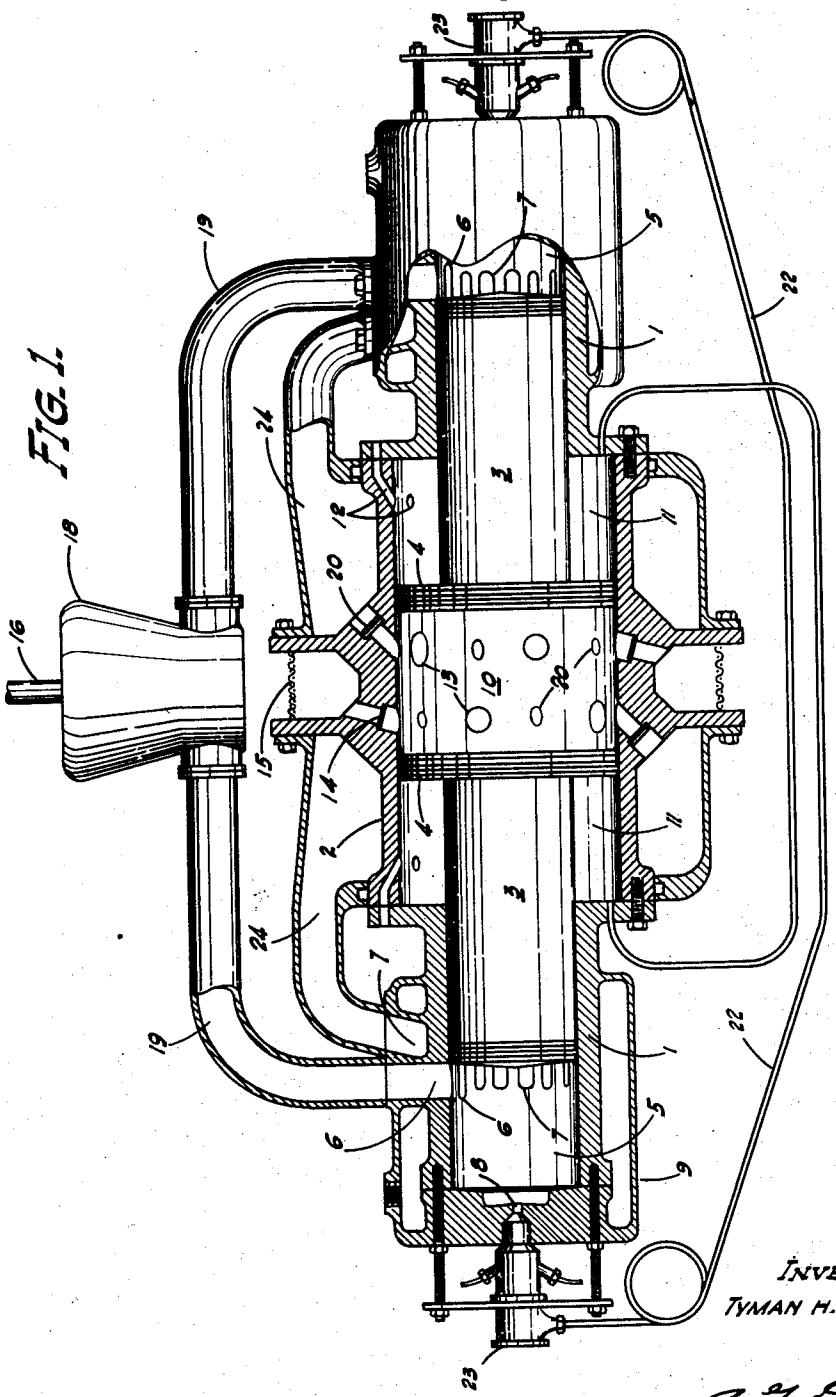
July 12, 1960 T. H. FIKSE 2,944,535

FREE PISTON ENGINE

Filed Jan. 23, 1958 4 Sheets-Sheet 1

FIG. 1.



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FREE PISTON ENGINE

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FIG. 7.

