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[54] **COMPOUND BRAYTON-CYCLE ENGINE**

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[52] **U.S. Cl.** ..... **60/59 T,** 60/DIG. 1, 60/327, 60/102

[51] **Int. Cl.** **F01k 3/18**

[58] **Field of Search** ..... 60/59 T, 59 R, DIG. 1, 60/13 F, 327

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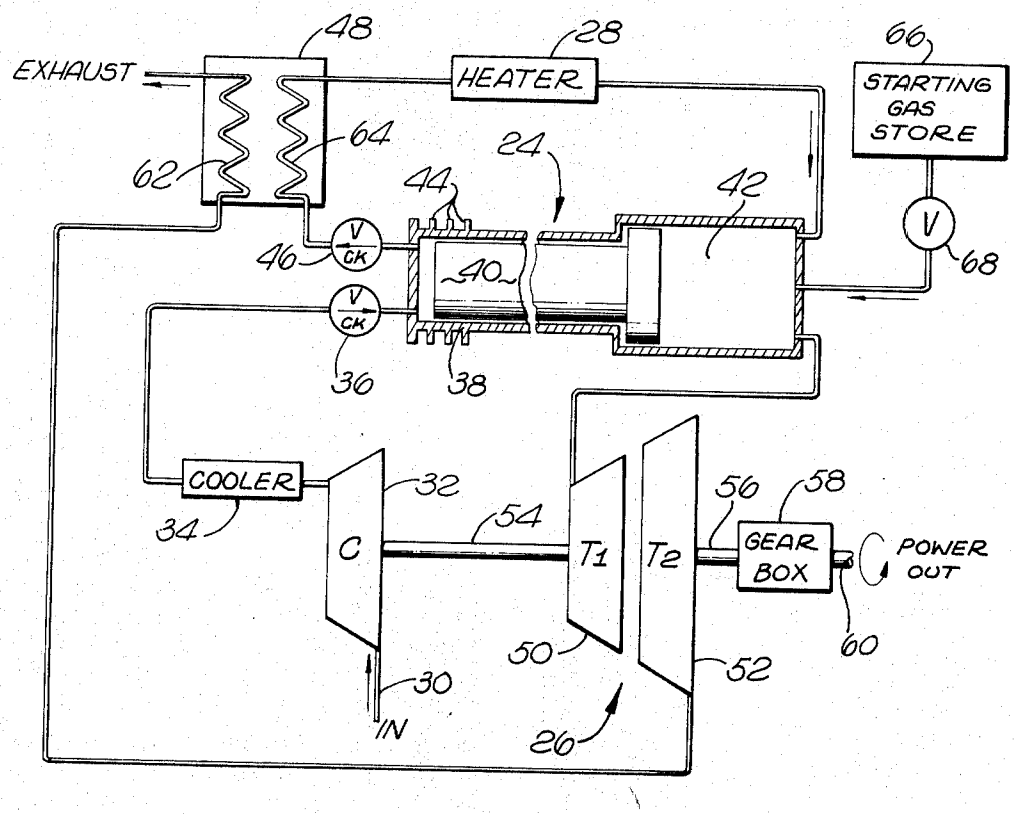
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Attorney, Agent, or Firm—B. G. Nilsson et al.

[57] **ABSTRACT**

A system is disclosed incorporating a reciprocating-piston compressor and drive arrangement for converting a portion of the heat of a working fluid to attain a pressure increase, with the resulting working fluid supplied to a turbine. As disclosed, the reciprocating structure is a free-piston engine with the compressor piston and drive-engine piston an integral structure. The housing of the free-piston structure incorporates cooling structure, for example so that the reciprocating compressor may approach isothermal operation. As disclosed, working fluid is heated to drive the free-piston engine, exhausting to drive the turbine which supplies mechanical output power. Also as disclosed, the turbine drives a rotary compressor or supercharger, which supplies intake fluid to the free-piston compressor, the output of which supplies the heater.

