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(54) **SYSTEM AND METHOD FOR THE PRODUCTION OF COMPRESSED FLUIDS**

(71) Applicant: **Regents of the University of Minnesota**, St. Paul, MN (US)

(72) Inventors: **William Keith Durfee**, Edina, MN (US); **David B. Kittelson**, Minneapolis, MN (US); **Lei Tian**, Minneapolis, MN (US)

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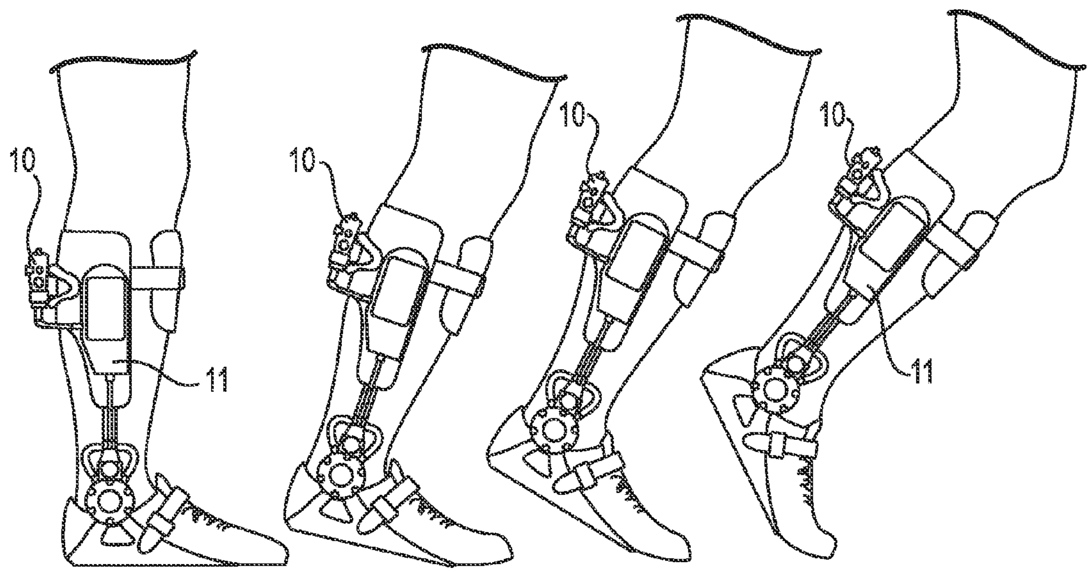
USPC **60/370**; 417/364

(57) **ABSTRACT**

The invention herein described consists of a single-cylinder free-piston engine system comprising a combustion cylinder, a compression cylinder, a seal between the two cylinders and a piston assembly, capable of being produced in a miniature scale (e.g., less than 10 cubic centimeters volume). The combustion cylinder consists of a holding chamber wherein fuel enters through a fuel inlet port before combustion, a combustion chamber wherein combustion occurs according to an HCCI process, after which the excess fuel and exhaust leaves the engine system through a port for exhaust, and a port extending from the holding chamber to the combustion chamber. The compression cylinder comprises a compression chamber wherein a compressible a compressible fluid enters through an inlet port, is compressed by the single-cylinder engine system, and the compressed fluid exits through an outlet port, and a rebound chamber wherein energy from the combustion process is conserved by a rebound element.



