constructed in two parts, a generator frame member 326 and a pre-stress adjustment member 327. Generator frame member 326 is fastened to engine frame 55 by suitable means such as screws, not shown, and includes a hollow inner chamber 328. The actuator rod 136 is disposed at one side of chamber 328 having an inwardly projecting end 329.

A stress rod 330 projects into chamber 328 at the opposite side and is disposed and guided for reciprocal movement in housing 325 coaxially with the longitudinal axis of actuator rod 136. At the opposite end stress rod 330 is provided with a shoulder 331 which is adapted to receive and center resilient means 332, such as a compression spring. Compression spring 332 is positioned on the end of an adjustment screw 333, which is threadably engaged in housing member 327. Pre-stress adjustment member 327 is fastened to generator housing 326 by suitable means, such as screws 334, through flanges 335.

Compressed between opposite sides of housing 326 are a column 336, a fulcrum cap 337, a first piezoelectric element 338, a terminal plate 339, a second piezoelectric element 340, a bearing cap 341, and a pivot screw 342.

Fulcrum cap 337 is adapted at one side to receive one pole of the first element 338 and at the opposite side to receive in a rockable knife edge bearing fit one end of column 336. Fulcrum cap 337 is rounded to each end and bears against the end surface of actuator rod 136 and the end surface of stress rod 330.

Column 336 is provided at each end with knife-edged bearing supports to permit slight pivotal movement with respect to its surface of engagement with the frame 326 and its surface of engagement with the fulcrum cap 337.

Terminal 339 is compressed between similar poles of the first element 338 and the second element 340, respectively, and is provided with a lead 343 for connection to ignitor 65. The opposite end of second element 340 is supported by bearing cap 341. At its other side, bearing cap 341 impinges on the knife edge of the upper segment on pivot screw 342. The lower segment of pivot screw 342 is threadably engaged in housing 326.

The length of column 336, and the stacked length of fulcrum cap 337, elements 338 and 340, plate 339, and bearing cap 341 are established greater than the distance between the opposite sides of frame member 326. In assembly, the longitudinal axis of column 336 is inclined at an angle α with a perpendicular to the axis of stress rod 330. The longitudinal axis of the stacked members at the opposite side is also disposed at an angle α with a perpendicular to the axis of stress rod 330. In assembled position, as shown in Fig. 18, the force of spring 332 produces compression in column 336 and elements 338 and 340.

Operation of the generator 324 is as follows: As the piston moves upward, cam follower 138 in groove 92 strikes the sloped portion thereof and is projected radially outward. Outward movement of actuator rod 136 moves fulcrum cap 337 to the left along with stress rod 330 against the urging of compression spring 332. Movement of fulcrum cap 337 to the left increases the distance between the seat for column 336 in housing 326 and the seat for the opposite end of column 336 in fulcrum cap 337. The increase in the distance between these seats decreases the amount of compression in column 336 relieving the compressive stress on first and second piezoelectric elements 338 and 340. The reduction in the compressive stress in first and second piezoelectric elements 338 and 340, respectively, at a rapid rate, causes these elements to generate an electrical potential between

opposite poles, and this potential is transmitted through lead 343 to the ignitor 71 of engine 50.

Adjustment in the compressive stress in the piezoelectric crystals 338 and 340 may be made by turning adjustment screw 333 and pivot screw 342. Wear in the pivots may be compensated for in the same way.

The piezoelectric generators 135 and 324 provide a common advantage in construction in that a plurality of piezoelectric elements are combined with their common poles electrically connected to a common terminal to greatly reduce the necessity for electrical insulation in a device of this class. Also, the same compressive force or stress on the elements will produce twice the output energy of one element because the deflection for the two elements is twice that for one element. In addition, each of these generator embodiments provides a means of utilizing the reciprocal motion of the free piston directly, to generate the ignition potential necessary for combustion. It would be a serious disadvantage and complication if means were not provided with the engine 50 to generate the necessary ignition potential directly, as the reciprocal motion of the piston would have to be converted to rotary motion for use in a conventional electric generator.

The compactness and light weight of the generators 135 and 324 facilitate the portability and maneuverability of free piston engine 50, and this is an important advantage when the engine is provided as either an impact tool, a saw, a pump, a compressor, a reciprocating electric generator or any other portable application.

Free piston engine fuel injector

Fuel injector 68 has been provided in combination with engine 50 to assure fuel admission which is precisely timed and which is directly initiated and sustained by the engine 50, as shown in Fig. 8.

As has been previously explained the continuous reliable operation of a free-piston engine under varying load condition requires precise control of combustion conditions. Proper timing, and fuel pressures, at the time of fuel injection are important factors in this combustion control so that the proper fuel quantity and dispersment are obtained.

Fuel injector 68 comprises a body portion 250 and a closure portion 251 assembled with a gasket 252 impressed there between and held in place by suitable means such as screws 253 positioned in counterbores 254. Body portion 250 is provided with a threaded insert portion 67 which is engaged in the head end 64 of combustion cylinder 53. Insert 67 is constructed with an end surface 255 having a fuel nozzle 66 opening therein.