10 Claims, 3 Drawing Figures



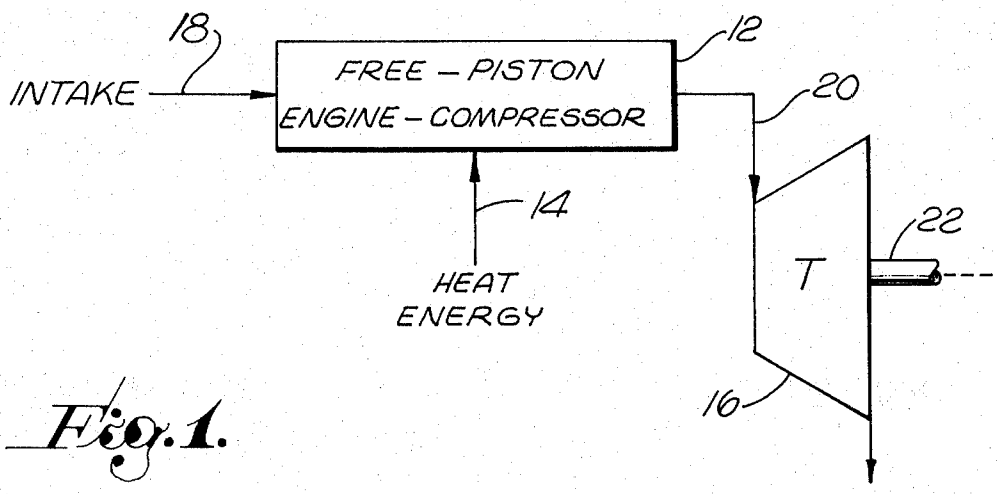

18
INTAKE
FREE – PISTON
ENGINE – COMPRESSOR
12
20
14
HEAT
ENERGY
T
22
16

Fig. 1.