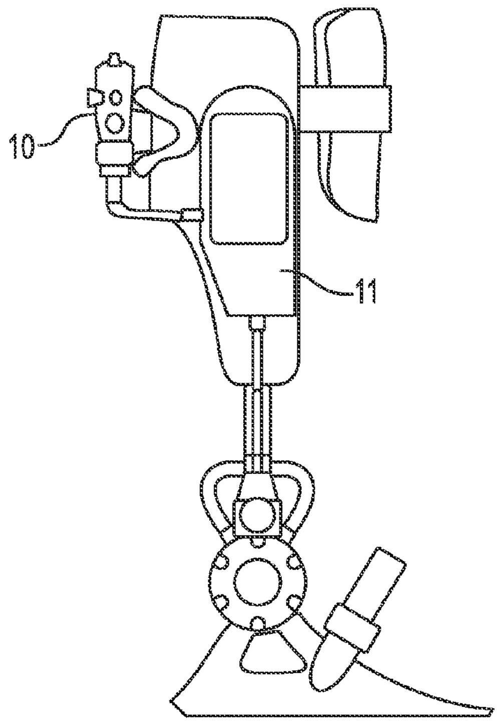


Fig. 1

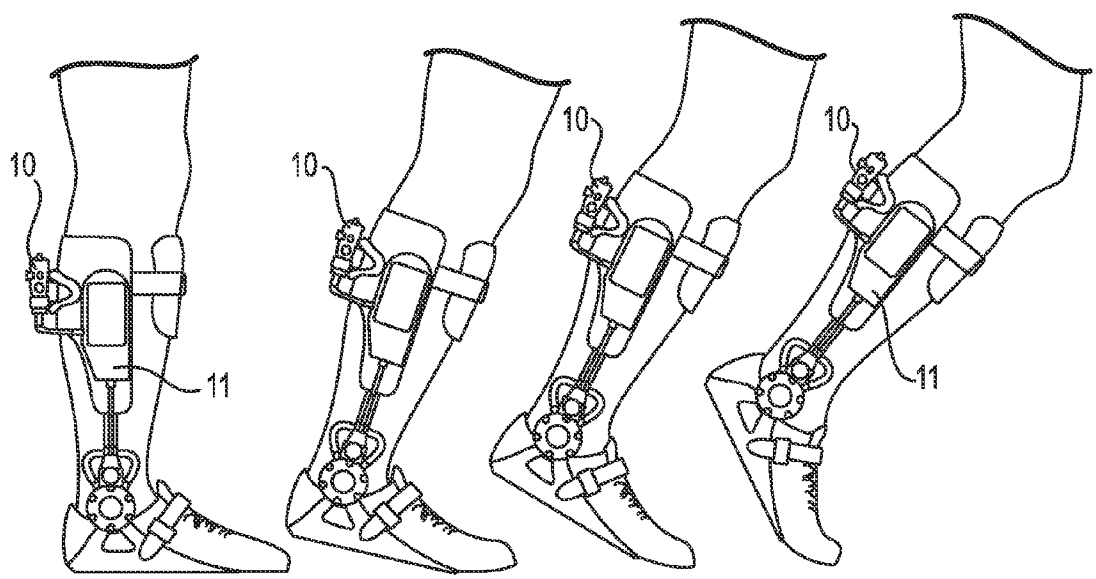


Fig. 2

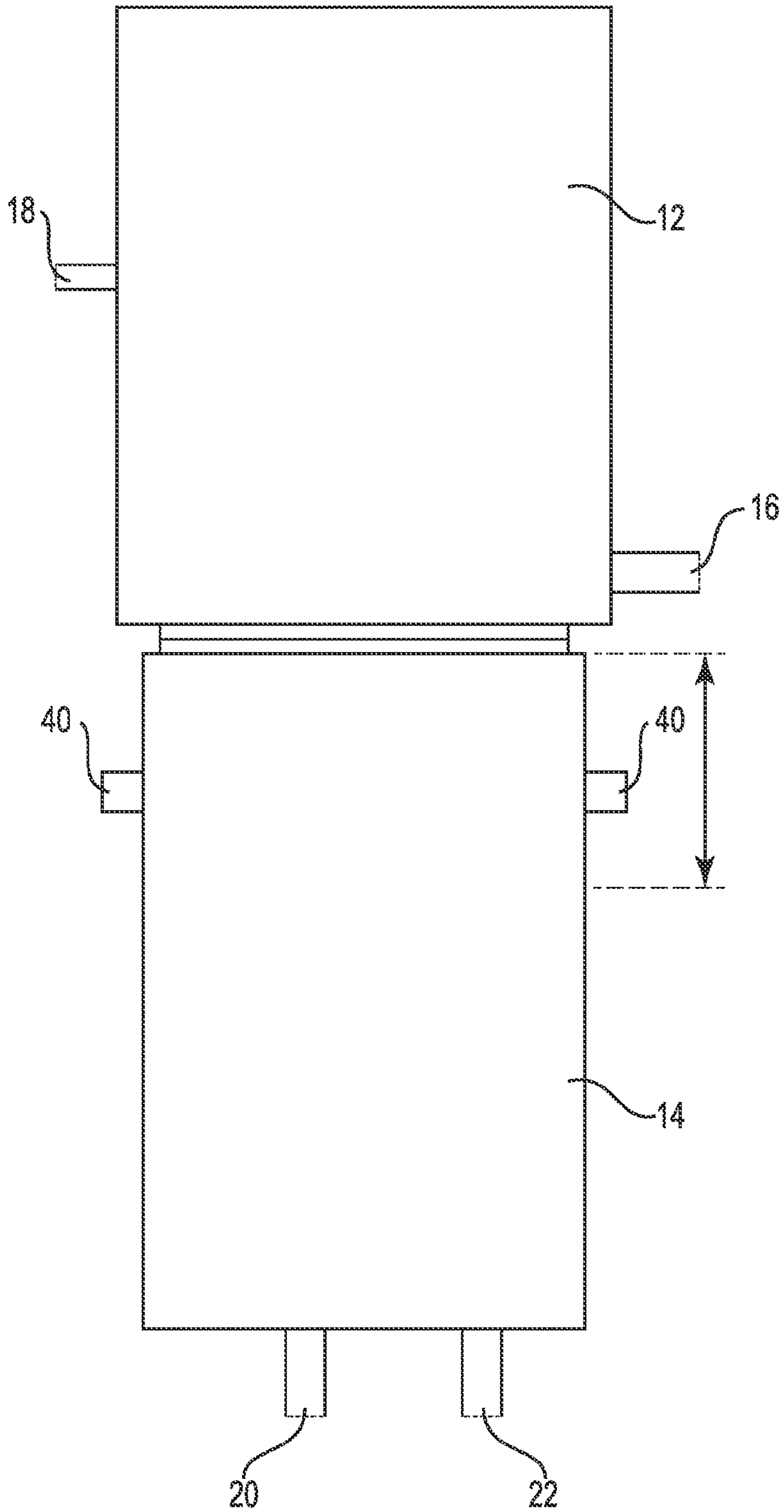


Fig. 3

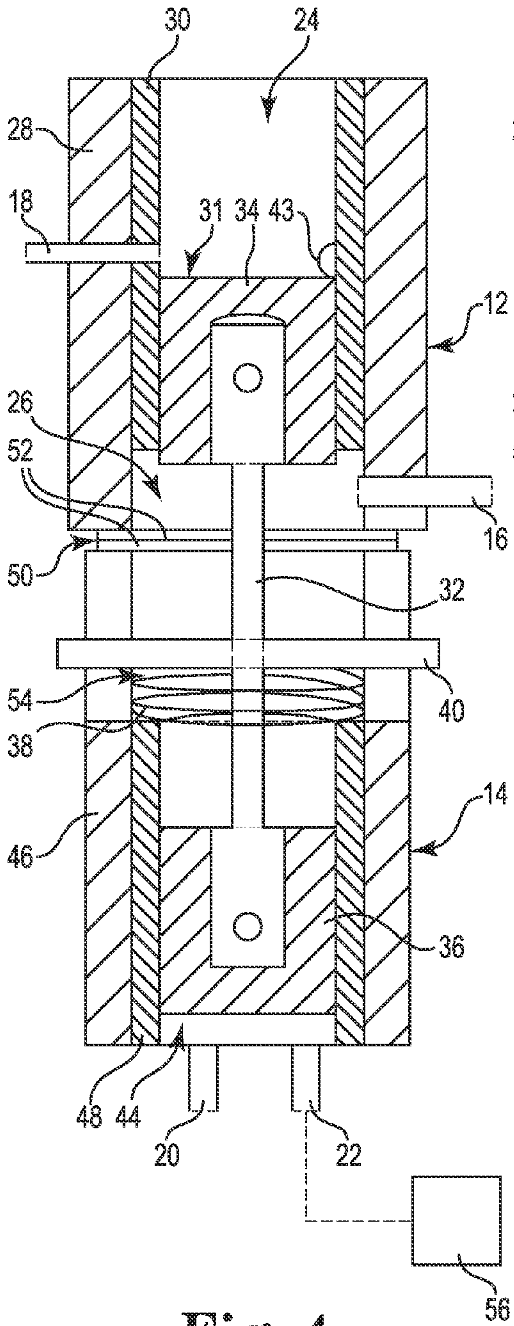

30
24
28
18
31
34
43
12
26
52
16
50
32
54
40
38
14
46
36
48
44
20
22
56

Fig. 4

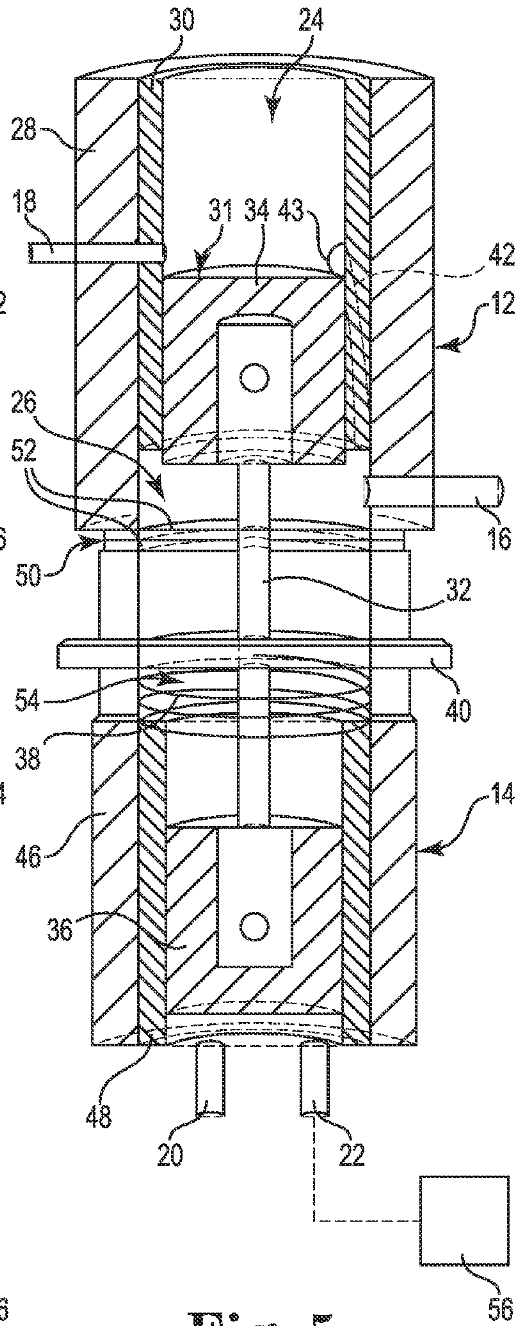

30
24
28
18
31
34
43
42
12
26
52
16
50
32
54
40
38
14
46
36
48
20
22
56

Fig. 5

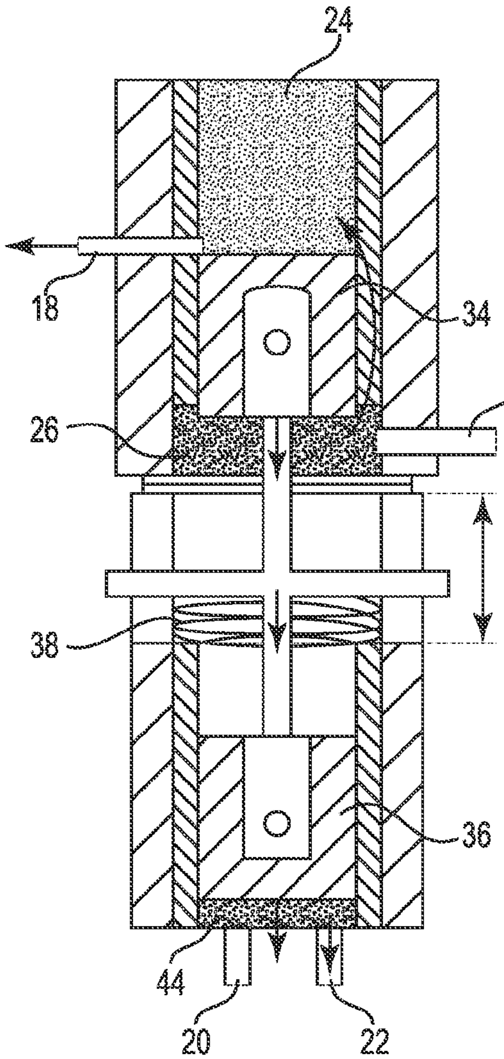


Fig. 6

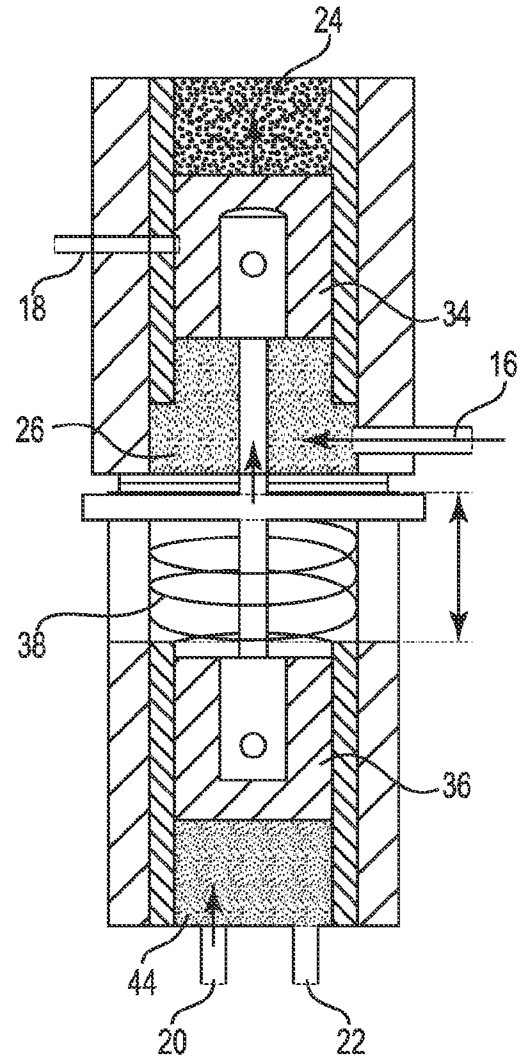


Fig. 7

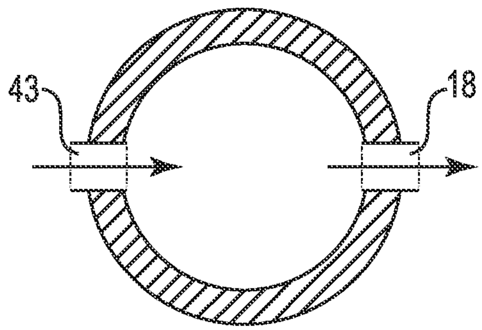


Fig. 8

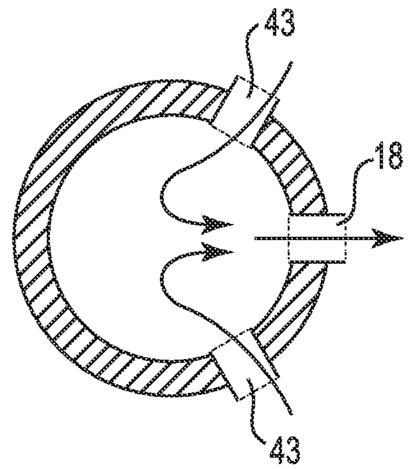


Fig. 9