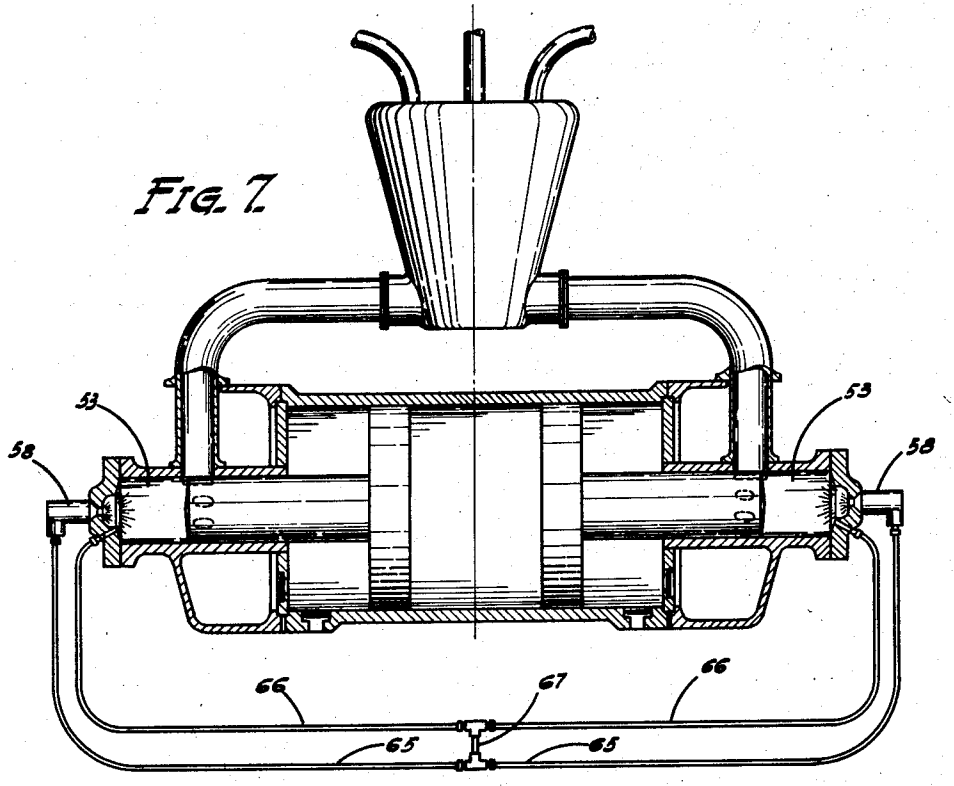


FIG. 2.

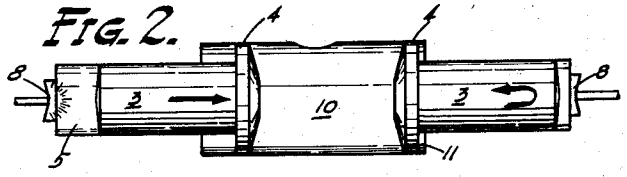


FIG. 3.

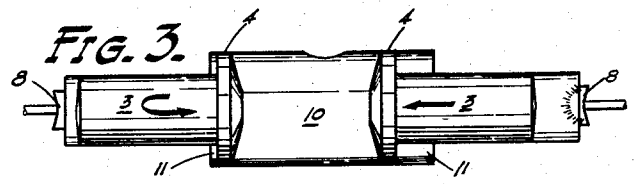
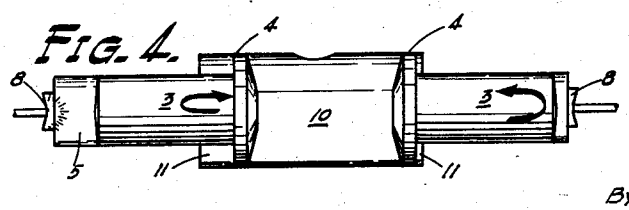


FIG. 4.



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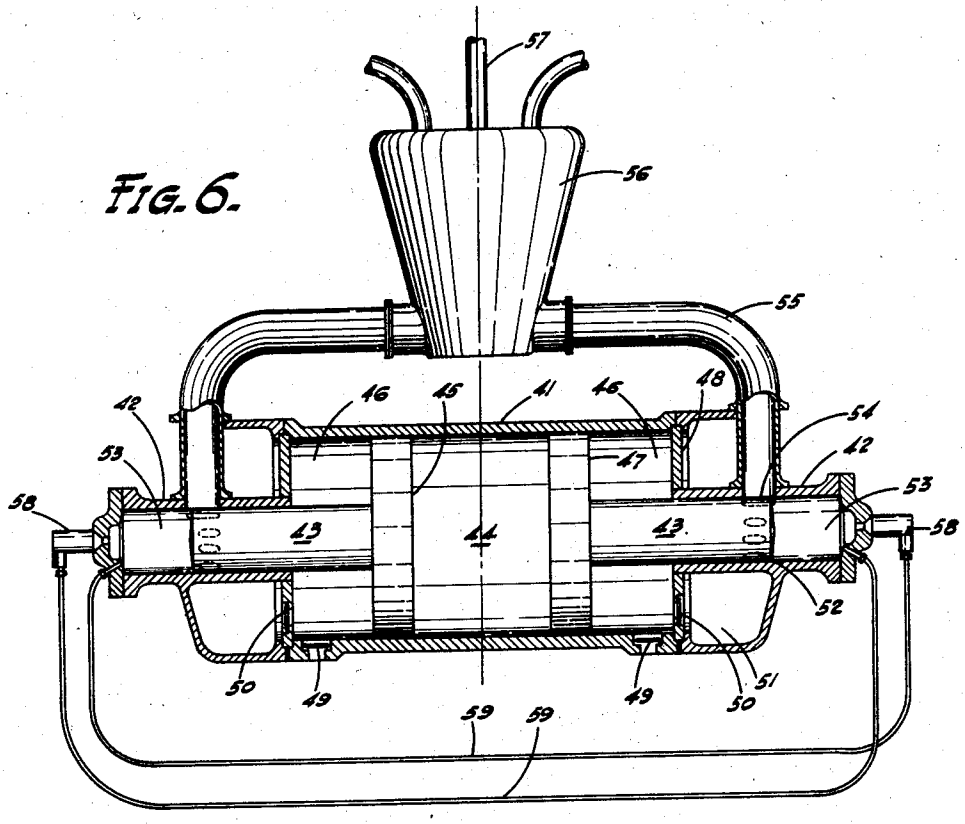
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FREE PISTON ENGINE