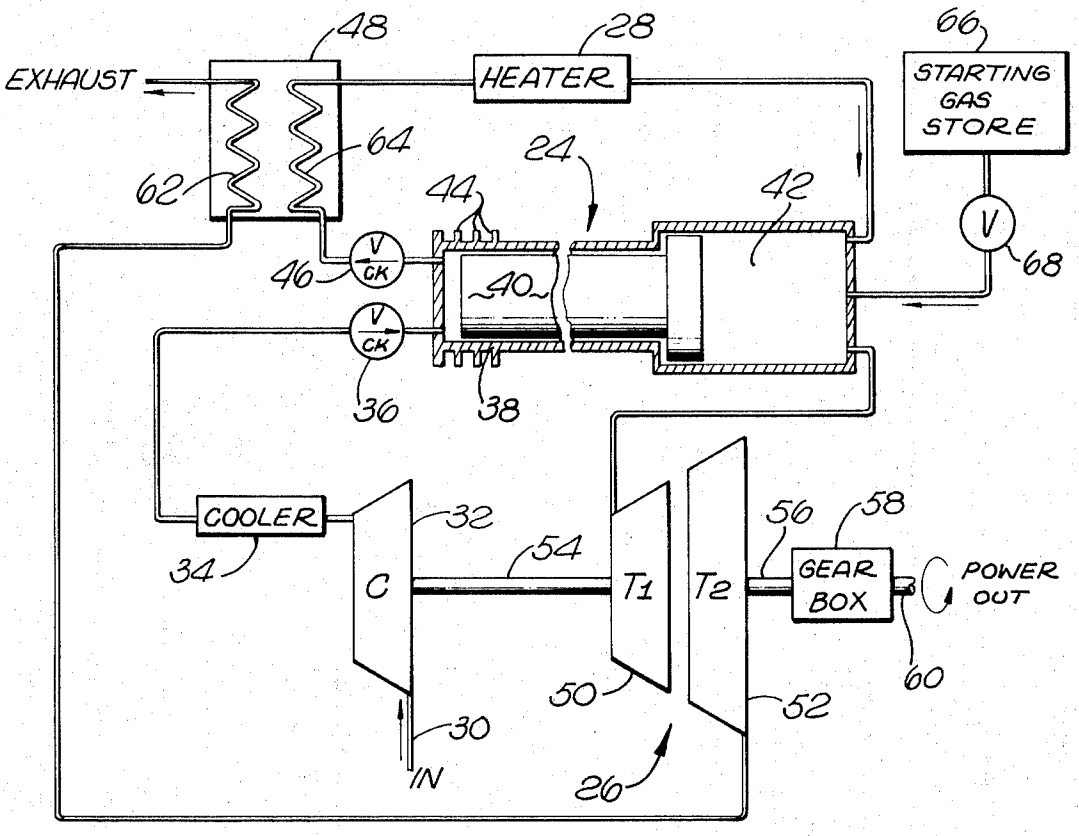
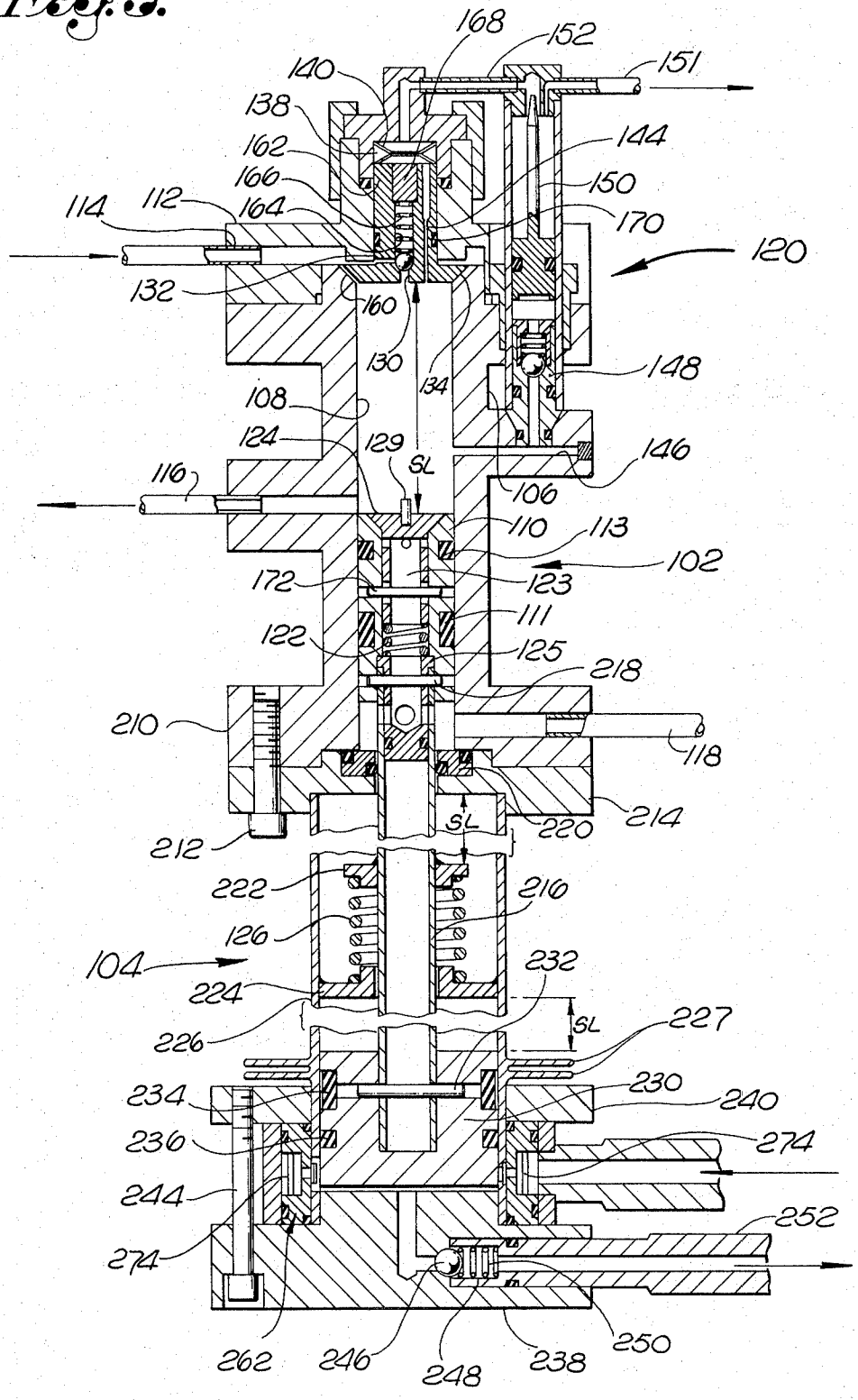

48
28
66
EXHAUST
HEATER
STARTING
GAS
STORE
64
62
24
44
42
V
68
46
CK
40
CK
36
38
COOLER
32
34
C
54
T1
T2
56
58
GEAR
BOX
POWER
OUT
60
50
52
30
IN
26

Fig. 2.