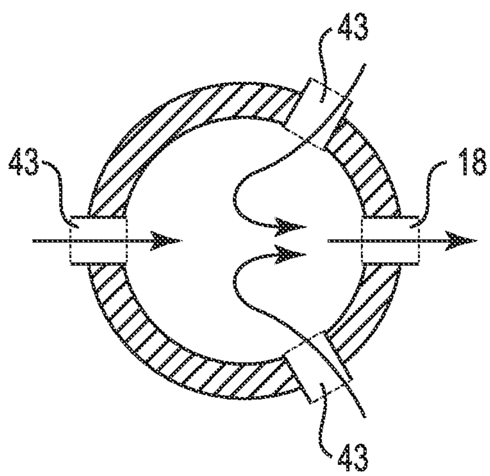


Fig. 10

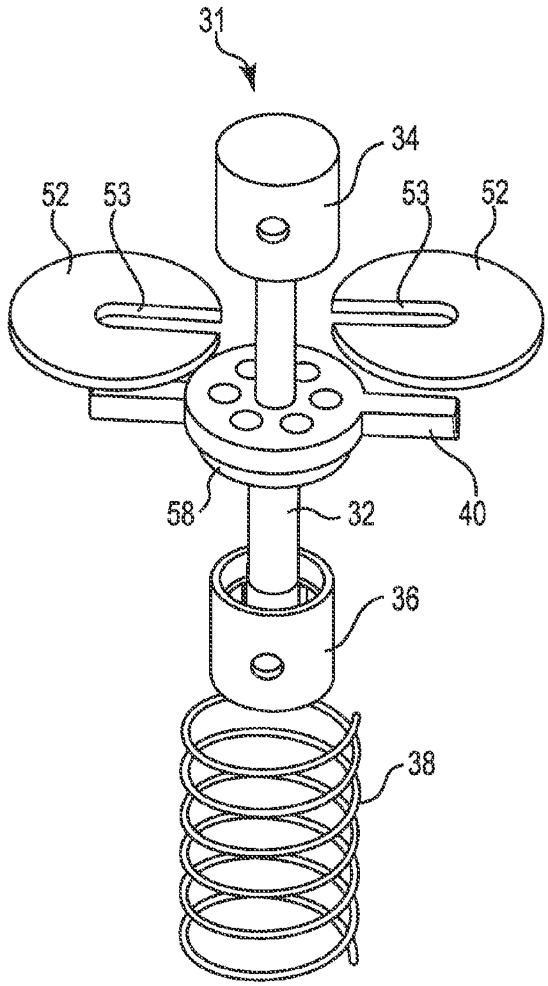


Fig. 11

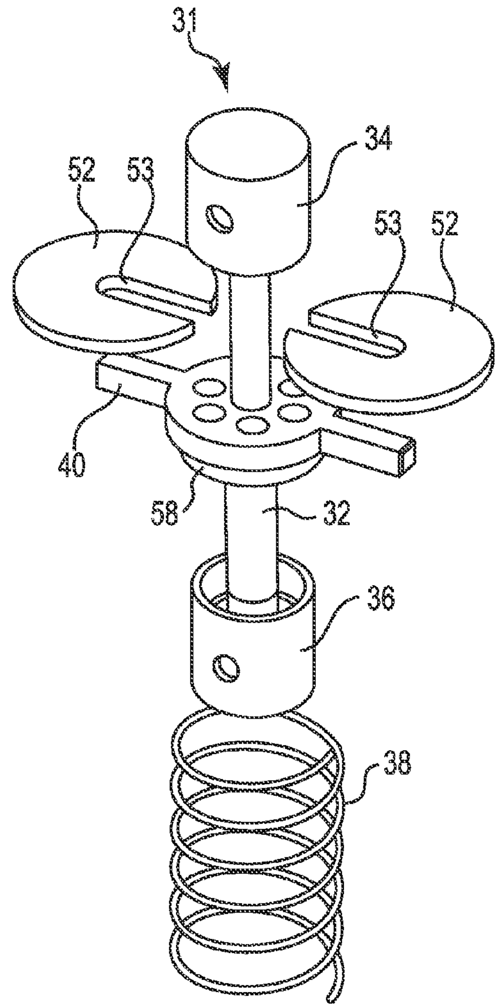


Fig. 12

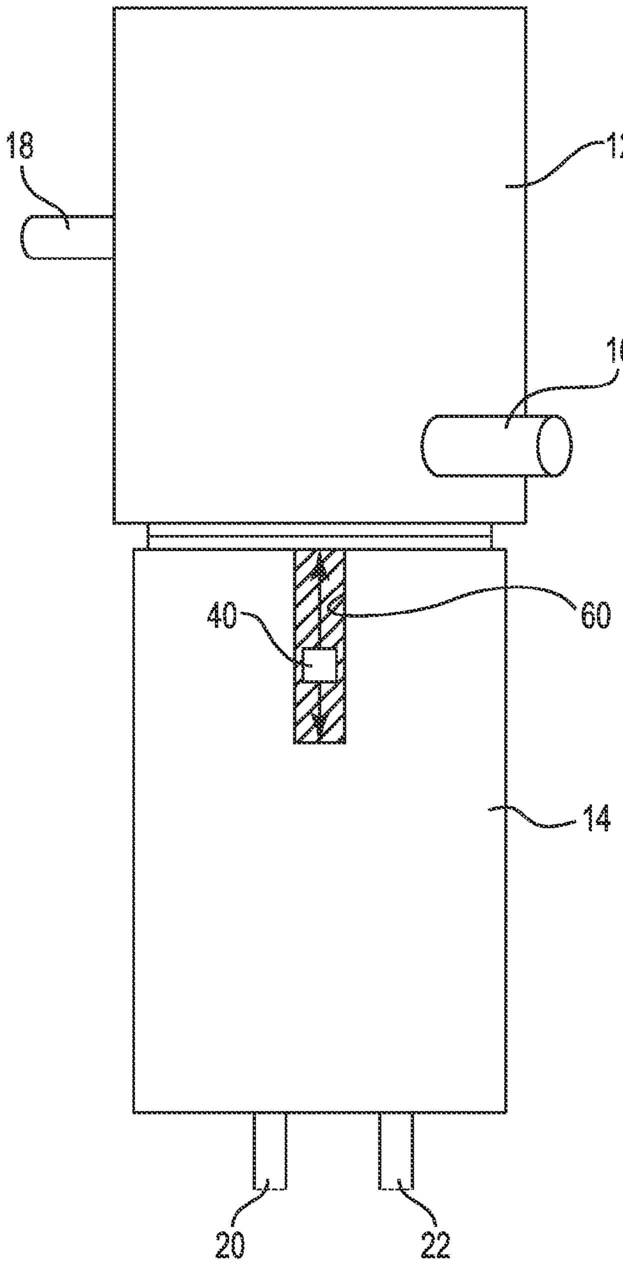


Fig. 13

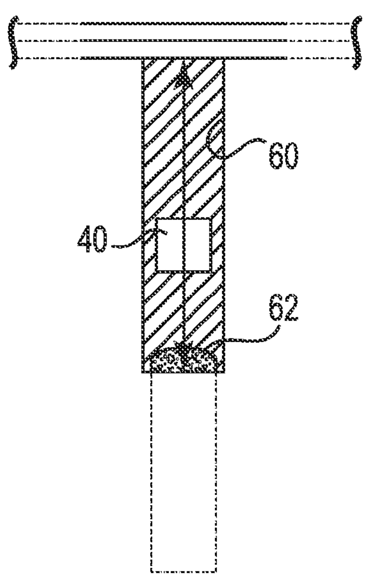


Fig. 14

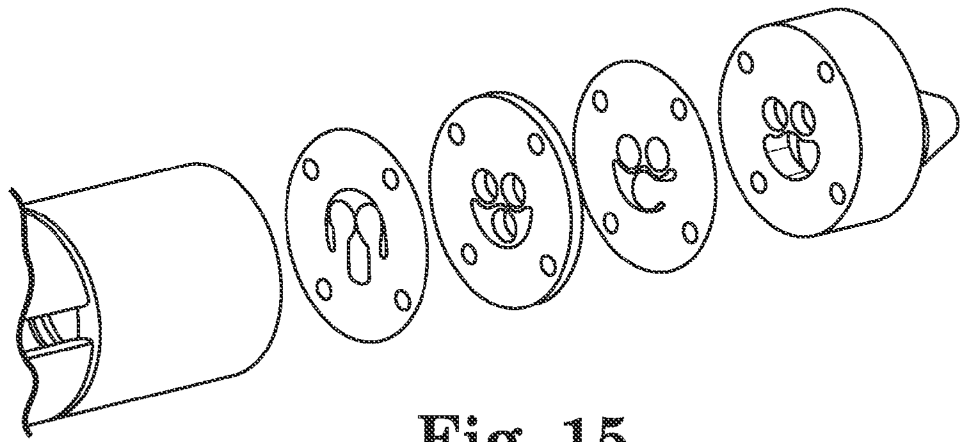


Fig. 15

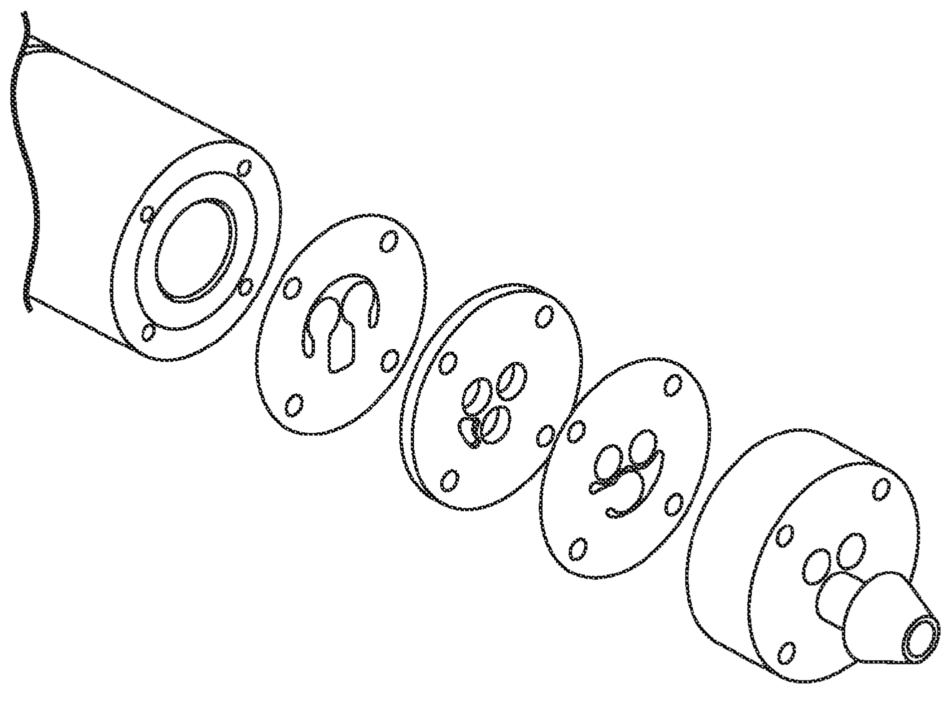


Fig. 16

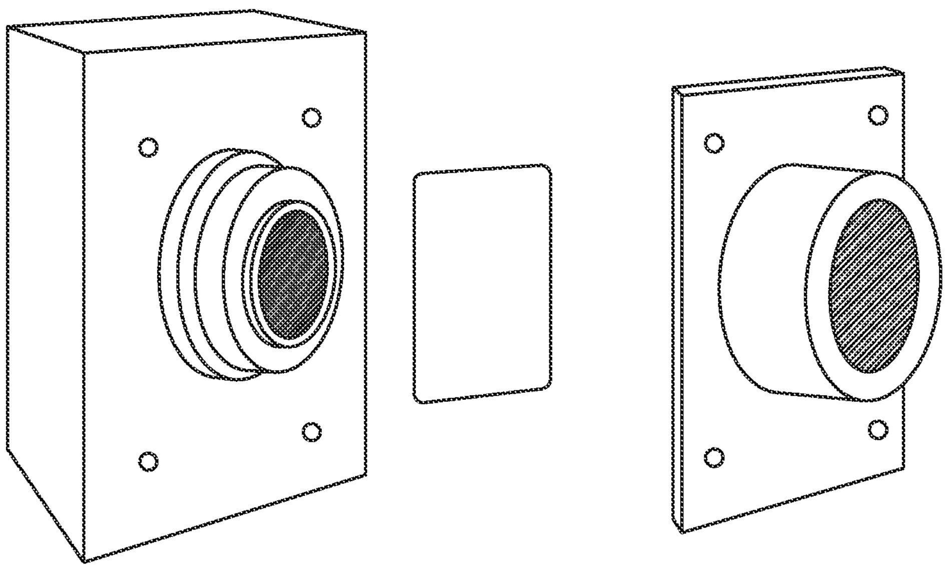


Fig.17

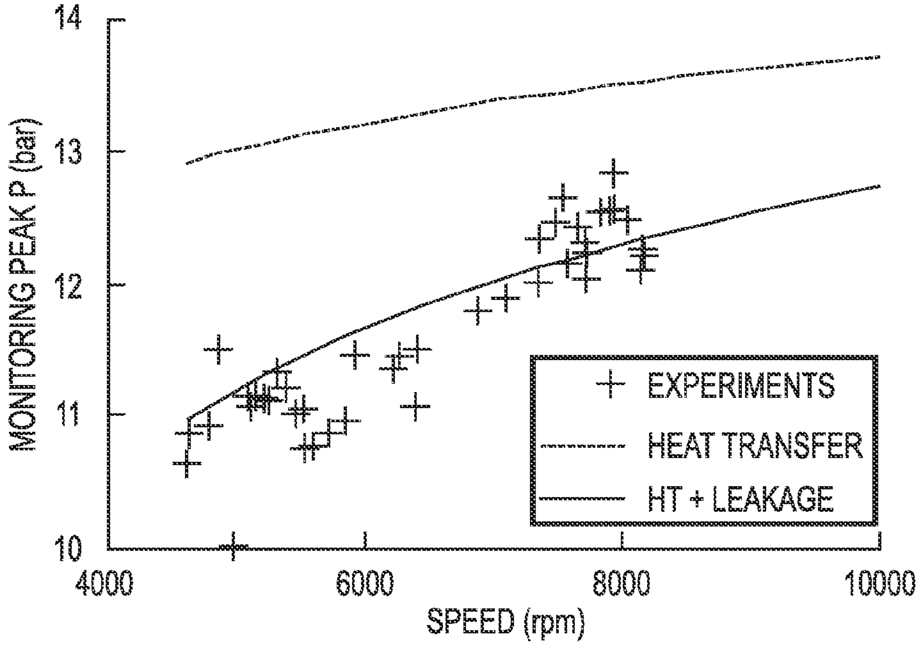

14
13
12
11
10
MONITORING PEAK P (bar)
4000
6000
8000
10000
SPEED (rpm)
EXPERIMENTS
HEAT TRANSFER
HT + LEAKAGE

Fig. 18

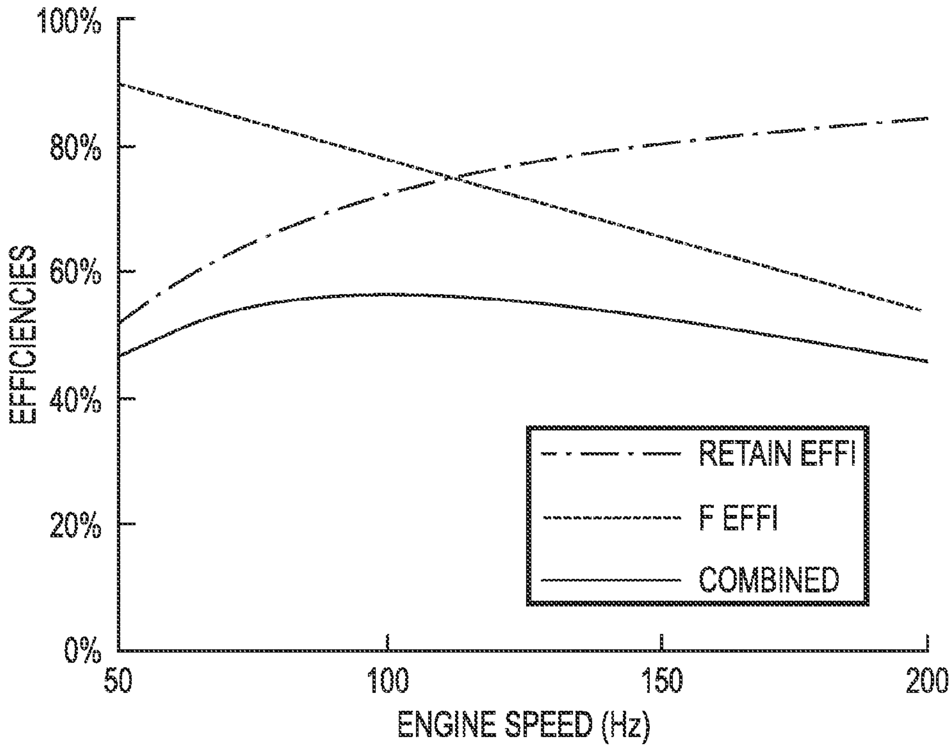

