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(54) **LOW EMISSIONS COMPRESSION IGNITED ENGINE TECHNOLOGY**

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(57) **ABSTRACT**

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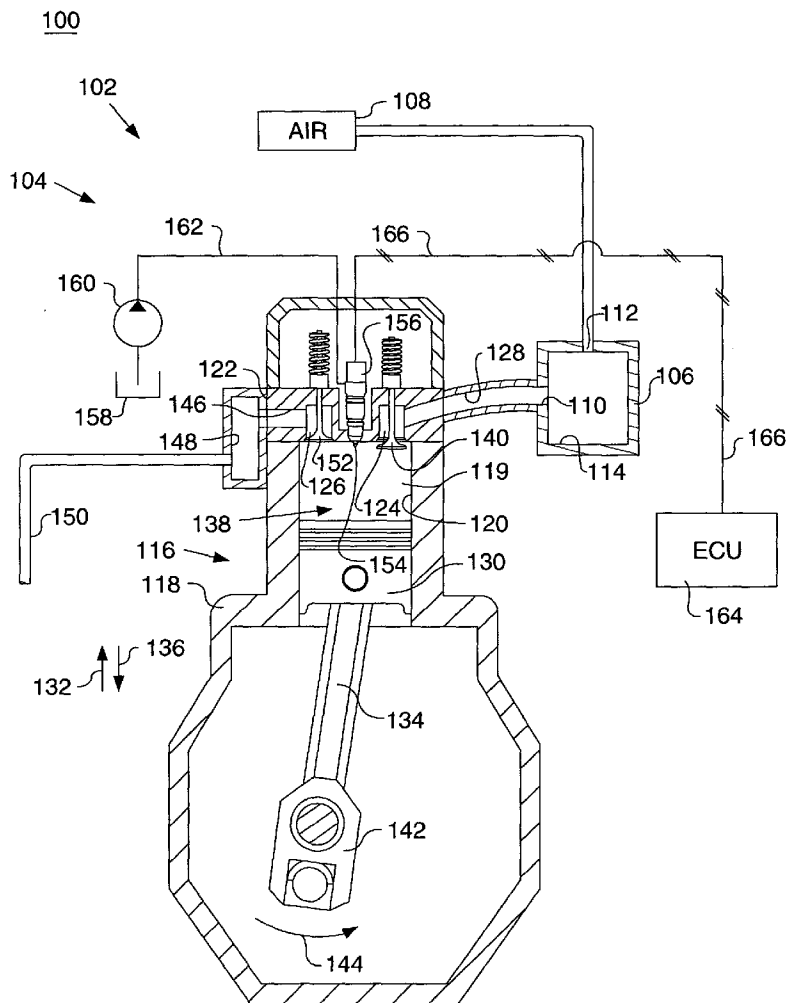
A method and apparatus for operating a compression ignition engine having a cylinder wall, a piston, and a head defining a combustion chamber. The method and apparatus includes delivering fuel substantially uniformly into the combustion chamber, the fuel being dispersed throughout the combustion chamber and spaced from the cylinder wall, delivering an oxidant into the combustion chamber sufficient to support combustion at a first predetermined combustion duration, and delivering a diluent into the combustion chamber sufficient to change the first predetermined combustion duration to a second predetermined combustion duration different from the first predetermined combustion duration.