Fig. 3.


168
152
151
140
138
162
166
144
150
114
112
164
170
120
132
160
130
134
148
108
124
129
SL
146
116
106
110
113
102
172
123
111
122
125
218
210
118
214
220
SL
212
222
216
126
104
232
224
SL
227
226
234
230
240
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274
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252
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262
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248
238
250

COMPOUND BRAYTON-CYCLE ENGINE

BACKGROUND AND SUMMARY OF THE INVENTION

In recent years, a vast effort has been directed toward developing an improved heat engine. Generally, the motive for that effort resides in the fact that the great number of existing internal combustion engines has created a significant problem of atmospheric contamination. In operation, the conventional internal combustion gasoline engine utilizes fuel in rapidly-occurring detonations, with the result that the combustion products frequently include live hydrocarbons, nitrogen oxides and other contaminants. Additionally, the conventional internal combustion engine has evolved to a rather complex mechanism and efficiency has been pushed substantially to the limits of production capabilities. Consequently, the need is widely recognized for an improved basic engine as for automotive use. The desirable characteristics for such an engine include good speed response, relatively-high efficiency, high power output and desirable torque-speed characteristics. Furthermore, the system should be easy to start and capable of being embodied in a simple design that is reliable and inexpensive.

The gas turbine has been recognized as a very useful engine in many applications and has been considered for automotive use. However, one of the major difficulties with that engine in automotive applications is poor speed response. Another problem resides in the difficulty of providing effective cooling. Although internally-cooled structures have been proposed, they tend to be rather complex both in manufacture and operation.

In general, the present invention is directed to a system affording a significant improvement in the characteristics considered above and which system would be well adapted for automotive use. Generally, the system involves the utilization of a reciprocating-piston compressor and drive engine, the latter of which is operated by fluid from a combustion system (or other heat source) to deliver working fluid to a turbine. More specifically, the reciprocating-piston unit is a free-piston structure thereby affording the advantages of a long stroke for high pressure ratios and effective cooling, low internal friction, effective variation of the stroke with good efficiency, relatively-high efficiency at off-design speeds and improved speed response.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, which consitute a part of this specification, exemplary embodiments exhibiting various objectives and features hereof are set forth, specifically:

FIG. **1** is a diagrammatic representation of the system of the present invention;

FIG. **2** is a detailed schematic diagram of an exemplary embodiment constructed in accordance with the present invention; and

FIG. **3** is a sectional view of a reciprocating engine structure as may be utilized in the system of FIG. **2.**

DESCRIPTION OF THE ILLUSTRATED EMBODIMENT

As required, a detailed illustrative embodiment of the invention is disclosed herein. The embodiment exemplifies the invention which may, of course, be embodied in other forms, some of which may be radically different from the illustrative embodiment as disclosed. However, the specific structural details disclosed herein are representative and they provide a basis for the claims which define the scope of the present invention.

Referring initially to FIG. **1**, the system is very generally indicated to include a free-piston engine-compressor structure **12** which is driven by heat energy as indicated by an input arrow **14,** to provide working fluid at a pressure to operate a turbine **16.** The structure **12** might receive air as a working fluid through an intake **18,** heat the air to drive the engine compressor (which compresses air at the intake), then provide the air at a substantially-increased pressure through a duct **20** to drive the turbine **16.** The turbine **16** then provides mechanical power to an output shaft **22.** Thus, high pressure ratios are attained by a simple mechanism which has several attendant and unobvious advantages including improved speed response.