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FIG. 6.



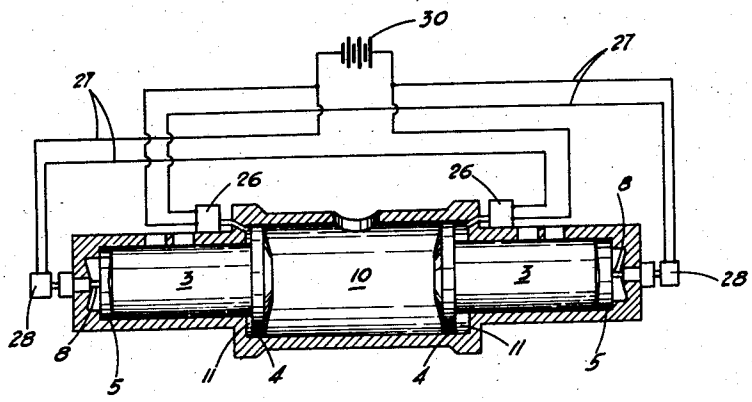


FIG. 5.

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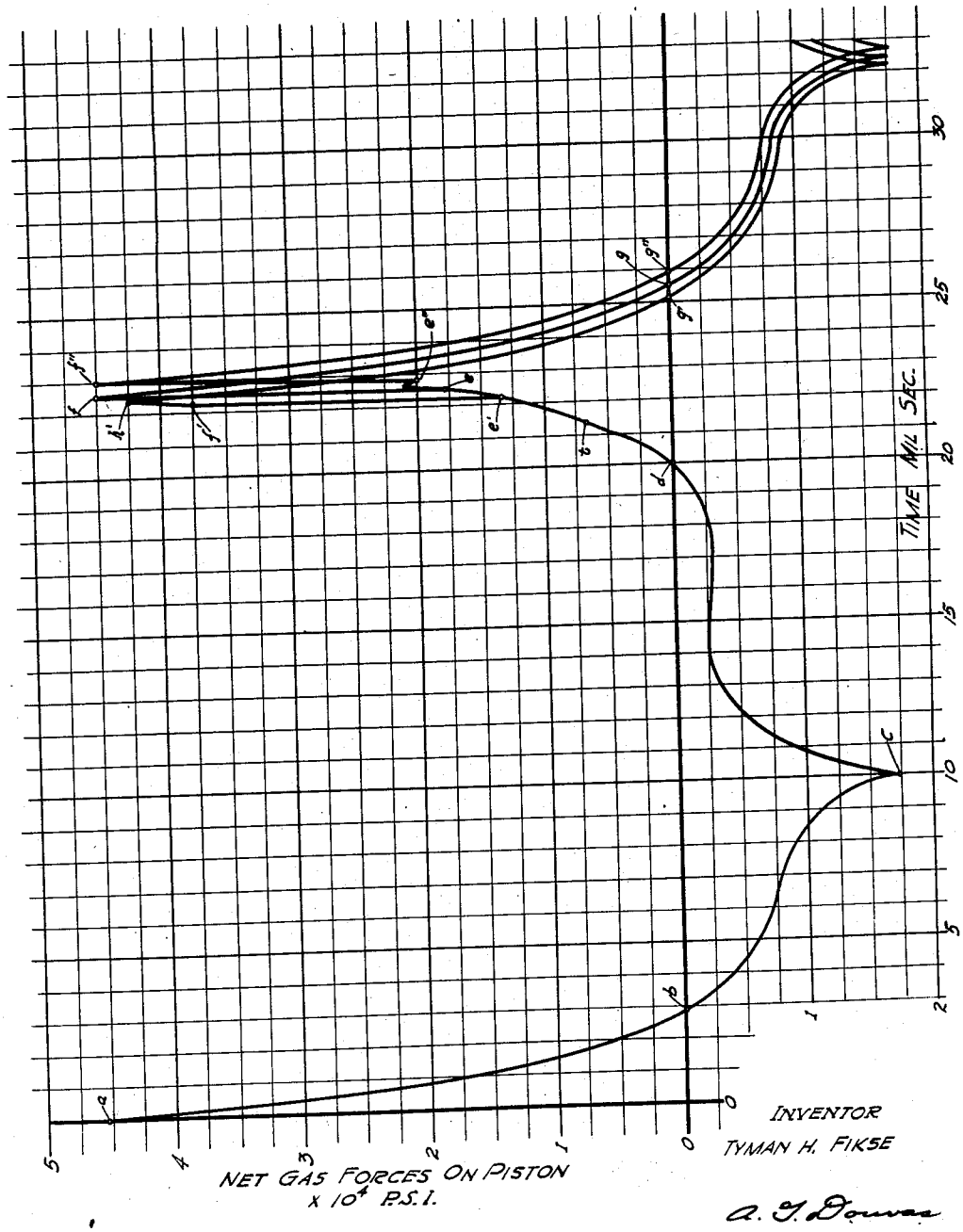
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FREE PISTON ENGINE