Body portion 250 of fuel injector 68 is provided with a laterally disposed bore 256 which terminates at one end in a wall with an aperture 257. At the opposite end bore 256 is counterbored and threaded, and receives an adjustable retainer screw 258. A plunger 259 is disposed within the bore 256 and is constructed to reciprocate therein in one direction when actuated by pressure of rocker arm 142 upon plunger stem 143. Operation of the plunger 259 in the opposite direction takes place under the urging of resilient means, such as compression spring 261 that engages plunger 259 at one end and retainer screw 258 at the opposite end.

An injector chamber 262 in the form of a counterbore having an upstanding passage-enclosing pedestal 263 is provided in the upper surface of the body portion 250. An injection conduit 264 connects bore 256 with fuel nozzle 66. At the opposite side, a chamber inlet passage 283 connects bore 256 with chamber 262.

Cover portion 251 is provided with a pressure chamber 265 in the form of a counterbore that is constructed to register with injection chamber 262. Recesses 266 are provided at the edges of chambers 262 and 265 to receive in assembly a diaphragm unit 267.

Diaphragm unit 267 comprises a centrally positioned flexible diaphragm member 268 having fastened thereto at each side annular washers 269 and centrally positioned pressure plates 270.

A diaphragm stop screw 271 is threadedly engaged in cover portion 251 in position to contract upper pressure plate 270 of diaphragm unit 267. The position of contract is adjustable by means of rotation of the diaphragm stop 271 and a particular setting may be held by means of a lock nut 272. Resilient means such as an injection chamber spring 273 is positioned in the injection chamber 262 over pedestal 263. Spring 273 engages lower pressure plate 270 at one end and the base of the injection chamber 262 at the opposite end.

An inlet conduit 274 communicates with a fuel line 275 through a conventional tube connection 276. Inlet conduit 274 communicates with pressure chamber 265 in one branch 277 and with plunger bypass conduit 278 in the other branch. Plunger bypass conduit 278 terminates in port 280 at the lower side of bore 256. A passage 281 provides communication between a position opposite port 280 and chamber inlet passage 283.

Plunger 259 is provided with an annular groove 282 in the outer surface thereof which is positioned to provide communication between port 280 and passage 281 when plunger 259 is in the extreme right hand position, as shown in Fig. 8.

In the operation of the fuel injector 68, fuel is supplied under pressure through fuel line 275. Fuel line 275 is connected to a fuel tank, designated generally as 290, and diagrammatically shown in Fig. 20. Fuel tank 290 comprises an upper accumulator portion 291 and a lower storage portion 292, which are hermetically sealed by a diaphragm 293. Accumulator section 291 is provided with a hand pump 294 and is connected to accumulator line 128 from chamber 111 of engine 50. Storage portion 291 is provided with a fill spout 295 that is equipped with a sealable cap 296.

In the normal operation of the engine, air in the accumulator portion 291 is maintained at an elevated pressure by reason of the communication established with bounce chamber 111 through line 128 and check valve 130. The elevated pressure in chamber 291 deflects diaphragm 293 downward putting the fuel under pressure. Pressurized fuel is transferred from tank 290 to fuel injector 68 through fuel line 275.

Fuel enters the fuel injector 68 through inlet conduit 294, passing to pressure chamber 265 through passage 277 and to injection chamber 262 through bypass conduit 278, groove 282, passage 281, and the upper portion of injection conduit 266. With the pressure equal on both sides of the diaphragm, i.e., at the same fuel injection pressure, the force of spring 273 keeps diaphragm unit 267 in its upper portion against diaphragm stop 281.

On the up stroke of piston 52, cam follower 140 follows the bottom of cam groove 93 forcing actuator rod 139 radially outward in bore 59 against the urging of spring 145. Outward movement of actuator rod 139 operates rocker arm 142 to force plunger stem 143 to the left, as shown in Fig. 8. Plunger 259 is moved to the left by plunger stem 143 until groove 282 aligns with injection conduit 264. The movement of groove 282 away from port 280 operates as a valve closure in inlet fuel conduit 274 at port 280; and injection chamber 262 is therefore sealed off from inlet fuel and inlet fuel pressure. With injection conduit 264 open from injection chamber 262 to nozzle 66 and with fuel in the pressure chamber 265 at a higher pressure than the pressure in the combustion cylinder, the force of spring 273 is overcome and diaphragm unit 262 moves downward forcing fuel from nozzle 66 into the combustion chamber.

The amount of fuel which is injected by the operation of the diaphragm depends upon the displacement or stroke of the diaphragm, and this is controlled by means of adjustment in the position of diaphragm stop 271.

When piston 52 returns on the downstroke actuator rod spring 145 and plunger spring 261 return the plunger 259, rocker arm 142, and actuator rod 139 to the starting position.