Considering the structure hereof in somewhat greater detail, reference will now be made to FIG. **2** wherein a reciprocating engine structure **24** is illustrated to operate in cooperation with a two-stage turbine **26.** As indicated above, the structure **24,** along with a heater **28,** provides pressurized working fluid for driving the turbine **26.** Assuming a working fluid of air, the fluid is drawn through an intake **30,** compressed by a rotary unit **32** then cooled by a cooler **34** and supplied through a check valve **36** to the compressor end **38** of the free-piston structure **24** (actuating valves and related structure not shown). The structure **24** incorporates a free piston **40** serving both the compressor end **38** and the engine end **42.** That is, the free piston **40** acts as the compression piston at the compressor end **38** and as the power piston at the engine end **42.**

The compressor end **38** incorporates cooling fins **44** (or other cooling apparatus) to enable a substantially isothermal compression of the working fluid. Consequently, the working fluid is exhausted from the structure **24** through a check valve **46** at a temperature which is not significantly higher than the temperature of the received fluid.

Initial heating of the fluid passing through the check valve **46** is in a heat exchanger or regenerator **48** in which the working fluid is heated by exhaust working fluid as described in greater detail below. From the regenerator **48,** the working fluid passes to the heater **28** which may comprise any of a variety of combustion systems or simply a source of heat, which may be waste heat. In any event, the working fluid is increased in temperature in the heater **28** whereby attaining a relatively high temperature at which the working fluid is introduced into the engine end **42** of the free-piston structure **24.** The operating details of the symbolically-represented structure **24** are disclosed below; however, functionally, the introduction of pressurized working fluid causes the piston **40** to reciprocate thereby accomplishing the compression action at the compressor end **38** as described above.

The working fluid exhausting from the engine end **42** is highly pressurized but somewhat cooled and accordingly, is well suited for introduction to the turbine **26.** Essentially, the turbine **26** includes a first stage **50** and a second stage **52.** The first stage **50** is connected through a rotary shaft **54** to the rotary unit **32** (com-

pressor). The second stage **52** of the turbine **26** is connected through a shaft **56** to a gear box **58** having a power drive shaft **60.** The turbine stage **52** exhausts through the regenerator **48.** Specifically, a fluid passage **62** carrying the exhaust from the turbine stage **52** is in heat-transfer relationship with the passage **64** which passes the working fluid prior to application to the heater **28.**

In view of the above structural description of the system of FIG. **2,** certain operating characteristics may now be considered. Initially, assuming the system is in an operating stage, air (or other working fluid) is drawn into the rotary compressor unit **32** for an initial compression to increase the pressure of the working fluid. Such a preliminary compression operation is useful in certain applications in view of the relatively-limited displacement of reciprocating equipment.

The cooler **34,** which receives the working fluid from the unit **32** may comprise simply a radiator for returning the preliminarily pressurized fluid to a temperature near ambient. Upon introduction of the preliminarily pressurized working fluid from the cooler **34** into the compressor end **38** of the structure **24,** the pressure is substantially increased after which the temperature is initially increased in the regenerator **48** and substantially increased in the heater **28.**

The pressurized working fluid from the heater **28** actuates the reciprocating structure **24** at the engine end **42** as described in detail below. It is to be noted that cooling may be introduced in the engine end **42** if desired. The exhaust from the engine end **42** is well suited to drive the turbine stage **50** followed by the turbine stage **52.** It is to be noted that by providing separate stages **50** and **52,** the rotary compressor unit **32** may be operated at high speeds to which it is well suited, while the power output load (driven by the second stage **52**) is somewhat independent of the first stage **50.**

In considering the operation of the system, a number of features are significant. First, the heater **28** may involve a lean fuel mixture designed for complete combustion without the contaminants attendant the exhaust from internal combustion engines. Second, the system also tends to be nonpolluting in view of the fact that it may be embodied in a unit with good efficiency therefore consuming less fuel. Specifically, the system enables a high pressure ratio and avoids the necessity of extremely high inlet temperatures to rotary machinery. The inherent nature of the free-piston structure **24** allows for a long stroke with high pressure ratios and allows high cooling areas in relation to the volume with the result that substantially isothermal compression can be attained as considered above. Additionally, the free-piston structure **24** involves no side loads and, accordingly, is a low-friction apparatus.

A further consideration resides in the fact that conventional gas turbines inherently possess poor speed-response characteristics as for tractor or automotive applications. However, the system of the present invention incorporating the reciprocating structure **24** responds quite rapidly to an increase in the fuel supply to the heater **28.** Accordingly, the combination represents a substantial improvement in that regard over conventional turbine systems. As a somewhat-related consideration, the free-piston structure also tends to afford variation in the stroke thereof in accordance with current power demands. It is also noteworthy that the structure **24** does not involve a significant change in efficiency with change in speed and affords good efficiency at operating speeds other than the designed optimum.