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FIG. 8.



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FREE PISTON ENGINE

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Filed Jan. 23, 1958, Ser. No. 710,663

10 Claims. (Cl. 123—46)

This invention relates to a new and improved free piston engine.

In the usual opposed free piston engine of the prior art, a pair of pistons operate opposite each other in a horizontally disposed cylinder. A mixture of air and fuel is fired within a central combustion chamber located between the pistons, and the resulting combustion of the fuel drives the pistons apart. As the pistons move outwardly, the pistons compress air at the ends of the cylinder. This compressed air bounces the pistons back to the center of the cylinder so that the operating cycle is continued.

The efficiency of this engine is detrimentally affected by non-synchronous movement of the pistons. Accordingly, complicated and cumbersome mechanical means are usually employed to interconnect the pistons for proper coordinated movements. The incorporation of mechanical synchronizing means requires that linkages project through the cylinder walls so that the piston movements may be appropriately interlocked by devices located externally of the cylinder. Friction and gas losses are particularly large due to the sealing requirements at the connections to the pistons and cylinder walls of the synchronizing means.

Accordingly, a principal object of this invention is to provide a new and improved opposed free piston engine characterized by high operational efficiency and simplified construction.

Another object is to synchronize the movements of oppositely movable pistons of an engine so that they maintain substantially corresponding relationships to their respective cylinders without mechanical interconnection of any form.

Another object is to provide improved means in a free piston engine for sensing the position of one piston and effecting initiation of the power stroke for the other piston when the one piston has reached a particular position.

These objects are attained herein by an engine arrangement in which two combustion chambers are disposed at the opposite ends of a composite cylinder formed in an engine block and containing two free pistons. A common main air compression chamber is centrally disposed between the adjacent ends of the pistons. The burning of fuel in the end combustion chambers drives the pistons inwardly. As the pistons move inwardly, the pistons compress the air within the main chamber. This compressed air bounces the pistons back to the ends of the cylinder to continue the cycle.

Synchronization of the pistons is effected by pneumatic sensing means that requires no connection to the pistons. A preferred synchronizing arrangement, for example, employs an auxiliary air compression chamber in the engine block for each piston. Air is compressed in each chamber when the associated piston approaches its most outward position. When a piston has reached a predetermined outward position sensed by the degree of compression of air in the associated auxiliary air compression chamber, initiation of the power stroke for the opposite piston is effected automatically. Thus, when each of the pistons reaches a critical outermost position, it effects initiation of the power stroke for the other piston.

In order that all of the features for attaining the objects of this invention may be readily understood detailed reference is herein made to the drawings wherein:

Fig. 1 is a side elevation of the free piston engine of the present invention with the cylinder walls broken away so as to show the internal construction;

Fig. 2 is a simplified longitudinal sectional view of the engine shown in Fig. 1 and illustrating the pistons in one possible operating position;

Figs. 3 and 4 are views related to Fig. 2 and showing the pistons in other possible operating positions;

Fig. 5 is a simplified longitudinal sectional view of the free piston engine of this invention and employing an alternative type of cross-synchronization control;

Fig. 6 is a side elevation of a Pescara type free piston engine modified to incorporate a cross-timing synchronization arrangement of the general type employed in the engine of Fig. 1;

Fig. 7 shows a modification to the cross-timing synchronization arrangements of Figs. 1 and 6; and

Fig. 8 is a graph showing the manner in which variations in the time of fuel injection vary the cycling frequency of individual pistons in a free piston engine.