(21) Appl. No.: **10/653,507**

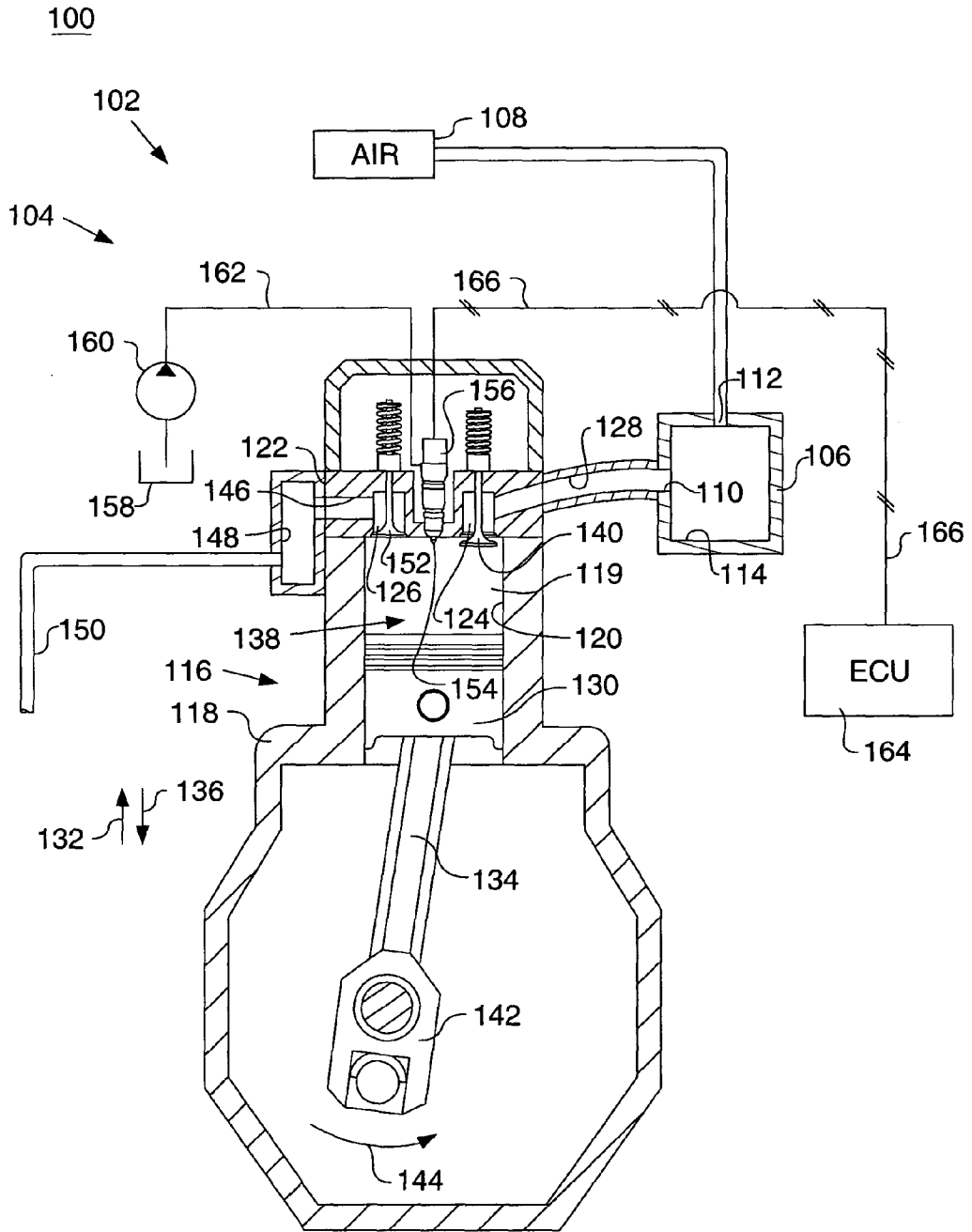
(22) Filed: **Sep. 2, 2003**

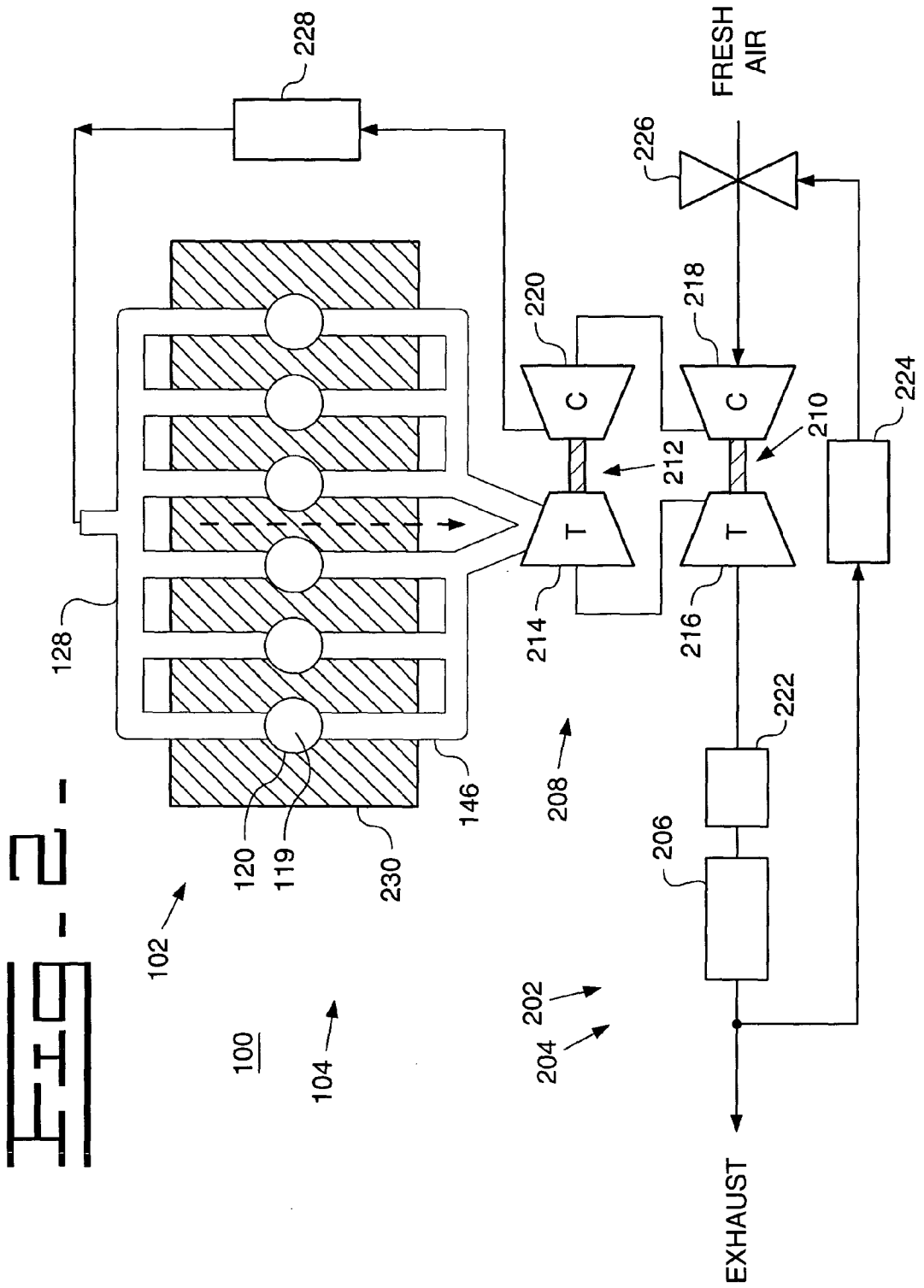
**Related U.S. Application Data**

(60) Provisional application No. 60/434,015, filed on Dec. 17, 2002.