As still a further consideration, the system of FIG. **1** is relatively easy to start. As disclosed, a reservoir or store **66** of starting gas is connected through a valve **68** to the engine end **42** of the structure **24.** Starting the engine system simply involves opening the valve **68** concurrently with the application of fuel to the heater **28.** As a consequence, the engine structure **24** begins to operate rapidly attaining pressure output levels to drive the turbine **26.**

An exemplary structure of the engine **24** will now be considered in detail with reference to FIG. **3** which shows an engine **102** and a compressor **104.** The engine **102** and the compressor **104** incorporate an integral free-piston structure which reciprocates and which is subjected only to sealing loads. Accordingly, high operating efficiencies may be obtained.

Considering the two component structures (engine and compressor) somewhat individually, the engine **102** comprises a block **106** (formed as by casting or machining) defining an internal cylinder **108** in which a piston **110** reciprocates. The piston **110** incorporates an axial exhaust valve as disclosed in detail below, while the intake valve is provided in the head **112** of the engine **102,** affixed at the upper end of the block **106.** Expanding gases to drive the piston **110** are received in the cylinder **108** through a passage or duct **114** (upper left) and are exhausted through passage **118** and to some extent through control passages, as the passage **116.** A control for the engine **102,** as generally indicated at **120** serves to accelerate the operation of the intake valve structure if desirable.

Considering the engine **102** in greater detail, the unit is depicted at the end of a power stroke, i.e. with the piston **110** at the bottom of the cylinder **108.** The piston carries a rub ring **111** and a sealing ring **113** to support sealing loads.

In the position illustrated, the gaseous charge in the cylinder **108** is discharged through the passage **116** (left) relieving the pressure within the cylinder **108** sufficiently for a coil spring **122** (located within the piston **110** and supported by a ferrule **125**) to lift a valve **124** from a seated position, opening a passage **123** through the interior of the valve **124** and the piston **110.** Under some circumstances (starting)some gas may also pass to exit through the passage **116.**

With the valve **124** in an elevated position, and the loss of pressure in the cylinder **108,** a coil spring **126** (lower portion of the structure) forces the piston **110** upwardly in a return stroke. At the top of the return stroke, a pin **129** (extending from the valve **124**) enters a bore **130** and unseats a ball **132** so that pressurized fluid from the passage **114** may enter the cylinder **108** through the bore **130.** Concurrently, the piston valve **124** is closed. As a consequence of the pressurization of a fragment of the cylinder **108** at the top of the return stroke, a head valve **134** (containing the ball **132**) is lifted from a seated position thereby providing an open passage for fluid from the pressure passage **114** into the cylinder **108.** The pressurization of the cylinder **108** through such a passage produces a downward force on the valve **124** (in the piston **110**) to maintain it closed, forcing the piston **110** downwardly to compress the spring **126.** Accordingly, the power stroke is initiated and continues until the piston reaches the po-

sition as shown in FIG. 3 at which the exhaust passage 116 is opened, and from which the cycle is repeated.

The closure of the head valve 134 (to halt the flow of fluid into the cylinder 108) actually occurs prior to the time when the piston 110 bottoms in the cylinder 108. Such closure is accomplished by balancing the pressure in the chamber 138 (above the cylinder head 112) with that in the cylinder 108. The chamber 138 contains a pair of Bellville springs 140, which urge the valve 134 closed. Accordingly, when the pressure in the chamber 138 approaches that in the cylinder 108, the springs 140 close the valve 134. The chamber 138 communicates with the cylinder 108 through a port 144 in the valve 134. An exhaust passage 152 from the chamber 138, also is provided through the control 120 which includes: a duct 146 (to the cylinder 108), a check valve 148, and a needle valve 150.