100%
80%
60%
40%
20%
0%
EFFICIENCIES
50
100
150
200
ENGINE SPEED (Hz)
RETAIN EFFI
F EFFI
COMBINED

Fig. 19

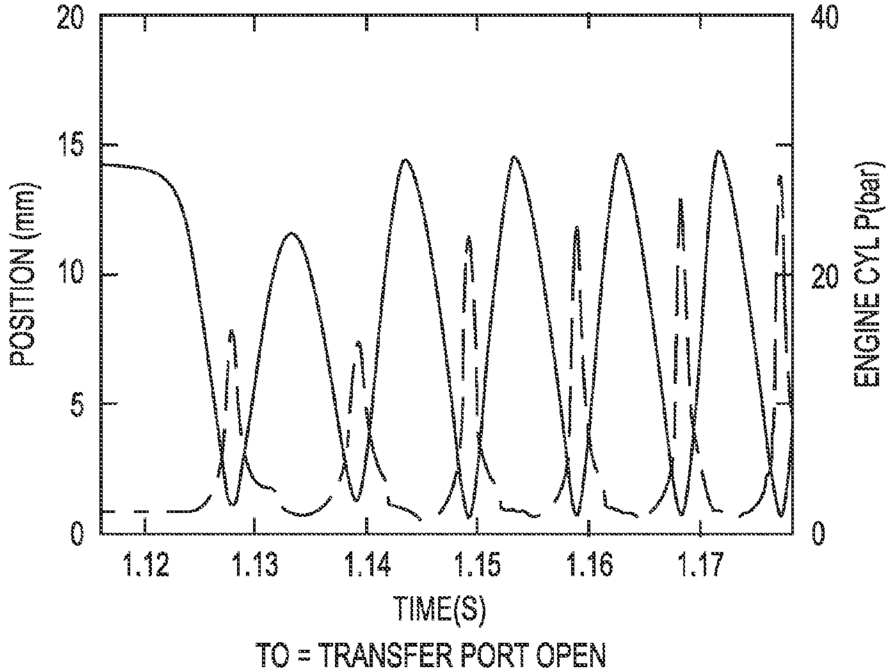

POSITION (mm)
ENGINE CYL P(bar)
20
15
10
5
0
40
20
0
1.12
1.13
1.14
1.15
1.16
1.17
TIME(S)
TO = TRANSFER PORT OPEN

Fig. 20

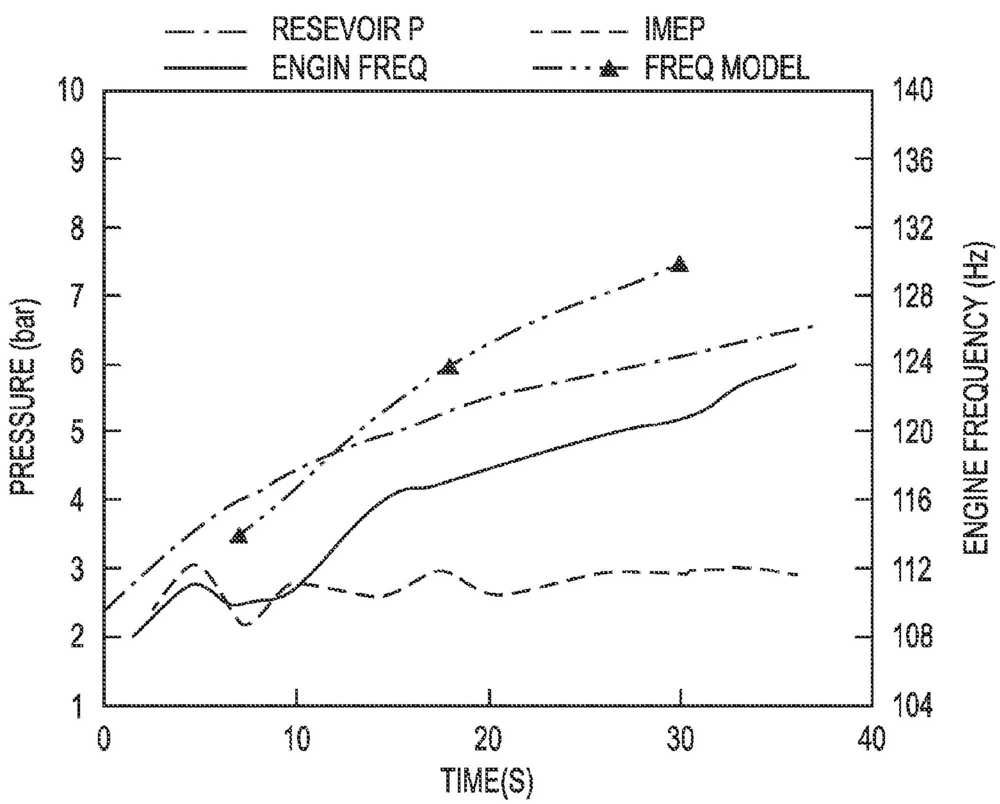

RESEVOIR P
IMEP
ENGIN FREQ
FREQ MODEL
PRESSURE (bar)
ENGINE FREQUENCY (Hz)
10
9
8
7
6
5
4
3
2
1
140
136
132
128
124
120
116
112
108
104
0
10
20
30
40
TIME(S)

Fig. 21

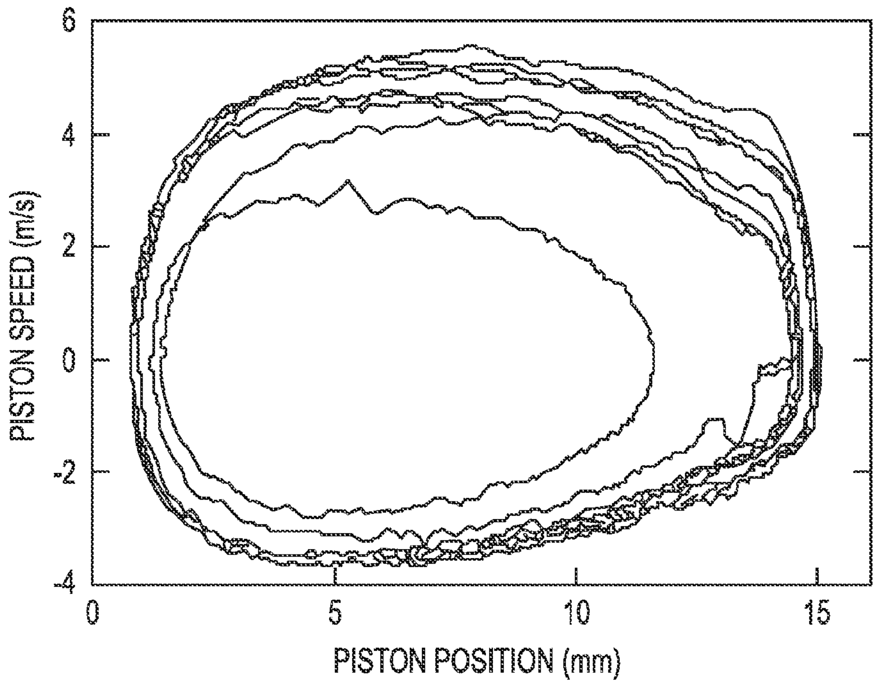

6
4
2
0
-2
-4
PISTON SPEED (m/s)
0
5
10
15
PISTON POSITION (mm)