In normal operation, the injection cycle is repeated once for each operating cycle of the engine, continuously, and directly timed by the actuation of piston 52.

In order to start the engine it is necessary that the fuel be pressurized for the first injection. When operation commences pressure in chamber 111 will normally be atmospheric, and therefore, means such as a hand pump 294 is provided to pressurize the fuel injection system before the engine is started. When starting, it also may be necessary to operate plunger 259 once manually by means of manipulation of rocker arm 142 to assure that the injection chamber 262 is completely filled with fuel under pressure.

The diaphragm operated fuel injector 68 of this invention is actuated directly by piston 52 and utilizes reciprocal motion for its operation. In the free-piston engine 50, the motion delivered is reciprocating, and therefore, the fuel injector 68 combines with the free-piston engine 50 to provide continuous reliable operation and a closely controlled combustion cycle.

In addition, the compactness of the fuel injector 68 is an advantage in that it increases the portability of the engine with which it is combined.

Another form of a fuel injector that may be combined with the free-piston engine 50 of this invention is designated generally as 350 and shown in Figs. 9 and 10. In general, fuel injector 350 comprises a body 351, a cover 352, a plunger 353, and resilient means 354, such as a compression spring.

Body 351 is constructed with a fuel-blast chamber 355, a pressure equalizer chamber 356, and a plunger chamber or bore 357. The blast chamber 355 is provided with a first conduit 358 for communication between the chamber 355 and the bore 357. Blast chamber 355 is also provided with an equalizer conduit 359 at a position removed from conduit 358. The equalizer conduit 359 provides communication between chamber 355 and bore 357. Chamber 356 is provided with a passage 360 between the chamber 356 and an annular groove 361 in the wall of bore 357. Both chambers 355 and 356 are closed by cover 352 which is held in place by suitable means, such as screws 362. A gasket 363 may be provided to assure that the chambers 355 and 356 are sealed from each other and from the atmosphere.

The plunger 353 is constructed to reciprocate between the extreme left-hand position shown in Fig. 9 and the extreme right-hand position shown in Fig. 10. At one end, plunger 353 is provided with a stem 364 in operative contact with rocker arm 142 of engine 50. At the opposite end spring 354 is disposed between the end of plunger 353 and the end of bore 357. An aperture 365 is provided in the end of bore 357 establishing communication between the atmosphere and the end of plunger 353. Intermediate the ends of the body portion of plunger 353 are provided a plurality of spaced passages 366 and 367.

Communication is provided between a fuel nozzle and bore 357 by a fuel injection conduit 370.

A fuel inlet conduit 371 is provided from a fuel supply tube 372, through connection fitting 373, to a recess 374 at the bottom side of bore 357. Fuel inlet conduit 371 is constructed to bypass blast chamber 355 and is sealed therefrom. An air inlet conduit 375 is provided in body portion 351 and cover 352 connected to air supply tube 376 by means of fitting 377. Air supply conduit 375 connects with bore 357 through a recess 378 in the side thereof and is constructed to bypass blast chamber 355, sealed therefrom.

In the free-piston engine 50 and fuel injector 350 combination, air supply tube 376 is connected to an accumulator such as chamber 291 by a conventional tubing con-

nection 377, and fuel supply tube 372 is connected to a fuel tank 290, such as the tank shown in Fig. 20.

In operation of the fuel injector 350, spring 354 forces stem 364 and plunger 353 to the extreme right-hand position, shown in Fig. 10, on the down stroke of the engine. When piston 52 comes up on the compression stroke rocker arm 142 forces plunger 353 to the extreme left-hand position, shown in Fig. 9, through actuator rod 139 and cam follower 140 in cam groove 93.

When plunger 353 reaches the right-hand position, pressurized fuel in inlet conduit 371, and recess 374 moves into fuel passage 366. Simultaneously, pressurized air in air inlet conduit 375 and recess 378, passes through passage 367 and conduit 358, and enters blast chamber 355. The air in blast chamber 355 is brought to a first pressure P_1 equal to that of the air in inlet tube 376. Equalizer chamber 356 is in communication with the atmosphere through conduit 360, groove 361, bore 357, and aperture 365.

As piston 52 moves upward on the compression stroke, plunger 353 moves to the left bringing passage 366 momentarily into a position of registry with conduit 358 and fuel injection conduit 370. At this momentary position, air in chamber 355 at pressure P_1 forces the fuel carried in passage 366 downward through fuel injection passage 370 and out through the nozzle by blast effect. This blast effect lowers the pressure in the blast chamber 355.

Continued travel to the left brings plunger 353 to the position shown in Fig. 9. In this position, passage 367 is aligned with conduit 359 and groove 361. This brings blast chamber 355 into communication with equalizer chamber 356, allowing pressure to decrease in chamber 355 and to increase in chamber 356 until they are equal. The volumes of chambers 355 and 356 are predetermined to be that which, in conjunction with the inlet air pressure and blast effect, will establish a pressure P_2 in chamber 355 substantially equal to combustion cylinder 53 pressure at the time fuel passage 366 registers with conduit 358 and conduit 370 on the down or power stroke.