The free piston engine illustrated in Fig. 1 is of the two-cylinder opposed type and includes an engine or cylinder block having two identical cylinder sections **1** and an intermediate compressor section **2** bolted together. The bore in the central compressor section is larger than the bores in the cylinder sections. The free pistons are housed in the engine block. These pistons each include a body portion **3** disposed in a cylinder bore formed in an engine block end section and an enlarged head **4** disposed in the bore of the central compressor section **2**. The body and head portions of each piston may have suitable sealing rings of conventional character associated therewith.

The engine is preferably of the two-stroke cycle type so that each combustion chamber **5** has inlet and exhaust ports controlled by movement of the associated piston body **3**. Compressor section **2** supplies air to air casing **24** through delivery valves **20**. This air is conveyed to combustion chamber **5** through inlet ports **7**. Each combustion chamber **5** is exhausted into manifold **19** through exhaust ports **6**, thereby energizing turbine **18** so that shaft power is delivered at **16**.

If the engine is of the liquid fuel injection type as illustrated, an injection nozzle **8** injects a stream of atomized fuel into the combustion chamber **5** when the injector mechanism is actuated. A conventional water cooling jacket **9** encircles each combustion chamber **5**.

The principal air compression chamber **10** is located between the heads **4** of the two pistons. An auxiliary air compression chamber **11** is located between each of the pistons and the adjacent cylinder section of the engine block. These auxiliary chambers constitute pneumatic sensing mechanism for determining the lengthwise position of each piston in the engine block. Vent passages **12** extend through the wall of the central section. These passages vent the chambers **11** behind the piston heads **4** during most of the stroke length of the pistons. Piston heads **4** cover the openings for passages **12** as the pistons move outwardly. Air is thus compressed in the auxiliary air compression chambers **11**.

The engine compresses air in the air compression chamber **10** between the piston heads **4**. This air is delivered through delivery check valve **20** to air casing **24**. When

the piston bodies 3 have moved inwardly sufficiently far to uncover inlet ports 7, the pressure of the air compressed in the air casing 24 provides scavenging for combustion chamber 5.

Chamber 10 has a clearance volume determined by the space between the two rows of delivery valves 20. This enables return energy to be provided for the pistons so that final compression can occur in combustion chambers 5. As the pistons 3, 4 are driven outwardly by the bounce of the air trapped between the piston heads, the momentum of the pistons carries them to substantially the outer ends of combustion chamber. When the pressure in the compression chamber 10 has been reduced below inlet pressure which may be atmospheric pressure, by the outward movement of the piston heads, additional air is supplied to the air compression chamber 10 through one or more air inlet ports 13. Several of these ports are disposed in two separate rows. Air passage through each of these ports is controlled by a check valve 14 which prevents air from being forced back out through a port 13 as the pressure of the air in the chamber 10 is increased by approach movement of the piston heads 4. Screen 15 filters the air flowing through check valves 14.

As mentioned previously, the pressure of the air in air compression chamber 10 is relied upon to drive the pistons 3, 4 outwardly after the exhaust ports 6 have been opened and the pistons have completed their power stroke. It is important that the pressure of the air in the chamber 10, taking into consideration the proportionately larger size of the piston heads 4 than the piston bodies 3, be sufficient to force the pistons outwardly to close the inlet ports 7 and then to compress the air or combustible mixture in the combustion chamber before the pistons reach their fully outward positions.

When the piston bodies 3 have been driven outwardly sufficiently far by the residual compressed air in chamber 10, the power strokes are initiated in the cylinders by burning of the combustible mixture therein. Under ideal conditions the two pistons move outwardly in perfect synchronization and the combustible mixture is burned simultaneously in both combustion chambers 5. If movement of the pistons is slightly out of synchronism, however, and combustion occurs in both cylinders simultaneously, the piston last to arrive at the outer end of its stroke receives a longer and more powerful force becaues ignition starts slightly before the end of the compression stroke and continues until the exhaust ports are uncovered. The effect, therefore, is for the drive on the lagging piston to cause this piston to catch up to the leading piston.