Fig. 22

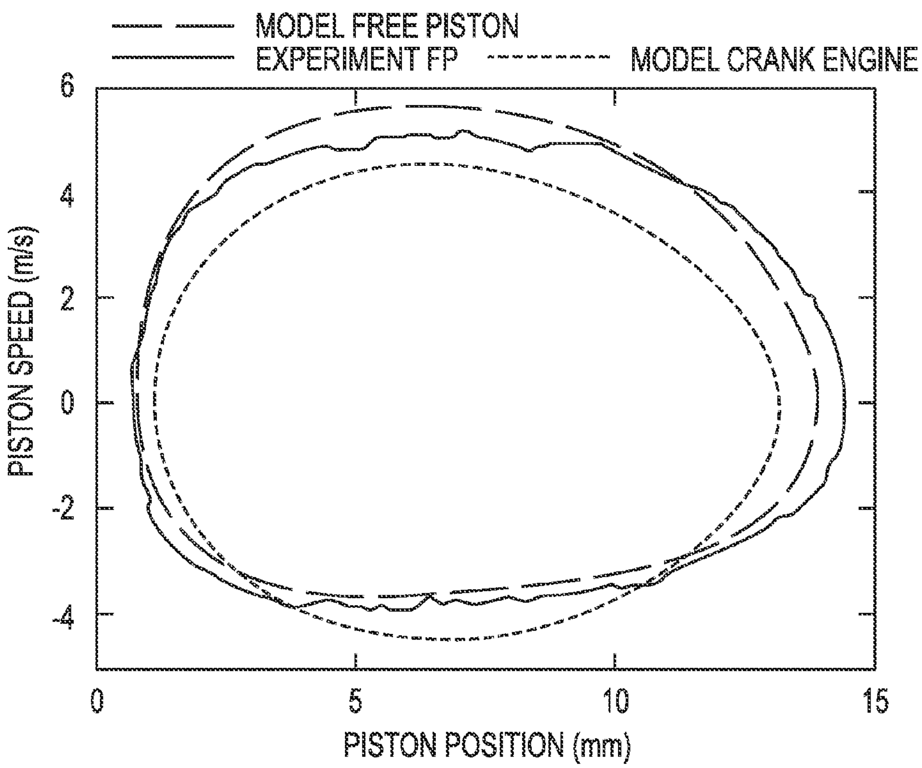

MODEL FREE PISTON
EXPERIMENT FP
MODEL CRANK ENGINE
6
4
2
0
-2
-4
PISTON SPEED (m/s)
0
5
10
15
PISTON POSITION (mm)

Fig. 23

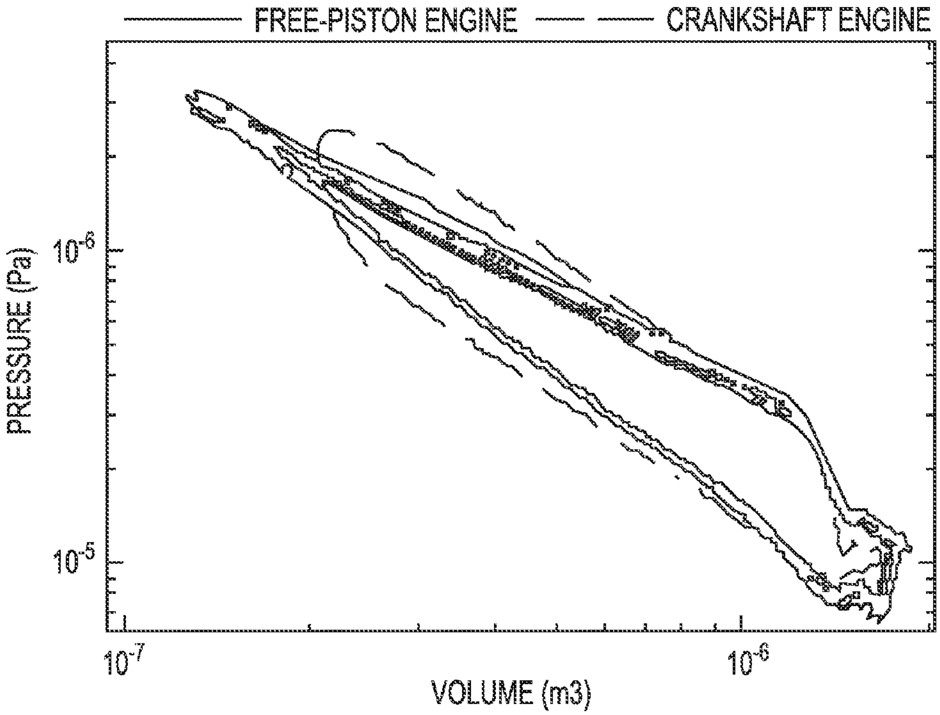

FREE-PISTON ENGINE
CRANKSHAFT ENGINE
PRESSURE (Pa)
10^-6
10^-5
10^-7
10^-6
VOLUME (m3)

Fig. 24

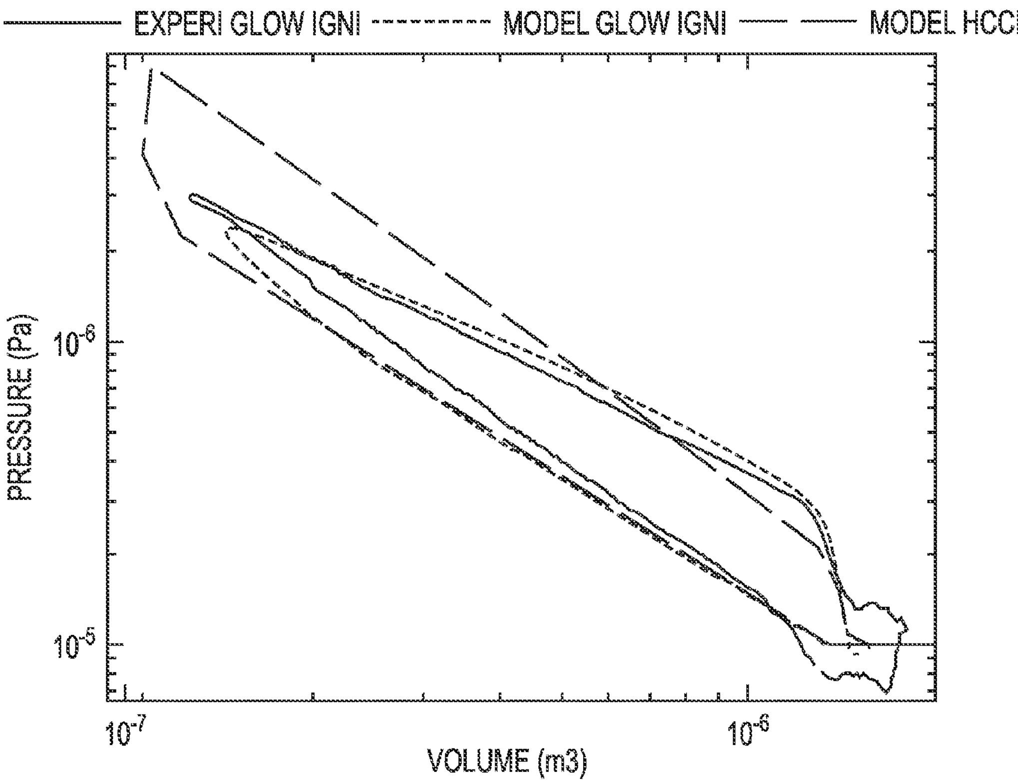

EXPERI GLOW IGNI
MODEL GLOW IGNI
MODEL HCCI
PRESSURE (Pa)
10^-6
10^-5
10^-7
10^-6
VOLUME (m3)

Fig. 25

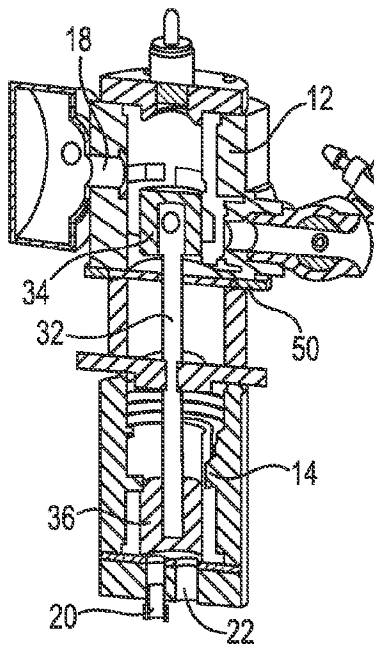


Fig. 27

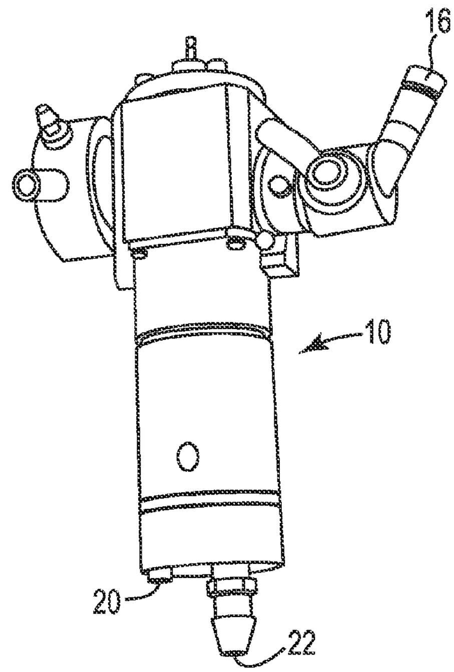


Fig. 26

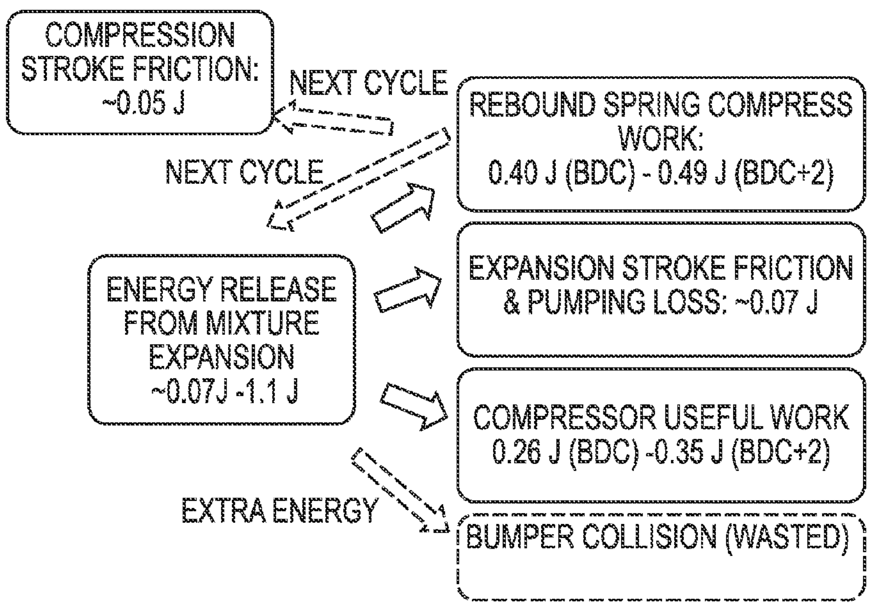


Fig. 28

SYSTEM AND METHOD FOR THE PRODUCTION OF COMPRESSED FLUIDS

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application No. 61/660,981, filed Jun. 18, 2012 and titled “SYSTEM AND METHOD FOR THE PRODUCTION OF COMPRESSED FLUIDS”, which is incorporated herein by reference in its entirety.