When the piston reverses and starts down, plunger 353 is urged and moves to the right by spring 354. At the time fuel passage 366 momentarily registers with conduit 358 and conduit 370, there is no air flow through passage 366 because of equal pressure conditions at both ends. This prevents the very bad problem of second injection which would occur if the pressure in chamber 355 were higher than the pressure in the combustion cylinder 53 on the down stroke of piston 52. When plunger 353 reaches its extreme right-hand position again, as shown in Fig. 10, the injection cycle is complete and ready for the next compression stroke. The injection cycle above-described continues repeatedly once for each cycle of engine 50.

Fuel injector 350 combines with engine 50 to provide a free-piston engine in which fuel injection is positive and precisely timed without auxiliary equipment, such as an air compressor or rotary timing cam shafts. The fuel injector 350 is operated directly from the reciprocating motion of the engine 50 and therefore utilizes the reciprocating motion of piston 52 without transformation to rotary motion. A rotary motion mechanism for driving auxiliaries would increase the size, cost, weight, and friction on engine 50.

Since fuel injector 350, utilizes the reciprocal motion of the engine 50, the engine is more compact and is quieter. Compactness reduces weight and increases the portability of the engine, as well as increasing the horsepower per pound of engine weight. In addition, the useful power of the engine is increased as there is less loss in friction and power for the fuel injection auxiliary.

Another form of fuel injector, that is operable directly through the reciprocating motion of piston 52 in a free-piston engine 50, is shown in Fig. 19. Fuel injector

380 in general comprises a body portion 381, a cover 382, a plunger 384, a needle valve 385, and an orifice tube 386. Body portion 381 and cover 382 are formed to be joined into a single unit at mating surfaces 387. A chamber 388 is formed by the body 381 and cover 382 each being provided with a semicylindrical cavity therein. A gasket 389 is disposed between the surfaces 387, and is adapted to be compressed when cover 382 is fastened tight by suitable means, such as screws 390.

Body 381 is provided with a lateral plunger bore 391 which connects at one end with a counterbore 392 of larger diameter. A compressed air supply tube 393 is connected to an air inlet conduit 394 by means of a suitable fitting 395. Air conduit 394 intersects bore 391 at one side in an aperture 396. At the opposite side of bore 391, a chamber inlet conduit 397 provides communication between bore 391 and chamber 388. At a position removed from the entrance of chamber conduit 397, an outlet passage 398 provides communication between chamber 388 and bore 391. Outlet passage 398 continues from a position at the opposite side of bore 391 to a fuel nozzle 399.

A fuel inlet tube 400 is connected to a fuel inlet conduit 401 by means of a suitable fitting 402. Fuel inlet conduit bypasses chamber 388 and is constructed to communicate with the central bore of orifice tube 386 at one end 403.

Needle valve 385 is threadedly engaged in body portion 381 in axial alignment with orifice tube 386 with the point of the needle 385 in the orifice end of tube 386.

Plunger 384 is provided with a plurality of annular grooved portions 404 and 405 which are spaced from one another a distance greater than the distance between inlet conduit 397 and the outlet conduit 398. At one end, plunger 384 is provided with a stem portion 406 of lesser diameter which is adapted to receive a collar 407 retained in position against a shoulder 408 by suitable means such as a cotter pin 409. Resilient means, such as a spring 410, is disposed between the bottom of counterbore 392 and collar 407. A cap 411 is positioned on the stem 406 and retained in position by rocker arm 142.

The fuel injector 380 is connected to frame 55 of engine 50 by means of a threaded insert portion 412.

As in the previous form of fuel injector 350, compressed air inlet tube 393 is connected to an accumulator, such as chamber 291, of fuel tank 290, shown in Fig. 20. Fuel inlet tube 400 is connected to the fuel tank 290.

Rocker arm 142 is actuated to the left (in Fig. 19) on the up stroke and to the right on the down stroke of piston 52.

In Fig. 19, plunger 384 is shown at its extreme right-hand position of travel which is the position corresponding with the maximum downward travel of piston 52 in engine 50. Groove 404 aligns with conduits 396 and 397 and air is forced by pressure across the end of orifice tube 386. A quantity of fuel from fuel inlet conduit 401 is carried into chamber 388. The amount of fuel carried may be adjusted by means of the threaded adjustment of needle valve 385. The fuel and air mixture swirls in chamber 388 at a pressure P_1 substantially equivalent to that of the inlet compressed air.

On the upward stroke of piston 52, rocker arm 142 forces plunger 384 to the left bringing groove 405 into alignment with outlet 398 and moving groove 404 out of alignment with conduits 396 and 397. When piston 52 arrives at its position of maximum upward travel, groove 405 is properly registered and the fuel in chamber 388 is injected into combustion chamber 53 through fuel nozzle 399 by reason of the higher pressure P_1 in chamber 388 than that in combustion cylinder 53.