**FIG. 1**





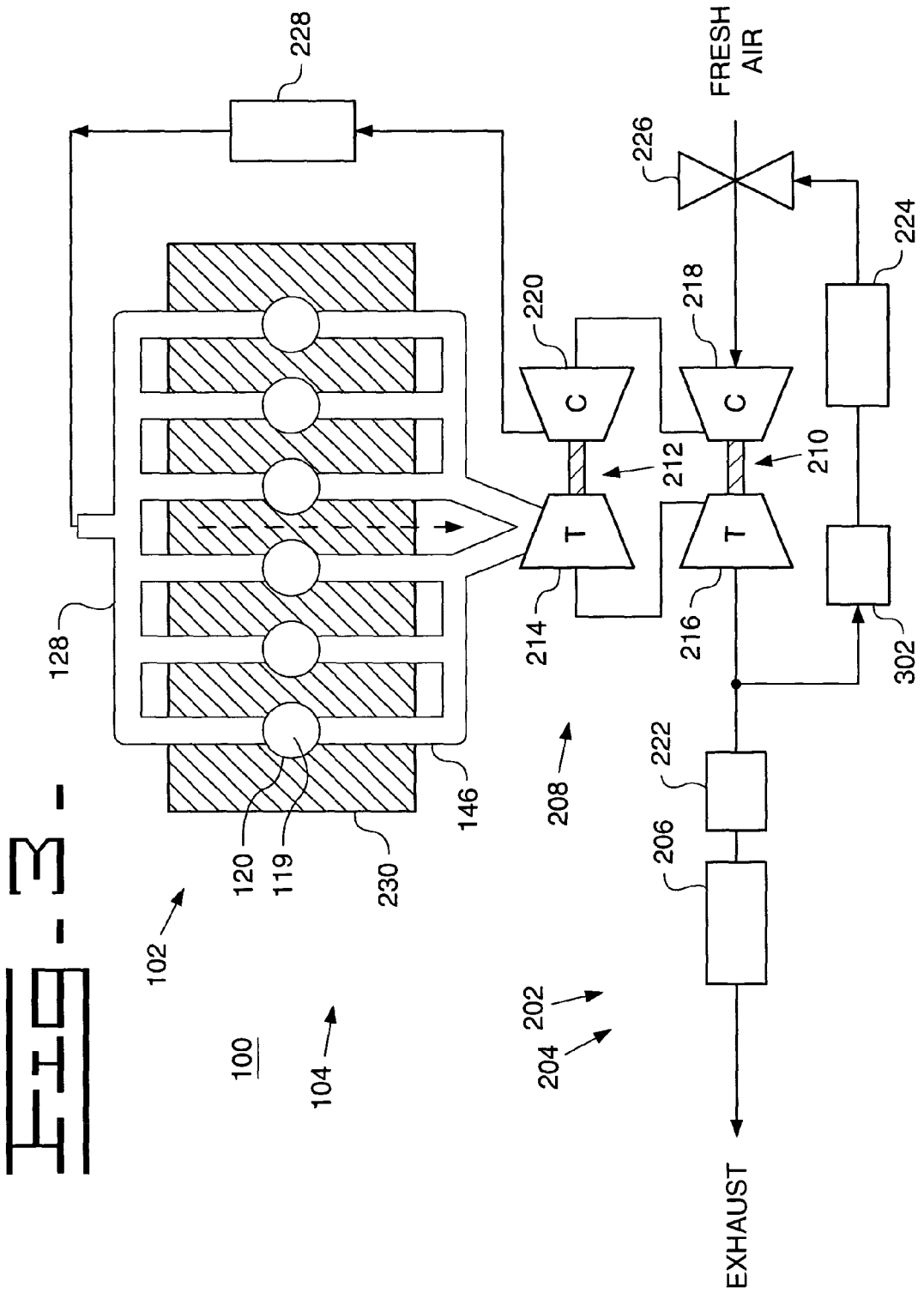


FIG. 4a.