GOVERNMENT RIGHTS

[0002] This invention was made with Government support under grant No. EEC-0540834, awarded by the National Science Foundation. The Government has certain rights in this invention.

FIELD

[0003] The present invention relates generally to a fluid pumping or fluid compression engine, such as utilizing an internal homogeneous-charge combustion ignition (HCCI) free-piston engine design. Such a fluid pump or compressor is capable of producing compact fluid power for applications requiring mobility.

BACKGROUND

[0004] There is a need for compact fluid pumps and compressors in fields such as orthotics, power tools, and robots. Applications in such fields require portable power to pressurize or compress fluid. For example, power tools may include pneumatic nail guns, branch clippers, garden pruners, or load lifting assistants. Such portable power is commonly derived from an electrical air compressor powered by a battery. However, the weight and energy density of the battery often limit portability. As an alternative, an internal combustion (IC) engine can be used as a compressed fluid power source in such applications. Compared to a battery, a miniaturized combustion engine can provide higher power density and higher energy density.

[0005] However, IC engines are difficult to miniaturize to sizes below approximately 10 cm^3(cubic centimeters). Challenges in miniaturizing existing IC engines to a small size include fabrication, control, friction, and blow-by leakage. For example, a four-stroke IC engine is difficult to fabricate at a miniature scale due to additional features such as a camshaft, valves, and rocker arms. As another example, in a two-stroke IC engine, spark plugs, fuel injectors, and various sensors are all difficult to miniaturize in order to operate in a small engine.

[0006] An alternative configuration involves homogeneous-charge combustion ignition (HCCI) engines. Such engines typically use a crankshaft. These engines also utilize active control schemes comprising mounted sensors and an actuator to regulate rebound, spark ignition or diesel compression ignition, and proper alignment. Due to the complexity of such a configuration and the need for a crankshaft, miniaturizing a full-scale HCCI crankshaft engine would be difficult.

[0007] Yet another alternative configuration utilizes a free-piston engine. A free-piston engine is a type of internal combustion engine not having a crankshaft. Without a crankshaft, this configuration is more compact and simpler than some other configurations. However, free-piston engines are difficult to regulate requiring active controls to regulate piston motion. Incorporating active control schemes at a miniature scale presents difficulties, especially given the limited space available in a miniature engine.

[0008] Another configuration involves glow plug ignition engines used in applications such as model aircraft to power a fluid compressor. Such engines are small in size and utilize glow plug ignition, wherein a glowing hot platinum wire is used in the combustion chamber to ignite the fuel air mixture through its thermal energy and catalytic effect. The problem with this engine configuration is low thermal efficiency caused by a slow combustion process. Furthermore, the use of a glow plug in this configuration limits further miniaturization.

[0009] Because of the inherent challenges in miniaturizing existing engine configurations, it would be beneficial to develop an engine that can be fabricated at a miniature scale, operate with reasonable power for portable use, and have a high enough power-to-weight ratio to be effective in orthotics, power tool, and robotics applications.

SUMMARY

[0010] A system for providing pressurized and/or compressed fluid comprising a fluid pump/compression cylinder, coupled to a combustion cylinder and a rebound chamber, and a piston assembly contained at least partially and capable of movement within the combustion cylinder and the fluid pump/compression cylinder, wherein the combustion cylinder comprises a holding chamber and a combustion chamber, and wherein the holding chamber and the combustion chamber may be connected by at least one port, and wherein the fluid pump/compression cylinder comprises a pump/compression chamber, and wherein the rebound chamber comprises a rebound system, and wherein the pump/compression chamber may comprise at least one inlet and at least one outlet.

FIGURES AND TABLES

[0011] FIG. **1** is a schematic diagram of an exemplary embodiment of the engine being used in conjunction with an orthotic leg/foot apparatus.

[0012] FIG. **2** is a schematic diagram of the exemplary embodiment of the engine of FIG. **1** being used in conjunction with an orthotic leg/foot apparatus as provided to a person’s leg and foot.

[0013] FIG. **3** is a schematic diagram of an exemplary embodiment of the present invention showing an exterior of an engine cylinder.

[0014] FIG. **4** is schematic cross-sectional view of an engine cylinder according to an exemplary embodiment of the present invention.

[0015] FIG. **5** is schematic cross-sectional view similar to FIG. **4**, but at an angle from the top of an engine cylinder according to an exemplary embodiment of the present invention.

[0016] FIG. **6** is a schematic cross-sectional view of a cylinder at a certain stage in the combustion cycle according to an exemplary embodiment of the present invention.

[0017] FIG. **7** is a schematic cross-sectional view of a cylinder at a different stage that in FIG. **6** in the combustion cycle according to an exemplary embodiment of the present invention.

[0018] FIGS. **8-10** are schematic cross-sectional views showing scavenging flow patterns.

[0019] FIG. **11** is a schematic diagram of a piston assembly, seal, and spring according to an exemplary embodiment.

[0020] FIG. **12** is a schematic diagram of the piston assembly, seal, and spring of FIG. **11** but shown from a angle to the side.

[0021] FIG. **13** is a schematic diagrams of an engine cylinder showing a slot for a starting element provided in a compression cylinder according to an exemplary embodiment.

[0022] FIG. **14** is an enlarged portion of the view of FIG. **13** showing the slot, a starting element and an absorption element at the end of the slot.

[0023] FIG. **15** is a schematic diagram of a valve according to exemplary embodiment of the present invention.

[0024] FIG. **16** is a schematic diagram of another valve according to exemplary embodiment of the present invention.

[0025] FIG. **17** is a schematic diagram of yet another valve according to exemplary embodiment of the present invention.

[0026] FIGS. **18-25** are graphical representations representing data from various experiments related to the performance of a free piston engine design of the present invention.

[0027] FIG. **26** is a perspective view of an exemplary embodiment of an engine design according to the present invention.

[0028] FIG. **27** is a perspective view in cross-section of the exemplary embodiment of an engine design of FIG. **26** and according to the present invention.

[0029] FIG. **28** is a schematic diagram of the energy balance of an engine according to an exemplary embodiment of the present invention.

DESCRIPTION

[0030] Small, light-weight portable engines producing compressed fluids are capable of use in applications such as orthotics, power tools, and robots. An example of such an engine is shown in FIGS. **1**A and **1**B, where the engine provides compressed fluid to power an orthotic leg/ankle system that may assist for example injured or disabled persons in walking. FIGS. **1** and **2** show the engine **10** attached to the back of the orthotic leg/ankle system **11**. According to a preferred embodiment, the engine **10** uses a liquid fuel and is free of external electric power cords and heavy electric batteries that could limit portability.

[0031] Designs according to the present invention are useful for compressing fluid, such as gases including air, as well as for hydraulic pumps, wherein non-compressible fluids, such as certain liquids, are pressurized and accumulated so as to generate hydraulic power, or as for alternator designs, wherein linear motion is converted to electrical energy, to generate electricity. The uniqueness of the designs of the present invention is based upon the extraction of work from linear motion of one or more pistons, as opposed to the extraction of work from rotary shaft output. As a result, piston pneumatic pumps, hydraulic pumps and alternators are contemplated applications for small engines of the present invention. For purposes of describing certain preferred embodiments of the present invention with the understanding that engines of the present inventions can be used as stated above, a fluid compression apparatus is described as follows.

[0032] Referring to FIG. **3**, an engine cylinder is shown comprising a combustion cylinder **12** and a compression cylinder **14**, which components may be made integrally or as separate components and connected together. The engine cylinder also comprises a fuel inlet **16**, an exhaust outlet **18**, a fluid inlet **20** and a compressed fluid outlet **22**, as are shown. The engine cylinder may comprise a metal alloy (such as an aluminum alloy) or other suitable materials.

[0033] As shown in FIGS. **4** and **5**, the combustion cylinder **12** may comprise a combustion chamber **24** and a holding chamber **26**. The combustion cylinder **12** is shown as comprising an outer cylinder **28** and a cylinder liner **30**. The cylinder liner **30** may comprise metal or metal alloys (e.g. steel, titanium or brass), layered metals (e.g. chrome-coated brass, anodized aluminum, or other electroplated metals), polymer-coated materials (e.g. polytetrafluoroethylene (PTFE, e.g. Teflon®) coated metals), or ceramic or ceramic-coated (e.g. diamond coated) materials or other suitable materials. A piston assembly **31** is illustrated comprising a piston rod **32**, connected on one end to a combustion piston-head **34** and on the other end to a compression piston-head **36**. Also, a rebound element **38** is shown located within the cylinder. As shown, one end of the piston assembly extends into and through the holding chamber and further into the combustion chamber. The combustion piston-head **34** is shown located inside the combustion cylinder. Piston and rod connection techniques including wrist pins and the like are well known and any such connection is contemplated. According to a preferred embodiment, as shown in FIGS. **3-7**, the piston assembly **31** comprises a free piston assemble, i.e., the piston assembly **31** is not connected to a crankshaft so as to provide linear output, i.e. compression or fluid pumping from the compression cylinder **14**.

[0034] In some embodiments, the piston assembly **31** may also comprise a starting element **40**. According to exemplary embodiments as illustrated, the starting element **40** comprises a starting handle for manual starting, but could otherwise comprise a compressed fluid starter, an electromagnetic starter, a spring-loaded starter, or otherwise. The purpose of the starting element is to cause at least one compression of fuel/air mix within the combustion chamber **24** so as to allow for a first combustion within the combustion chamber **24** to drive the piston **34** and thus piston assemble **31** away from the end of the combustion chamber **24**.

[0035] The combustion cylinder **12** also comprises the inlet **16** as such can be operatively connecting a fuel source (e.g. a carburetor or a fuel injector system). The inlet preferably opens into the holding chamber **26**. It accordance with a preferred embodiment, the holding chamber **26** is connected for fluid communication to the combustion chamber **24** by way of a passage **42** that opens into the combustion chamber **24** at a determined position (discussed more below) by way of a port **43**. The passage **42** may comprise a space provided along and within the wall of the combustion cylinder liner **30** to fluidly connect the combustion and holding chambers **24** and **26**. For example, the space may be created by removing material from the combustion cylinder liner **30**. The combustion cylinder **12** also comprises the outlet or exhaust **18** for connecting the combustion chamber **24** to a space outside the combustion cylinder. In an exemplary embodiment, the space outside the combustion cylinder **12** is an exhaust system.

[0036] The compression cylinder **14** comprises a compression chamber **44** with the compression cylinder shown as connected to one end of the combustion cylinder **12**. According to an preferred embodiment, the compression cylinder **14** may also comprise an outer cylinder **46** and a cylinder liner **48**. The cylinder liner may comprise metal or metal alloys (e.g. steel, titanium or brass), layered metals (e.g. chrome-coated brass, anodized aluminum, or other electroplated metals), polymer-coated materials (e.g. PTFE coated metals), or ceramic or ceramic coated (e.g. diamond coated) materials, or other suitable materials. Alternatively, the compression cylinder **14** may also comprise glass or polymeric materials (e.g. PTFE). A seal **50** (described in greater detail below) is preferably located at one end of the combustion cylinder **12**, forming a boundary between the holding chamber **26** and another chamber, such as the compression cylinder or another (intermediate) chamber (e.g. the rebound chamber). As shown in FIGS. **4** and **5**, the seal **50** preferably includes a plurality of disc-like elements **52** that are supported in position by being sandwiched between the ends of the combustion cylinder **12** and the compression cylinder **14**. As shown in FIGS. **11** and **12**, these discs **52** are slotted as shown at **53** so as to allow for passage of the piston rod **32** as it is movable back and forth. By using plural discs **52**, an effective boundary can be provided to the holding chamber **26** so that inlet gas/air mixture or other combustible fuel does not flow into the compression cylinder or any of its chambers. The slots **53** are preferably tightly fit to the piston rod's **32** diameter to minimize leakage. The pistons are rigidly connected so as to move together. The result is a holding chamber **26** sealed on the one side bounded by the seal **50** that varies in volume with movement of the combustion piston **34** without regard to the movement of the compression piston **36**.