The movement of plunger 384 to the left compresses spring 410. This compression of spring 410 returns

plunger 384 to the position shown, as rocker arm 142 moves to the right on the down stroke of piston 52.

In another method of operation of fuel injector 380, the position of groove 405 is established with respect to the travel of plunger 384 so that on the up stroke of piston 52 groove 405 passes to the left beyond registry with conduit 398. This provides for an earlier fuel injection on the up stroke of piston 52. In this method of operation, the size of chamber 388 is determined in conjunction with the fuel injection pressure and the cylinder compression pressure so that on the return movement of plunger 384 the pressure in chamber 388 and combustion cylinder 53 will be substantially equal. Therefore, no second injection will occur when groove 405 passes registry with conduit 398.

When piston 52 reaches its lower position, plunger 384 returns to its extreme right-hand position, shown in Fig. 19, and the injection cycle is complete for one cycle of engine 50. The injection cycle repeats consecutively once for each complete cycle of engine 50 and under direct and precise timing control from the operation of piston 52 and engine 50. Fuel injector 380 combines with engine 50 utilizing the reciprocating motion generated by the engine directly and a rotary motion mechanism is not required. A rotary motion mechanism for driving auxiliaries would increase cost, weight, size, and friction.

Since fuel injector 380 utilizes the reciprocating motion of the engine 50, the engine is more compact and is quieter. Compactness reduces weight and increases the portability of the engine, as well as increasing the horsepower per pound of engine weight. In addition, the useful power of the engine is increased as there is less loss in friction and power for the fuel injection auxiliary.

Inertia system

An operational characteristic of a conventional free-piston engine that limits the type of applications on which it may be used, is the lack of inertia to provide sufficient flywheel effect to carry the engine through misfires or sudden momentary increases in load above the full-load capacity of the engine. By flywheel effect is meant the carry-over of energy from one cycle to the next. Some free-piston engines have enough flywheel effect to allow sustained operation with one misfire, but these engines will usually stall if two consecutive misfires occur. As occasionally occurs in an internal-combustion engine operation, momentary malfunction of fuel or injection system may cause misfires or poor combustion for three or four cycles. The conventional crankshaft engine with a flywheel and rotating parts has sufficient energy stored in these parts to carry the engine over these misfires or weak combustion cycles. Also, in some instances, the load may increase momentarily beyond the full load capacity of the engine, which may be overcome by the flywheel effect of rotating parts in the conventional engine.

Whatever flywheel effect that may be available in the operation of free-piston engines is produced by the energy storage in resilient bodies on each cycle and the return of this energy to the piston on or for the next stroke. In the free-piston engine 50 of this invention, the resilient bodies are the air masses trapped in the bounce and counterchambers, and the fuel air mixture in the combustion chamber.

To provide an inertia system for free-piston engines which will carry the engine through several cycles, the inertia apparatus 400, shown in Fig. 21, and its associated method of operation are disclosed. In the apparatus 400, a cylinder 401 is provided having closure means at each end. At one end means for connection to a load, such as a bushing and support 402, is fastened to or formed as a part of cylinder 401. A piston 403 is disposed within cylinder 401 and is adapted to reciprocate therein. Piston 403 partitions cylinder 401 into compression chambers 406 and 407 at opposite ends. The

piston is connected to a piston rod 404 which operates through the opposite end of cylinder 401 by means of a sealed sliding fit. At the outer end, piston rod 404 is provided with a threaded coupling 405 which is adapted to be connected to the piston rod 94 of free-piston engine 50.

Chambers 406 and 407 are filled with a gas, such as air, that can be compressed to resiliently store energy. Alternately, other resilient-energy storage means, such as metallic or rubber springs, could be axially aligned in chambers 406 and 407.

In the operation of engine 50 with the inertia apparatus 400 attached, on each power stroke of the piston 52, the resilient means in chamber 406 is compressed and on each compression stroke of the piston 52 the resilient means in chamber 407 is compressed. On alternate strokes, while the resilient means is compressed in one chamber, such as 407, the stored energy of compression in the opposite chamber 406 is released to the system. On the following power stroke of piston 52, the stored energy in the opposite chamber 407 is released to the system. During normal operation of the engine, the energy storage alternates back and forth between chambers 406 and 407 on each successive power and compression stroke of piston 52.

Power for friction losses in the inertia system is added in the work load of engine 50. Pressure relief valves 113 and 114 on the compression cylinder of engine 50 are adjusted to allow for the storage of energy in the system in excess of bounce, fuel compression, and deceleration requirements. Energy is transmitted to the work by means of the connection to bushing 402.