It is proposed herein to use the action of air compressed in the auxiliary compression chambers 11 to effect initiation of the power strokes. The pressure from one of these auxiliary compression chambers is transmitted through a small conduit 22 to a power stroke initiating device 23. In the particular engine illustrated which is of the liquid fuel injection type, such power stroke initiating device may be an actuator for the plunger of the injection nozzle 8. Thus compression of air in an auxiliary air chamber 11, effected by outward movement of a piston beyond the apertures 12, senses the approach of the piston to its maximum outward position.

The left auxiliary compression chamber 11 is connected by one conduit 22 to the right cylinder power stroke initiating device 23, and the right auxiliary compression chamber 11 is connected by a second conduit 22 to the left cylinder power stroke initiating device 23. Such an interconnection functions effectively to maintain synchronization of the piston movements without a mechanical connection between the pistons.

To illustrate particular instances, examples of relative piston positions are shown in Figures 2, 3 and 4. In Figure 2, for example, the right power piston is shown at its extreme outermost position at the instant of reversal of movement. Compression of the air in the right auxiliary compression chamber 11 has caused the left nozzle to inject notwithstanding the fact that the left piston is lagging and has not yet reached its outermost position. The left piston continues to compress the air and ignition does not occur until slightly before the left piston reaches its outermost position as indicated in Figure 3.

The air compressed in the right combustion chamber 5 by outward movement of the right piston initiates movement of the right piston toward the left, but such movement is not as rapid as it otherwise would be because no fuel has been delivered to the right cylinder to effect combustion. When the left piston reaches its outermost position, however, the pressure in the left auxiliary compression chamber 11 effects combustion of fuel into the right cylinder.

Under these circumstances the left lagging piston receives a full power impulse, and the right leading piston receives a comparatively weak impulse because the exhaust ports are opened relatively soon after the fuel is injected. This enables the left piston to catch up with the right piston so that thereafter they will tend to move in synchronism. The less the pistons are out of phase, of course, the more easily they may be brought into coordinated phase movement by this technique. It will be understood that the situation discussed is unusually exaggerated.

A still more exaggerated situation representing possibly the worst conceivable condition of lack of synchronization is illustrated in Figure 4. In this example, the right piston has moved to its outermost position causing fuel to be injected into the left cylinder while the exhaust ports 6 in the left cylinder are still open so that no power impulse can occur. Also it is assumed that the left piston is about to be returned to the right by the slightly compressed air in the left combustion chamber and without closing the ports 6.

Under these circumstances, the left piston has not moved far enough to the left so that the air in the left auxiliary compression chamber 11 will effect initiation of the power stroke in the right cylinder 5 by injecting liquid fuel into it. Consequently, the right piston is returned to the left only by the compression of air in the right combustion chamber 5. Under these circumstances, the movement of the right piston to the left will drive the left piston to the left as the air is compressed in main compression chamber 10, and the more rapidly moving right piston also will be bounced back to the right by the compressed air. By this operation the left piston probably will be driven to the left far enough so that ultimately air will be sufficiently compressed in the left auxiliary compression chamber 11 to initiate the injection of fuel into the right cylinder 5, and the right piston will rebound outwardly to the right far enough to effect injection of fuel into the left cylinder 5. Despite the much greater distance travelled by the right piston over that travelled by the left piston, fuel injection will finally occur in both cylinders. Therefore, the pistons will be driven to approach synchronism, and within a few strokes the pistons should be completely synchronized.

In view of the foregoing explanation as to the manner in which the cross-connections between the auxiliary compression chambers and the power stroke initiating devices induce coordinated and synchronized movement of the two pistons, the question may be raised as to how the movement of the pistons could ever get out of synchronization as in the examples discussed. Such departure from synchronization could occur if one injection nozzle should suddenly become clogged or partially clogged and should free itself. Likewise, the pistons could lose synchronism when the fuel is shut off and the engine is stopping if the friction on the two pistons were not identical.

To start the engine it is desirable that the two pistons be approximately in the positions shown in Figure 1 in

which the pressure in the chamber **10** is atmospheric and the pistons are in the same phase relationship. With the pistons thus located a connection could be made to the valves **14** to supply a quick puff of air for producing an abrupt and brief impulse on the piston heads **4** to drive the pistons **3** toward their outermost positions.

The quick outward movement of the pistons **3** would effect injections of fuel when the pistons are approaching their outermost positions.

If the pistons **3**, **4** are not both in the same positions relative to their cylinders when the initial puff of air is discharged into the principal compression chamber **10**, a non-synchronized operation such as described above might occur for a short period following initiation of the engine operation.