As indicated above, the pressurization of the chamber 138 to close the valve 134 desirably occurs well prior to the time when the piston 110 reaches the bottom of the cylinder 108. That is, for efficiency and noise considerations, it is desirable to allow the expanding gas within the cylinder 108 to be contained prior to the end of the stroke, and to complete the stroke without the introduction of additional gas. Accordingly, within the limits of the design considerations, the passage 144 is provided of a size to pressurize the chamber 138 so as to close the valve 134 at the desired time. However, in view of the sometime difficulty of maintaining such a critical flow path, the feedback control 120 serves to provide specific control of the pressure in the chamber 138.

When the piston 110 drops below the duct 146 (intermediate right on cylinder 108) if the pressure in the cylinder 108 is above a predetermined level, the check valve 148 is opened and the needle valve 150 is closed, thereby delaying the relief of the chamber 138 through an exhaust duct 151. Consequently, the chamber 138 is pressurized more rapidly to move the valve 134 downward, shutting off the flow of intake gas into the cylinder 108. Thus, the control is accomplished so that the cylinder 108 receives a charge of gas while the valve 134 is lifted, then the piston 110 moves downwardly to a predetermined point, at which location the valve 134 drops to a seated position allowing the charge of gas to continue to expand driving the piston 110 to the completion of its stroke. As indicated above, at the bottom of the stroke, the cylinder 108 experiences a reduced pressure and is cleared of gas during the return stroke with the valve 124 lifted in the piston 110 and the valve 134 closed in seated engagement with the block 106.

Although the valves 124 (in piston 110) and 134 (in head 112) are of different size, they are structurally somewhat similar. Specifically, considering the structure of the intake valve, the actual valve 134 defines an annular tapered surface 160 which seats against a mating surface of the block 106 to accomplish closure. From the surface 160 the valve 134 extends upwardly in a cylindrical section 162 which is matingly received within a bore in the head 112. Of course, the head 112 may be variously affixed to the block 106. Above the bore 130 an enlarged bore 164 is provided, containing a spring 166 for urging the ball 132 downward into a seated position. A plug 168 closes the bore 164 and provides support for the spring 166. A sealing-ring seal 170 is provided about the cylindrical section 162 of the valve to support a sealing load.

The piston 110, as indicated above, incorporates the valve 124 which is somewhat similar to the structure of the valve 134. However, the valve 124 incorporates an axially-extending pin 129 to act on the ball 132. The valve 124 is urged upwardly out of the piston 110 by the spring 122 and its movement is limited by a transverse pin 172 extending through elongated axially-parallel slots in the tubular section of the valve 124 and received in a transverse bore through the piston 110. In the closed position, the spring 122 is compressed by the force on the face of the valve 124 resulting from the pressure in the cylinder 108.

Recapitulating and summarizing, the intake valve 134 (located in the head 112) is closed when the piston 110 completes a return stroke at which time the cylinder 108 is charged to accomplish a power stroke. Prior to the completion of the power stroke, the valve 134 closes under the force of the Bellville springs 140 allowing the contained charge to complete the downward stroke of the piston 110.

On completion of the downward stroke by the piston 110, the valve 124 (in the piston 110) opens under the force of the spring 122 in a balanced pressure situation. Consequently, the return stroke is accomplished by the spring 126 while clearing residual fluid from the cylinder 108. On completion of the return stroke, the pin 129 engages the ball 132 to open a pressurizing passage, and results in the valve 134 being lifted from a seated position to accomplish the next stroke. Thus, it may be seen that the piston 110 reciprocates in the cylinder 108 and drives the compressor 104 in the integrated system of FIG. 2.

Consideration will now be given to the action of the piston 110 to actuate the compressor 104. The lower end of the engine block 106 incorporates a flange 210 (drawing center) which is affixed by bolts 212 to a mating flange 214 comprising the upper end or head of the compressor 104. A connection tube 216 passes concentrically through the flanges 210 and 214 and is coupled to the piston 110 by a transverse pin 218 extending through: the ferrule 125, the tube 216 and the piston 110. The elongated tube 216 extends downwardly through a seal 220 and receives a spring-support flange 222 affixed thereto. The lower end of the elongated tube 216 terminates in a concentric piston 230 affixed therein by a transverse pin 232. A rub ring 234 and a sealing ring 236 are provided in the piston 230.