In the event of combustion failure, or a sudden load increase in excess of maximum capacity, the energy stored in chamber 407 returns the piston 52 for the next power (normally) stroke. Energy in chamber 406 returns the piston for the next compression stroke. If combustion occurs at head-end position, the engine picks up the load and continues. However, if combustion fails again the cycle may be repeated once or several more times as the energy is supplied by the resilient energy in chambers 406 and 407. The number of stored "inertia cycles" which may be built into the inertia apparatus and system is determined by the size of the apparatus 400 and the resilient means used in chamber 406 and 407, in conjunction with the characteristics of engine 50. The ratio of the stored energy to that developed by combustion of the fuel determines the number of inertia cycles or the flywheel effect in the engine.

While the inertia apparatus 400 is shown as detached from the engine 50, in some situations the inertia system may be provided integrally with the free-piston engine. This is accomplished by constructing the bounce chamber 111 and the counterchamber 112 with sufficient capacity to receive the required amount of compressed air for resilient energy storage in the inertia system. However, in many cases because of the necessity that these chambers 111 and 112 perform the control requirements together with other engine functions, they cannot be constructed with sufficient capacity to provide a significant increase in flywheel effect.

In another form, the inertia system may be provided in apparatus 410 schematically shown in Fig. 22. In this embodiment, a cylinder 411 is connected to or formed integrally with the frame of a free-piston engine 51a. The piston rod 95a is connected to a piston 412 that is adapted to reciprocate in cylinder 411. Piston 412 is connected to a load (now shown) by means of a reciprocal shaft 413. As in the previous embodiment piston 412 partitions cylinder 411 into chambers 414 and 415 where air may be alternately compressed for the resilient storage of energy to produce a flywheel effect.

The operation of the inertia apparatus 410 is the same as the operation of the apparatus 400 with the excep-

tion that the output energy of the engine is transmitted directly to the load by means of shaft 413 and the resilient energy for flywheel effect is stored with respect to the frame of the engine 51a. In the previously disclosed form of Fig. 21 the energy stored for flywheel effect is stored in a separate system which feeds back to the engine through piston rod 404.

A free-piston engine having the inertia system provided by apparatus 400 or 410 is capable of operation with the same reliability and constancy when subjected to ignition or fuel supply failures or suddenly applied high loads as rotary engines having a mechanical flywheel. When the inertia system herein disclosed is combined with the constant full-load operation method previously disclosed for the free-piston engine 50, a free-piston engine is provided that is capable of sustained operation under rapidly changing load and combustion conditions. It is believed that additional advantages may be obtained in the use of the inertia system if the apparatus is constructed with a natural frequency which is the same as that of the free-piston engine.

We claim:

1. In a two-cycle, free-piston internal combustion engine: a frame; a combustion cylinder and a coaxial greater diameter compression cylinder mounted in said frame; a free-piston having a portion of greater diameter, mounted for reciprocation in said cylinders, the greater diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing gas in said bounce chamber and said counterchamber to decelerate and return said piston; means for transferring output energy of said engine to a work article or load; a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined amount when less than all of the energy produced for output in said engine is transferred to a work article or load; a piezoelectric generator on said engine operated cyclicly by the reciprocation of said piston providing ignition in said combustion cylinder; and a fuel injector in communication with said combustion cylinder operated cyclicly by the reciprocation of said piston providing fuel in said combustion cylinder for said ignition.

2. In a two-cycle, free-piston internal combustion engine: a frame; a combustion cylinder and a coaxial greater diameter compression cylinder mounted in said frame; a free piston having a portion of greater diameter, mounted for reciprocation in said cylinders, the greater diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing gas in said bounce chamber and said counterchamber to decelerate and return said piston; means for transferring output energy of said engine to a work article or load; a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined amount when less than all of the energy produced for output of said engine is transferred to a work article or load; a piezoelectric generator on said engine operated cyclicly by the reciprocation of said piston providing ignition in said combustion cylinder; a fuel injector in communication with said combustion cylinder operated cyclicly by the reciprocation of said piston providing fuel in said combustion cylinder for said ignition; and an exhaust ejector chamber disposed around said combustion cylinder to extract the excess heat of combustion from said combustion cylinder by fluid flow therethrough, said flow induced by the velocity of exhaust gases from said engine.

3. A two-cycle, free-piston internal combustion engine: comprising a frame; a combustion cylinder and a coaxial greater diameter compression cylinder mounted in said frame; a free-piston having a portion of greater

diameter, and mounted for reciprocation in said cylinders, the greater diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing gas in said bounce chamber and said counterchamber to return and decelerate said piston; means for transferring output energy of said engine to a work article or load; and a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined amount when less than all of the energy produced for output in said engine is transferred to a work article or load.

4. In a two-cycle, free-piston internal combustion engine, providing output energy in the form of translatory motion: a frame; a combustion cylinder in said frame; a compression cylinder of greater diameter, coaxial with the combustion cylinder, and contiguous thereto within said frame; a free-piston having a portion of greater diameter mounted for reciprocation in said compression cylinder; means for transferring output energy of said engine to a work article or load; and a pressure relief valve deposited adjacent to each end of the compression cylinder of said engine, each pressure relief valve being adjusted to limit the compression cylinder pressure at an end in the event the energy produced for output is unused.