In Figure 5 a modification is shown in which the engine block and piston structures are the same as those described and the same reference numerals have been employed where applicable. In this embodiment, however, it is desired to minimize the response time lag resulting from building up pressure in the auxiliary compression chambers **11** and transmitting this pressure to the opposite end of the engine. The air ducts **22** are therefore made short, and they are connected to pressure actuated circuit making devices **26** which may be conventional pressure switches. Each of these pressure switches is connected by conductors **27** to a different solenoid **28** incorporated in a solenoid fuel valve or solenoid controlled injection mechanism. A suitable power supply **30** is connected in the circuits to energize the solenoids **28** when the pressure switches **26** are closed.

As soon as the pressure in an auxiliary compression chamber **11** is sufficient to close a pressure switch **26**, it will energize the associated solenoid **28** to effect injection of liquid fuel as illustrated in Fig. 5. The operation and construction of the engine is otherwise similar to that described in relation to Figs. 1 through 4.

Figure 6 shows a revised arrangement of a Pescara type free piston engine utilizing the herein disclosed cross-timing arrangement. This engine structure comprises a central cylinder portion **41** and two identical end cylinder portions **42** of lesser diameter. The central and end cylinder portions carry two double diameter pistons **43**. The chamber **44** located within the central cylinder **41** and positioned between the piston heads **45** is utilized as the bounce space. In the conventional Pescara engine this space is divided at the extreme ends of the engine.

The spaces **46** within the central cylinder and between piston shoulders **47** and end walls **48** are utilized as primary air compression spaces. Check valves **49** provide entry to these spaces during the inward strokes of pistons **43**. Check valves **50** provide delivery passages for air compressed in chambers **46** during the outward strokes of pistons **43**. The air delivered through check valves **50** is retained in air chambers **51**.

When pistons **43** are at a sufficient inward position to maintain ports **52** open between air chambers **51** and combustion chambers **53**, passage of scavenge air is effected from air chamber **51** to combustion chambers **53** and thence outwardly through exhaust ports **54**. Exhaust ports **54** are connected to exhaust manifold **55** and turbine **56**. Output work is derived from the expansion of the gases delivered to manifold **55** and taken off as shaft work at **57**.

The general arrangement of the bounce chamber, air compression chamber, and the combustion chamber is identical with that of the Pescara type engine, except the structure adjacent the center line of Fig. 6 is located at the cylinder ends of the conventional engine and the cylinder end portions of Fig. 6 are placed end to end to form the central portion of the conventional engine. The rearrangement shown in Fig. 6 is necessary to provide separate combustion chambers **53** in which injection timing can be independently controlled.

The cross-timing arrangement herein comprises a fuel injector **58** associated with each combustion chamber **53**. A conduit **59** connects each injector **58** with the opposite combustion chamber **53**. Accordingly, the left injector **58** is actuated to initiate injection in the right combustion chamber **53** and right injector **58** is actuated to initiate injection in the left combustion chamber **53**. Synchronization occurs in the manner hereinbefore described with reference to the structure shown in Fig. 1.

Fig. 7 shows a modification in the cross-timing synchronization arrangements employed in the free piston engines of Figs. 1 and 6. For purposes of illustration, the modified arrangement is shown in conjunction with the free piston engine of Fig. 6. It should be understood, however, that the modification is also directly applicable to the engine construction of Fig. 1.

In Fig. 7, the conduits **65**, connected to injector mechanisms **58**, lead directly one to the other. Likewise, conduits **66**, connected to combustion chambers **53** (or to auxiliary air compression chambers **11** in Fig. 1), lead directly one to the other. Intermediate portions of the connected conduits **65** and the connected conduits **66** are joined one to the other by a short conduit **67**. Accordingly, both injectors **58** are actuated in response to a pressure that is the average of the pressures present in combustion chambers **53** (or auxiliary chambers in Fig. 1). This average pressure always exceeds the pressure present in any combustion chamber **53** that is defined by a lagging piston **43**. Accordingly, fuel injection is initiated earlier in this latter chamber than would otherwise be the case, and therefore synchronism is attained as hereinbefore described.

Fig. 8 shows a graphical representation of the piston forces against time in the engines herein described. The curves of this diagram show the manner in which early or late fuel injection affects the cycling frequency of individual pistons in a free piston engine having no mechanical synchronizing means.

The force-time curve for perfect synchronization is represented by the curve *abcdefg*. Injection occurs instantaneously at the inner dead point *e*. The pressure rise resulting from the injected fuel is represented by the *ef* portion of the curve.

Since the curves shown are force-time curves, the area under these curves is representative of an impulse energy quality. With respect to curve *abcdefg*, certain areas are related inasmuch as points *b*, *d*, *g* are points of maximum piston velocity and points *a*, *c*, *f* are points of zero velocity.