The flange 222 restrains the main spring 126 at the upper end while the flange 224 (affixed to a finned external housing cylinder 226 restrains the lower end of the spring 126. As indicated above, the spring 126 lifts the piston 110 during the return stroke of the engine 102. The external housing cylinder 226 carries fins 227 affording cooling means for the compressor end of the structure.

Summarizing, the piston 230 is connected by the extending tube 216 to the engine piston 110 so as to be forcefully reciprocated within the housing cylinder 226 whereby to accomplish compression of the working fluid. In that regard, the lower end of the compressor as shown in FIG. 3 incorporates check valves to facilitate compressor action. Specifically, the lower end of the cylinder 226 is closed by a block 238 which is received within the cylinder and which is affixed to a retaining ring 240 by bolts 244. The ring 240 may be af-

fixed to the cylinder **226** by welding or other techniques. An exhaust check valve is provided in the block **238.** Specifically, a ball **246** and a spring **248** are contained within a chamber **250** as a check valve as well known in the prior art. The chamber **250** communicates with a duct **252** from which pressurized fluid is delivered.

The intake check valve for the compressor **104** is provided in a somewhat annular form. Specifically, a valve ring **262** and an annular vane **274** of thin resilient metal are housed to cooperate with bores which afford check valve operation. Of course, other forms of check valves as well known in the prior art may be employed.

As indicated above, the present system may be embodied in various forms; however, the reciprocating structure as disclosed in FIG. **3** is an effective form of the structure **40** as depicted in FIG. **2.** Of course, other components of the system of FIG. **2** may be as well known in the prior art to provide an integrated, effective operating system.

Summarizing the salient features of the system hereof, it is important to note that the reciprocating structure **24** affords a considerably-more responsive system than is provided by a conventional turbine engine. Additionally, as indicated above, by providing cooling means, e.g. fins **44,** at the compressor end **38** of the reciprocating system, compression may approach isothermal operation. The use of the rotary compressor unit **32** in the combination enables the provision of the reciprocating structure **24** as a much smaller unit. In that regard, the total system compares favorably in physical size with conventional internal-combustion engines. Also, with regard to internal-combustion engines, the system hereof permits the use of a lean fuel mixture in the heater **28,** which may comprise various combustion systems or sources of waste heat, so as to provide substantially non-contaminating products of combustion.

As indicated above, the system hereof may be variously embodied, and accordingly, the scope hereof is as set forth in the following claims.

What is claimed is:

1. An engine system for providing mechanical power from heat energy, comprising:

a reciprocating-piston compressor connected to receive intake fluid for providing pressure fluid;

a reciprocating-piston fluid-actuated drive engine for driving said reciprocating-piston compressor;

a heater for receiving said heat energy to heat said pressure fluid from said compressor, said heater being connected to supply drive fluid to said drive engine; and

a turbine means connected to be driven by exhaust fluid from said drive engine to provide mechanical power.

2. An engine system according to claim **1** wherein said compressor and drive engine comprise a free-piston system.

3. An engine system according to claim **2** wherein said free-piston system includes a drive piston, a compressor piston mechanically connected to said drive piston and a cylindrical housing enclosing said pistons.

4. An engine system according to claim **3** wherein said pistons are axially aligned.

5. An engine system according to claim **1** further including a regenerator for transferring heat from fluid exhaust from said turbine, to said pressure fluid.

6. An engine system according to claim **1** wherein said drive engine includes a housing incorporating cooling means.

7. An engine system according to claim **2** further including a rotary compressor connected to supply intake fluid to said reciprocating piston compressor, said rotary compressor being driven by said turbine.

8. An engine system according to claim **7** further including a cooling unit connected between said rotary compressor and said reciprocating-piston compressor for cooling said intake fluid.

9. A system according to claim **8** wherein said turbine means comprises a two-stage turbine with one stage providing said mechanical power and another stage driving said rotary compressor.

10. A system according to claim **2** wherein said free-piston system includes a drive piston, a compressor piston mechanically connected to said drive piston and a cylindrical housing enclosing said pistons, further including a regenerator for transferring heat from fluid exhaust from said turbine, to said pressure fluid, further including a rotary compressor connected to supply intake fluid to said reciprocating piston compressor, said rotary compressor being driven by said turbine, and further, a heater means for adding heat to supply the desired power output.

* * * * *