5. A two-cycle, free-piston internal combustion engine comprising: a frame; a combustion cylinder and a coaxial greater diameter compression cylinder mounted in said frame; closures for the exterior ends of said cylinders; a free-piston having a portion of greater diameter, mounted for reciprocation in said cylinders, the greater diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing gas in said bounce chamber and said counterchamber to return and decelerate said piston, and to compress and transmit air for future use in the combustion cycle of said engine; means for transferring output energy of said engine to a work article or load; and a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said respective chambers from exceeding a predetermined amount when less than all of the energy produced for output in said engine is transferred to a work article or load.

6. A two-cycle free-piston internal combustion engine according to claim 5 wherein a hammer is supported in said frame for reciprocation by said piston actuating a piezoelectric generator comprising: a pair of piezoelectric elements, each element being mounted at one end of common polarity to a terminal; an ignitor mounted in said frame in said combustion cylinder and electrically connected to said terminal; a housing member supporting in a socket one of said elements at the end of opposite polarity of the other of said elements and guided for reciprocal movement in said housing; said hammer impacting said anvil upon said reciprocation; and resilient means for removing said hammer from said anvil; whereby an electrical potential is generated between said ignitor and said frame equal to the combined potential generated in both of said piezoelectric elements to ignite combustion in said combustion cylinder upon each reciprocation of said piston.

7. A two-cycle, free-piston internal combustion engine comprising: a frame; a combustion cylinder and a coaxial greater-diameter compression cylinder mounted in said frame; closures for the exterior ends of said cylinders; a free-piston having a portion of greater-diameter, mounted for reciprocation in said cylinders, the greater-diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing air in said bounce chamber and said counterchamber, to

return and decelerate said piston, and to compress and transmit air for future use in the combustion cycle of said engine; means for transferring output energy of said engine to a work article or load; a first relief valve on said bounce chamber for preventing the pressure in said chamber from exceeding a predetermined amount necessary to return said piston on the compression stroke of said engine; and a second relief valve on said counterchamber for preventing the pressure in said counterchamber from exceeding a predetermined amount necessary to decelerate said piston in conjunction with the pressure of compression in said combustion cylinder at the end of said compression stroke.

8. A two-cycle, free-piston internal combustion engine comprising: a frame; a combustion cylinder and a coaxial greater-diameter compression cylinder mounted in said frame; closures for the exterior ends of said cylinders; a free piston having a portion of greater diameter, mounted for reciprocation in said cylinders, the greater-diameter portion of said piston partitioning said compression cylinder into a bounce chamber at the side of said greater-diameter portion removed from said compression cylinder and a counterchamber at the side of said greater-diameter portion adjacent to said combustion cylinder, said piston in reciprocation alternately compressing air in said bounce chamber on the power stroke of said engine to return said piston on the compression stroke and compressing air in said counterchamber on the compression stroke of said engine to decelerate said piston; means for transferring output energy of said engine to a work article or load; and a first relief valve adjacent the closure of said compression cylinder providing communication between said counterchamber and the atmosphere for preventing the pressure in said counterchamber from exceeding a predetermined value; and a second relief valve adjacent the opposite closure of said compression cylinder providing communication between said counterchamber and the atmosphere for preventing the pressure in said counterchamber from exceeding a predetermined amount; whereby excess energy produced for output in said engine is released from said chambers.

9. In a reciprocating-motion apparatus of the class providing output energy on both directions of reciprocation, a free-piston internal combustion engine having a unidirectional power stroke connected to and driving said apparatus comprising: a frame; a combustion cylinder and a coaxial greater-diameter compression cylinder mounted in said frame; a free-piston having a portion of greater-diameter and mounted for reciprocation in said cylinders, the greater-diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation providing output energy on the power stroke of said engine and energy for compressing gas in said bounce chamber to return said piston and providing output energy on the compression stroke of said engine; and a first relief valve on said bounce chamber and a second relief on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined value when less than all the energy produced for output in said engine is used in said apparatus.

10. In an impact tool of the class driven by a free-piston internal combustion engine, the combination of: a frame; a combustion cylinder and a coaxial greater-diameter compression cylinder mounted in said frame; a free-piston having a portion of greater diameter, mounted for reciprocation in said cylinders, said greater-diameter portion partitioning said compression cylinder into a bounce chamber and a counterchamber and said piston in reciprocation alternately compressing gas in said bounce chamber and said counterchamber to return and decelerate said piston; an anvil mounted for movement in said frame from a first position projecting into said compression cylinder for impact by said piston to a second position withdrawn from said compression cylinder; tool holder means for positioning a tool in contact with said anvil; a first relief valve on

said bounce chamber for preventing the pressure therein from exceeding a predetermined value on the power stroke of said engine when said anvil is in said second position; and a second relief valve on said counterchamber for preventing the pressure therein from exceeding a predetermined value on the compression stroke of said engine when said tool returns energy to said piston on impact.