For simplicity in analysis, the effects of friction are neglected in the following discussion. Proceeding from *a* to *b*, the area under the curve is equal to the kinetic energy of the piston at *b*, and this kinetic energy is in turn equal to the area under the curve from *b* to the piston zero velocity point *c*.

Proceeding from point *c*, the area under the curve from *c* to *d* equals the kinetic energy of the piston at *d*, and this area also equals the area under the curve from *b* to *f*, *f* being a point of zero piston velocity.

For convenience, the period of the curve is defined as the time from *b* to *g*. If injection occurs at some increment of time prior to the *e* time, then the area beneath the curve from *d* to *h'* represents the kinetic energy of the piston at point *d*. It should be noted that the *h'* time is sooner than the *f* time, therefore the piston zero velocity time is advanced by early injection. For early injection the cycle period is then *bg'*.

If injection were to occur at some time after the ideal, such as at *e''*, the resulting cycle period would then be *bg''*.

Inasmuch as all systems have fuel and ignition delays, the pressure that initiates injection at *e* is sensed at a time *t* earlier than *e*. The portion of the curve from *t* to *e* thus represents the ignition delay.

It should be understood that the above described arrangements are illustrative of the principles of this invention and that numerous other arrangements can be devised without departing from the scope of the invention.

What is claimed is:

1. A free piston engine comprising an engine block defining a cylinder therein, a pair of opposed free pistons disposed within said cylinder to establish a bounce chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder and means supplying a combustible fuel mixture to said combustion chambers.

2. A free piston engine comprising an engine block defining a cylinder therein, a pair of axially aligned opposed free pistons disposed within said cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, means supplying fuel to said combustion chambers, and means supplying air to said combustion chambers.

3. A free piston engine comprising an engine block defining a cylinder therein, a pair of axially-aligned opposed free pistons disposed within said cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, means supplying fuel to said combustion chambers, means supplying air to said combustion chambers, means exhausting said combustion chambers, and means synchronizing said pistons for motion in reverse directions relative one another.

4. A free piston engine comprising an engine block defining a cylinder therein, a pair of opposed free pistons disposed within said cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, two fuel injection devices each communicating with a different one of said combustion chambers, and means independently actuating each of said fuel injection devices in response to the predetermined positioning relative to the engine block of the piston communicating with the other combustion chamber.

5. A free piston engine comprising an engine block defining a cylinder therein, a pair of opposed free pistons disposed within said cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, and means independently initiating combustion in each of said combustion chambers in response to the predetermined positioning relative to the engine block of the piston communicating with the other combustion chamber.

6. A free piston engine comprising an engine block defining a cylinder therein, a pair of opposed free pistons disposed within said cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, two pressure-actuated fuel injection devices each communicating with a different one of said combustion chambers, means associated with each of the pistons and developing a pressure responsive to the position of the associated piston relative to the engine block, and means independently connecting each of the fuel injection devices with the pressure means associated with the piston of the opposite combustion chamber.

7. A free piston engine comprising an engine block defining a cylinder therein, a pair of opposed free pistons disposed within said cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, two pressure-actuated fuel injection devices each communicating with a different one of said combustion chambers, means associated with each of the pistons and developing a pressure responsive to the position of the associated piston relative to the engine block, means connecting both of said pressure developing means one to the other to develop an intermediate pressure, and means actuating both of said fuel injection devices in response to a predetermined intermediate pressure.

8. A free piston engine comprising an engine block defining a composite cylinder therein, a pair of axially-aligned opposed free pistons disposed within said composite cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, two fuel injection devices each communicating with a different one of said combustion chambers, and means independently actuating each of said fuel injection devices in response to the attainment of a pre-determined pressure in the combustion chamber of the opposite piston.

9. A free piston engine comprising an engine block defining a composite cylinder therein, a pair of axially-aligned opposed free pistons disposed within said composite cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, two pressure-actuated fuel injection devices each communicating with a different one of said combustion chambers, means independently associated with each of the pistons and defining an auxiliary chamber developing a pressure therein responsive to the position of the associated piston relative the engine block and means independently actuating each of said fuel injection devices in response to the attainment of a predetermined pressure in the auxiliary chamber associated with the opposite piston.

10. A free piston engine comprising an engine block defining a cylinder therein, a pair of axially-aligned opposed free pistons disposed within said cylinder to establish a compression chamber therebetween and a pair of combustion chambers at opposite ends of said cylinder, means supplying fuel to said combustion chambers, means exhausting said combustion chambers, and means timing the injection of fuel into each combustion chamber in response to the attainment of a pre-determined condition in the opposite combustion chamber.

References Cited in the file of this patent

UNITED STATES PATENTS

2,473,204	Huber	June 14, 1949
2,711,719	Huber	June 28, 1955