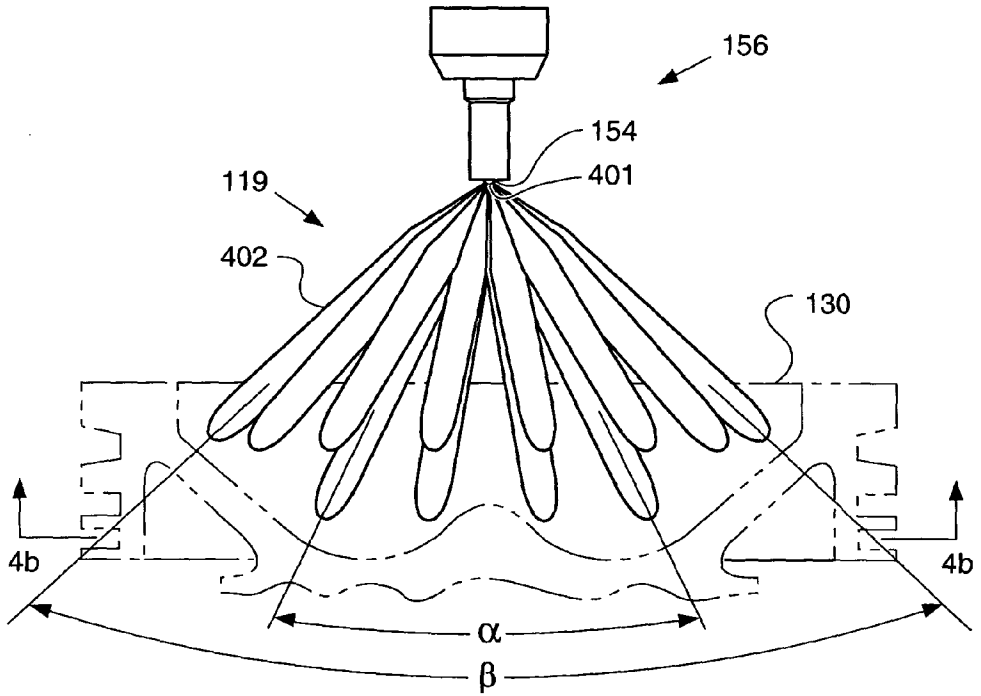
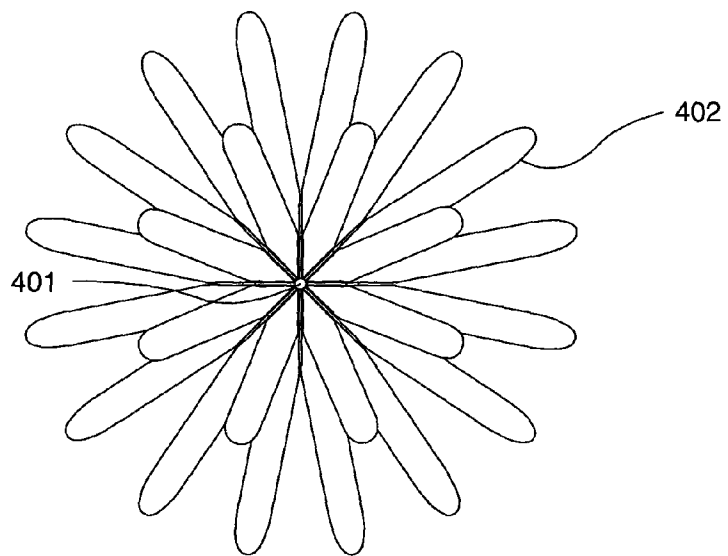
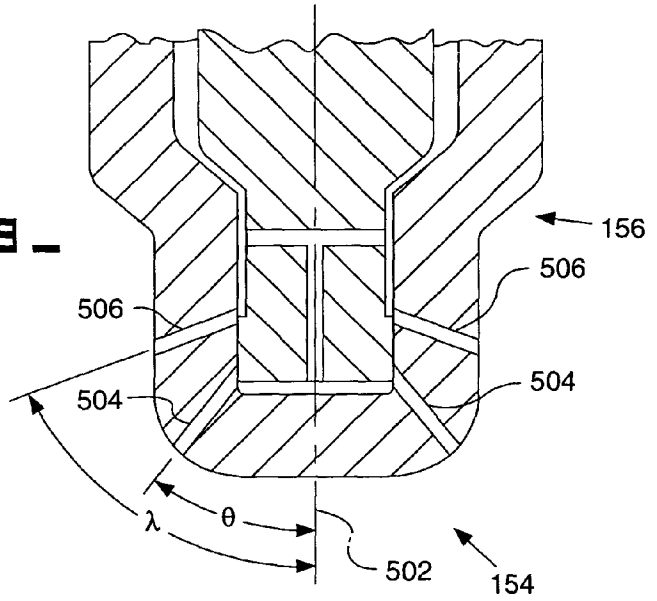