11. A free-piston internal combustion engine comprising: a frame; a combustion cylinder and a coaxial greater-diameter compression cylinder mounted in said frame; a free-piston having a portion of greater diameter mounted for reciprocation in said cylinders, said greater-diameter portion partitioning said compression cylinder into a bounce chamber and a counterchamber, and said piston in reciprocation alternately compressing gas in said bounce chamber and said counterchamber to decelerate and return said piston; a compensator valve, in communication with said compression cylinder, passing a portion of said compressed gas and limiting the output of said compression cylinder for maintenance of adequate pressure for engine operation at all associated work levels; and a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined valve when less than all the energy produced in said engine for output is transferred to said work.

12. A two-cycle free-piston internal combustion engine comprising: a frame; a combustion cylinder and a coaxially greater diameter compression cylinder mounted in said frame; a free piston having a portion of greater diameter, mounted for reciprocation in said cylinder, the greater diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing air in said bounce chamber and said counterchamber to return and decelerate said piston; means for transferring output energy of said engine to work article or load; a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined amount when less than all of the output energy of said engine is transferred to a work article or load; an electric igniter mounted in said combustion chamber; a plurality of piezoelectric elements, each being mounted at an end of common polarity to a terminal electrically connected to said igniter; means fastened to said frame for supporting at least one of said elements at the end of opposite polarity; means urged by said piston and movably carried by said frame for impacting at least one other of said elements at an opposite end to produce an electrical potential between said igniter and said frame equal to the combined potential generated in all of said plurality of piezoelectric elements; whereby ignition is initiated in said combustion cylinder upon each reciprocation of said piston.

13. A two-cycle free-piston internal combustion engine comprising: a frame; a combustion cylinder and a coaxially greater diameter compression cylinder mounted in said frame; closures for the exterior ends of said cylinders; and a free piston having a portion of greater diameter, and mounted for reciprocation in said cylinders, the greater-diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing air in said bounce chamber and said counterchamber to return and decelerate said piston, and to compress and transmit air for future use in the combustion cycle of said engine; means for transferring output energy of said engine to a work article or load; a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined amount when less than all of the output energy of said engine is transferred to a work article or load; an electric igniter mounted on said frame in said combustion cylinder; a plurality of piezoelectric

elements, each being mounted at an end of common polarity to a terminal electrically connected to said igniter; means fastened to said frame for supporting at least one of said elements at the end of opposite polarity; means urged by said piston and movably carried by said frame for impacting at least one other of said elements at an opposite end to produce an electrical potential between said igniter and said frame equal to the combined potential generated in all of the said plurality of piezoelectric elements; whereby combustion is ignited in said combustion cylinder upon each reciprocation of said piston.

14. A two-cycle, free-piston internal combustion engine comprising: a frame; a combustion cylinder and a coaxially greater diameter compression cylinder mounted in said frame; a free piston having a portion of greater diameter, mounted for reciprocation in said cylinders, the greater diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing air in said bounce chamber and said counterchamber to return and decelerate said piston; means for transferring output energy of said engine to a work article or load; a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined amount when less than all of the output energy of said engine is transferred to a work article or load; an electric igniter mounted in said frame in said combustion cylinder and electrically connected to a terminal; a pair of piezoelectric elements, each element being mounted at one end of common polarity to said terminal; a housing member fastened to said frame supporting one of said crystals at the end of opposite polarity; an anvil supported by the end of opposite polarity of the other of said crystals; a hammer supported for reciprocation in said housing by said piston and impacting said anvil upon said reciprocation; and resilient means for removing said hammer from said anvil; said impact producing an electrical potential between said igniter and said frame equal to the combined potential generated in said pair of crystals, whereby combustion is ignited in said combustion cylinder upon each reciprocation of said piston.

15. In a two-cycle, free-piston internal combustion engine: a frame; a combustion cylinder and a coaxially greater diameter compression cylinder mounted in said frame; a free-piston having concomitant cam means, and having a portion of greater diameter, mounted for reciprocation in said cylinders, the greater diameter portion of said piston partitioning said compression cylinder into a bounce chamber and a counterchamber, said piston in reciprocation alternately compressing gas in said bounce chamber and said counterchamber to decelerate and return said piston; means for transferring output energy of said engine to a work article or load; a first relief valve on said bounce chamber and a second relief valve on said counterchamber for preventing the pressure in said chambers from exceeding a predetermined amount when less than all of the energy produced for output in said engine is transferred to a work article or load; a reciprocably operated piezoelectric generator on said engine actuated cyclically by said cam means with the reciprocation of said piston providing ignition in said combustion cylinder; and a reciprocably operated fuel injector in communication with said combustion cylinder actuated cyclically by said cam means with the reciprocation of said piston providing fuel in said combustion cylinder for said ignition.

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