[0037] Referring again to FIGS. **4** and **5**, according to a preferred embodiment, the piston assembly **31** extends into the compression chamber **44**. The piston assembly **31** is also shown extending into and through a rebound chamber **54**. The compression piston-head **36** is positioned to be located inside the compression cylinder **14**. The compression cylinder **14** also preferably comprises the fluid inlet **20** and the compressed fluid outlet **22**. The fluid inlet **20** can thus connect the compression chamber **44** to a space outside of the compression cylinder **14**. For example, the space outside of the compression cylinder **14** may be the environment. According to an embodiment of the present invention, the compressed fluid outlet **22** may connect the compression chamber **44** to a compressed fluid storage system, for example an accumulator, schematically shown in FIGS. **4** and **5**. Many types of fluid accumulators are well-known, and any of such accumulators could be used in accordance with the present invention.

[0038] As shown in FIGS. **4** and **5**, according to a preferred embodiment, the compression cylinder **14** also comprises the rebound chamber **54**. According to any exemplary embodiment, the rebound chamber **54** also comprises an elastic rebound element **38** (e.g. an element that does not experience permanent deformation when compressed). For example, the rebound chamber **54** may house a spring as the rebound element **38** that may comprise a coil spring, a wave spring, or another embodiment to store and return sufficient energy. The spring may comprise metal or metal alloys (e.g. steel, titanium or beryllium) other suitable materials. Alternatively, the rebound element may be configured as a system, such as a pneumatic, electrical, magnetic, or hydraulic system. According to alternative embodiments, the rebound element can be housed in either of the holding chamber **26** or the compression chamber **44**. According to a preferred embodiment as illustrated, the rebound element **38** of a compressive type can be located within the rebound chamber **54**. According to a preferred embodiment, the rebound chamber **54** and the rebound element **38** may be located between the seal **50** and the compression piston-head **34**, as seen in FIGS. **4** and **5**. More specifically within the illustrated embodiment, the spring as the rebound element **38** sits against a seat portion **58** (see FIGS. **11** and **12**) of the manual start element **40** and against the internal edge of the compression cylinder sleeve **48** so as to provide an effective bias to the start element **40**, which is fixed with the piston rod **32** for axial movement thereof along with the combustion piston **32**. According to an alternative embodiment, one end of a spring may be attached to the piston rod **32**.

[0039] As shown in FIG. **6**, according to an embodiment of the present invention, the engine may comprise a two-stroke engine utilizing a scavenging process allowing exhaust to exit while a fuel mixture enters the combustion chamber **24**. As the piston assembly **31** moves away from the combustion end of the cylinder, the exhaust outlet may be exposed to the combustion chamber **24**, letting out the exhaust, slightly before the fuel inlet port **43** is exposed, letting in the fuel mixture and allowing for the completion of the scavenging process. The fuel mixture may comprise a fuel (e.g., a hydrocarbon mixture, such as diesel fuel, an alcohol, such as methanol, or another gaseous or liquid fuel, such as dimethyl ether) and a source for oxygen (e.g. air). The fuel mixture may also comprise a lubricating agent, such as oil or other suitable lubricant. According to an exemplary embodiment, the fuel mixture may comprise, as necessary, between 1 and 20 percent lubricating agent. In alternative embodiments, other methods to lubricate the engine may include utilizing a separate lubricant reservoir, lubricant dripping, or lubricant impregnated materials. In embodiments utilizing fuel injection methods, the oxygen source may enter the combustion chamber through an inlet valve.

[0040] Referring again to FIG. **6**, according to the illustrated embodiment, movement of the piston assembly toward the compression end causes the compression piston-head **36** to compress fluid within the compression chamber **44**, which in turn causes positive pressure to build-up in the compression chamber **44**. The compressed fluid may then be let out of the compression chamber **44** through the fluid outlet **22**, which may be regulated by a compressed fluid outlet valve or the like. The movement of the combustion piston-head **36** toward the compression-end of the cylinder also causes a compression of the rebound element **38** for example by causing the compression spring to be compressed, as shown in FIG. **6**.

[0041] According to the exemplary embodiment as shown in FIG. **7**, approximately at the time the piston assembly **31** begins to move back toward the combustion-end of the cylinder, a homogenous or near homogeneous fuel-oxygen mixture is preferably initiated so as to enter through the fuel inlet **16** into the holding chamber **26**. The fuel inlet **16** may be regulated by a fuel inlet valve or the like as are conventionally known. According to an exemplary embodiment, the fuel inlet valve may comprise a reed valve or other method wherein the fuel inlet **16** and outlet **18** for exhaust valves are exposed to the combustion chamber **24** at the appropriate time. In alternative embodiments, a fuel inlet valve and the outlet for exhaust may be controlled electronically and may comprise a sensor assembly. As the piston assembly **31** begins to move toward the compression-end of the engine, the combustions piston head **34** begins to pressurize the fuel mixture while the piston head **34** is still blocking the mouth(s) of the port(s) according to an embodiment. Further movement of the piston assembly toward the compression end (as seen FIG. **6**) exposes the port **43** of the passage **42** and the outlet **18** for exhaust, allowing the positive pressure of the fuel mixture to cause the mixture to enter the combustion chamber **24** from the holding chamber **26** and through the passage **42** and out the port(s) **43** so as to also simultaneously force the exhaust out of the combustion chamber **24** through the outlet **18** for exhaust. According to alternative embodiments, fuel and/or a source for oxygen may be injected directly into the combustion chamber **24** (e.g. direct injection). Alternatively, fuel and/or a source for oxygen may be separately introduced.

[0042] As shown in FIG. **7**, according to the illustrated embodiment, the compressed rebound element **38** (e.g. spring) will exert a biasing force causing the piston assembly **31** to move (i.e. return) toward the combustion-end of the cylinder. The movement of the compression piston-head **36** away from the compression end may lower the pressure in the compression chamber **44** due to the simultaneous or nearly simultaneous closing of the fluid outlet valve **22**. As the compression piston head **36** moves, fluid (e.g. air) may enter through the fluid inlet **20**, which may be regulated by a fluid inlet valve, into the compression chamber **44**.

[0043] The movement of the piston assembly **31** toward the combustion-end of the cylinder (as seen in FIG. **7**) will eventually effectively block the port **43** of passage **42** and the exhaust outlet **18**. According to a preferred embodiment, the movement of the piston assembly **31** may continue until the fuel-oxygen mixture reaches a compression corresponding to sufficient pressure and temperature, to cause ignition of the charge and initiating combustion. The force of combustion may cause positive pressure to build-up in the combustion chamber pushing the piston assembly **31** toward the compression-end of the cylinder.

[0044] As shown in FIGS. **8-10**, the combustion cylinder **12** may comprise one or more ports, which ports would include an inlet **43** (as the port opening directly into the combustion chamber **24**) and an outlet or exhaust **18** (as a portion opening directly from the combustion chamber **24**). The ports may be configured to enable scavenging, such as cross-flow scavenging, uni-flow scavenging, or loop-flow scavenging (also known as Schnuerle type scavenging). According to an exemplary embodiment, the combustion cylinder **12** comprises the two or more ports as shown in FIGS. **8-10** in a configuration taking advantage of loop-flow scavenging. As shown in FIG. **9**, the mouths of the ports **43** and **18** can be positioned such that the inlet flow is directed away from the exhaust outlet such that the gases initially enter a combustion chamber **24** moving away from the exhaust outlet **18**. As shown in FIG. **10**, the configuration may comprise three (or more) ports **43** wherein the port **43** located opposite the exhaust outlet **18** in the combustion chamber **24** is also directed away from the exhaust outlet **18**.

[0045] As shown in FIGS. **11** and **12**, the piston assembly **31** may comprise a piston rod **32**, connected on one end to a combustion piston-head **34** and on another end to a compression piston-head **36**, and a compression element as a rebound element **38**. According to an exemplary embodiment, the compressing element **38** is at least partially provided inside the compression cylinder **14** above the compression piston-head **36**. The piston assembly **31** may comprise one or more wrist or other type pins attaching the piston-heads to the piston rod **32**. The piston rod **32** may comprise one or multiple diameters throughout its length to accommodate assembly, for example, to accommodate the diameter of the pin used to attach a piston-head to the piston rod **32**. The combustion piston head **34** may be comprised of metal (e.g. titanium, steel, or aluminum), metal alloys, or metal mixtures. The compression piston head **36** may also be comprised of metal or metal alloys (e.g. titanium, steel, or aluminum), polymeric materials (e.g. PTFE, nylon, or other polymers)), ceramic materials, graphite, or other suitable materials.

[0046] Multiple variables, such as the operating frequency, affect the efficiency and the output power of the engine. The power output of the engine can be adjusted to accommodate the requirements of the planned end-use application. For example, a 10 W output may be appropriate for an orthotic appliance, whereas a lift-assist application may require a power output as high as 100-200 W. To achieve the desired power output, the frequency of the engine can be adjusted by the selection of the materials and construction of the piston assembly and the rebound element. Also, the frequency and the displacement may be varied. For example, the material and dimensions of the piston heads and piston rod may be chosen to reach a suitable weight relative to the stiffness (i.e. the spring constant or spring rate) of the rebound element (e.g. spring). On the other hand, a suitable rebound element may be chosen to match the weight of the piston assembly and to achieve an optimal rebound effect. For example, a rebound element that is too stiff will absorb too much of the energy created by combustion, thus lowering the output power of the engine. A rebound element that is not stiff enough will have difficulty returning the piston assembly back into position to pressurize and ignite the fuel, thus causing poor or incomplete combustion. According to a preferred embodiment, the rebound effect causes sufficient compression of the fuel-oxygen mixture to ignite the mixture without the use of another source of ignition, such as a glow plug or a spark plug. An optimal operating frequency will minimize leakage and friction, and maximize compressed fluid output power. Other materials (e.g. for the engine cylinders) may be chosen keeping in mind the desired portability and light weight. For example, according to a preferred embodiment, the engine cylinders may comprise aluminum or aluminum alloys, as opposed to heavier metals.

[0047] The seal **50**, for example, can comprise a double jaw seal, as such may be used to isolate the holding chamber **26** from the rebound chamber **54**. The seal configuration is preferably chosen so that it fits tightly around the piston rod **32** while permitting the piston rod to slide along the slots **53** and the seal **50** effectively prevents a substantial amount of fuel-oxygen mixture from escaping from the holding chamber **26** into another area, for example, a rebound chamber or a compression chamber. The seal **50** may comprise multiple elements **52**, as described above, with each element **52** made up of polyether ether ketone (PEEK), bronze, PTFE, or other suitable material or combination of materials. The efficiency of the seal **50** affects the leakage of fuel from the holding chamber **26**. A tighter, more efficient seal will improve (i.e. lessen) leakage and advantageously allow for smaller bore-size engines (e.g. a few millimeters or micro- or nano-scale engines) to be operational.

[0048] As shown in FIG. **13**, the starting handle element **40** may extend through an axially extending slot **60** provided along a wall of the compression cylinder **14** according to an exemplary embodiment. In alternative embodiments, another method of initially displacing the piston assembly may be used such that a starting handle may not be required. FIG. **14** shows an alternative embodiment of the slot **60** comprising a means, such as a rubber bumper **62** for preventing impact (e.g.

a spring, air chamber, or the like) positioned to prevent the starting handle element **40** from impacting the cylinder wall at the end of the slot.

[0049] According to exemplary embodiments, many different types of valves may be chosen for the various inlets and outlets. For example, stacked valves shown in FIGS. **15** and **16** can be chosen to control the flow of compressed fluid from the device. Such a stacked valve construction can be designed based upon well-known and conventional techniques where the stacked elements together control the fluid flow from the device outlet. As shown in FIG. **17**, the valve at the fuel inlet may be a Reed-type valve according to an exemplary embodiment, as Reed valves themselves are well known. The valve may comprise metal or metal alloys, such as stainless steel, steel, titanium, or other suitable materials.

EXAMPLES

[0050] A number of experiments were conducted to study the construction and operating parameters of engines in accordance with the present invention. The experiments were conducted either by utilizing various computerized models, or by studying prototypes of engine designs.

[0051] In the first example, engine blow-by leakage was modeled and compared against experimental data utilizing a small glow-plug engine. As shown in FIG. **18**, simulation data of heat transfer alone and heat transfer and leakage were compared to experimental data measuring motoring peak pressure. Results from the model and experimental data show that motoring peak pressure increases with engine speed, as measured by rotations per minute, indicating that miniature engines can be run at high speed to avoid excessive blow-by leakage.

[0052] In another example, engine leakage and friction efficiencies were modeled in combination to determine optimal engine speeds (i.e. frequencies) as shown in FIG. **19**. High engine speed may reduce leakage and heat transfer losses but may increase friction loss. Considering these two factors, optimal operating ranges were approximately between 100 and 150 Hz. Along with knowledge of a target engine output power, engine speed assists in determining the appropriate engine size.

[0053] In the third example, the combustion cylinder pressure, piston position, compressed air reservoir pressure, engine frequency and indicated mean effective pressure (IMEP) were modeled using a computer model and a glow ignition prototype engine (a remote-control-aircraft engine) to estimate the compressed fluid power output of the engine. As shown in FIG. **20**, the combustion chamber pressure built up from about 15 bar to about 20 bar and above after the piston movement began to expose the exhaust outlet to the combustion chamber and scavenging occurred, supplying the engine with fresh fuel-oxygen mixture for the next cycle, thus increasing the pressure. As shown in FIG. **21**, pressure in the compressor chamber rose with operating time as pressure in the reservoir attached to the compressed fluid outlet rose. Engine frequency also increased with operating time to approximately a range between 112 and 123 Hz as predicted by the model. Compressed fluid power was calculated to be approximately 5 W.

[0054] In the fourth example, the complex and unrestrained motion of a free-piston, glow-plug configuration was measured as piston speed versus piston position as shown in FIG. **22**. As a comparison, the free-piston model data and experimental data were compared to a model crank engine as shown in FIG. **23**. The free-piston model accurately fits with the resulting experimental data indicating that the model was able to accurately predict engine dynamics.

[0055] The fifth experiment was conducted comparing a free-piston engine with a crankshaft engine of the same size also utilizing glow-plug ignition. Results, as shown in FIG. **24**, indicate that a higher compression ratio of around 10 in the free-piston engine resulted in average cycle efficiency of approximately 18.1 percent as compared to the compression ratio of 5.3 and average cycle efficiency of about 22 percent of the crankshaft engine.

[0056] The sixth experiment was conducted to compare model HCCI performance with model glow-plug ignition performance and experimental glow plug performance. Results, as shown in FIG. **25**, indicate that model glow-plug ignition performance accurately predicted the experimental glow-plug ignition performance. The model predicts that the heat release efficiency of the HCCI free-piston engine will be approximately 41 percent as compared to the 25 percent of the glow-plug engine.

[0057] A miniature fluid compression engine is illustrated within FIGS. **26** and **27**. The cylinder was specifically constructed for test purposes and was made of stainless steel with cylinder liners made of chrome plated brass. The dimensions of this specific example of an engine of the present invention includes the device being approximately 110 millimeters in length and approximately 38 millimeters in diameter with a 12.5 millimeter inside bore. With an attached carburetor and muffler, the engine system was approximately 75 millimeters wide. The operating frequency of the engine was optimized by adjusting the weight of the piston assembly and the stiffness of the spring to avoid leakage (which may be caused by a low frequency), high friction and noise (which may be caused by a high frequency). The pistons were preferably made of aluminum alloy, resulting in a weight of the moving parts of 33 grams. The spring system was made of steel and had a 1500 N/m resistance, measured approximately 2.5 millimeters in height at rest and has a pre-load force of 19 N. The system utilized glow plug ignition, a manual starter and a methanol-based fuel mixture. Using these parameters, the desired operating frequency of 100 Hz was achieved. As constructed, the combustion cylinder chamber had a volume measuring 0.13 cubic centimeters with a compressor cylinder chamber volume of 2.0 cubic centimeters when the spring was fully extended. When the spring was compressed completely, the engine cylinder chamber volume measured 1.7 cubic centimeters with a compressor cylinder chamber volume of 0.36 cubic centimeters. Designed with a 2 mm overstroke, the engine is able to account for variations in piston travel, resulting in weak and strong cycles. The piston travel is long enough to enable scavenging and of a length that would result in metal to metal collision without the use of a bumper. Therefore a rubber bumper was incorporated to absorb some of the shock of the manual ignition handle impacting the cylinder. The energy balance of the engine is shown schematically in FIG. **28**.

[0058] It is important to note that the construction and arrangement of the elements of the inventions as described in this application and as shown in the figures above is illustrative only. Although some embodiments of the present inventions have been described in detail in this disclosure, those skilled in the art who review this disclosure will readily appreciate that many modifications are possible without materially departing from the novel teachings and advantages of the subject matter recited. Accordingly, all such modifications are intended to be included within the scope of the present inventions. Other substitutions, modifications, changes and omissions may be made in the design, operating conditions and arrangement of the preferred and other exemplary embodiments without departing from the spirit of the present inventions.

[0059] It is important to note that the system and method of the present inventions can comprise conventional technology (e.g., engine cylinders, pistons, valves, carburetors, mufflers, fuels, lubricants, etc.) or any other applicable technology (present or future) that has the capability to perform the functions and processes/operations indicated in the FIGURES. All such technology is considered to be within the scope of the present inventions.

What is claimed is:

1. A system for providing pressurized or compressed fluid comprising a fluid pumping/compression cylinder coupled to a combustion cylinder and a rebound chamber, and a piston assembly contained at least partially and capable of movement within the combustion cylinder and the pumping/compression cylinder, wherein:

the combustion cylinder comprises

a holding chamber on a first side of a combustion piston, the holding chamber comprising at least a fuel inlet; and

a combustion chamber on a second side of the combustion piston;

wherein the holding chamber and the combustion chamber may be connected by at least one passage that is openable and closeable by movement of the combustion piston;

and wherein the pumping/compression cylinder comprises a fluid chamber on a first side of a pumping/compression piston;

and wherein the rebound chamber comprises a rebound system;

wherein the pumping/compression chamber comprises at least one inlet and at least one outlet.

2. The system of claim **1** wherein the piston assembly is a free piston assembly and is not connected to a crankshaft.

3. The system of claim **1** wherein the piston assembly comprises a piston rod connected on one end to a combustion piston head and on the other end to a compression piston head.

4. The system of claim **1** wherein the piston assembly comprises a starting element.

5. The system of claim **4** wherein the starting element comprises a compressed fluid starter, an electromagnetic starter, a spring-loaded starter, or a starting handle.

6. The system of claim **4** wherein the starting element comprises a bar extending beyond the outer cylinder.

7. The system of claim **1** wherein the compression cylinder comprises the rebound chamber.

8. The system of claim **1** wherein the compression chamber comprises the rebound chamber.

9. The system of claim **1** wherein the holding chamber comprises the rebound chamber.

10. The system of claim **1** wherein the rebound system comprises an elastic element.

11. The system of claim **10** wherein the elastic element comprises a spring.

12. The system of claim **10** wherein the elastic element comprises a pneumatic or hydraulic system.

13. The system of claim **1** wherein the combustion chamber is configured to utilize loop-flow scavenging to remove exhaust.

14. The system of claim **1** wherein the combustion chamber includes at least one inlet port and at least one exhaust port and wherein the orientation of the inlet port relative to the exhaust port enables scavenging.

15. The system of claim **19** wherein the inlet ports and exhaust ports are positioned such that as the piston assembly moves away from the combustion chamber, the exhaust ports are exposed before the inlet ports are exposed.

16. The system of claim **20** wherein the exposure of the port for exhaust and the inlet port or ports are controlled electronically through a sensory assembly.

17. The system of claim **1** comprising a seal coupled to the combustion cylinder and the compression cylinder so that fuel is substantially prevented from escaping from the combustion cylinder into the compression cylinder.

18. The system of claim **17** wherein the seal comprises a jaw seal.

19. The system of claim **18** wherein the seal comprises polyether ether ketone.

20. The system of claim **1** wherein the compression cylinder comprises a means for preventing collisions between metal elements.

21. The system of claim **20** wherein the means for preventing collisions comprises an elastic element.

22. The system of claim **21** wherein the means for preventing collisions comprises a rubber bumper.

23. A method for providing compressed fluid comprising the steps of:

intaking fuel and oxygen within a combustion chamber;

compressing fuel and oxygen by a piston within the combustion chamber by a first movement of a piston assembly and causing ignition of the fuel and oxygen mixture;

combusting the fuel and oxygen mixture;

causing a second movement of a piston assembly as a result of the combustion within the combustion chamber, wherein the second movement is opposite in direction from the first movement;

storing potential energy in a rebound system;

compressing a fluid;

releasing compressed fluid;

releasing potential energy from the rebound system;

causing a third movement of the piston assembly in an opposite direction from the second movement by action of the released energy from the rebound system and from energy of the compressed fluid within a compression chamber;

intaking a next cycle of fuel and oxygen; and

exhausting combusted fuel and oxygen from the combustion chamber.

24. The method of claim **23**, wherein the intaking of fuel and oxygen comprises supplying fuel and oxygen to a holding chamber within a cylinder that includes the piston assembly comprising a piston rod connected between a combustion piston and a compression piston, the combustion chamber being positioned on one side of the combustion piston within the cylinder and the holding chamber being positioned on an other side of the combustion piston within the cylinder, and further wherein the intaking steps comprise fluidly flowing fuel and oxygen from the holding chamber to the combustion chamber through a passage within the cylinder.

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