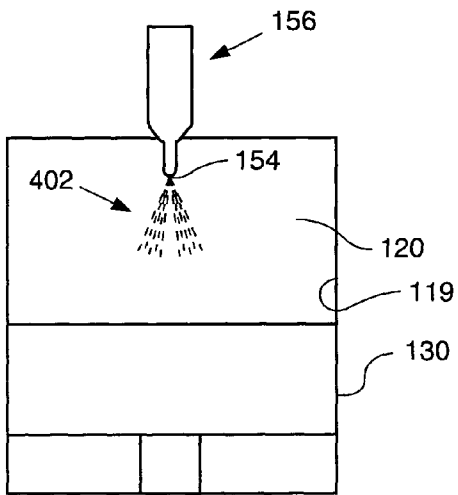
FIG. 4b.



**FIG. 5a.**



**FIG. 5b.**



**FIG. 5c.**

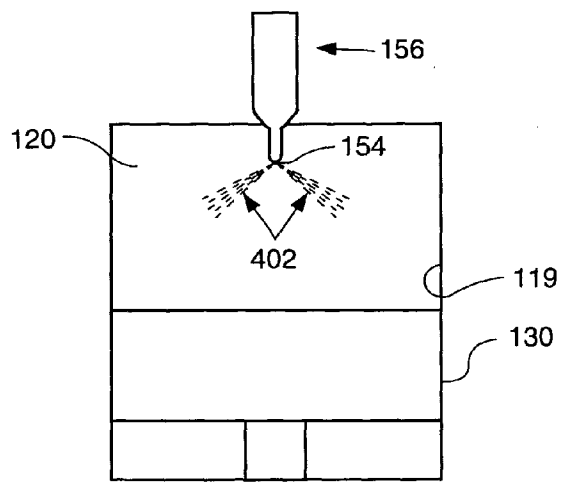
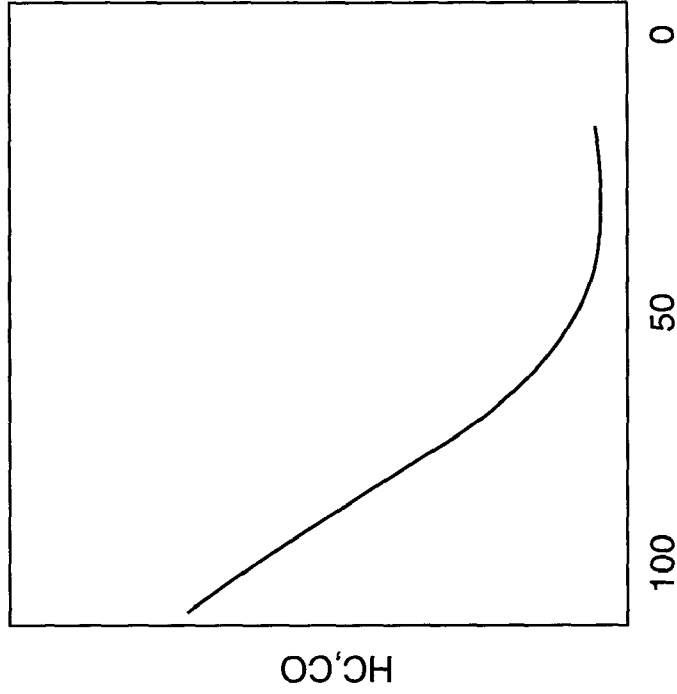
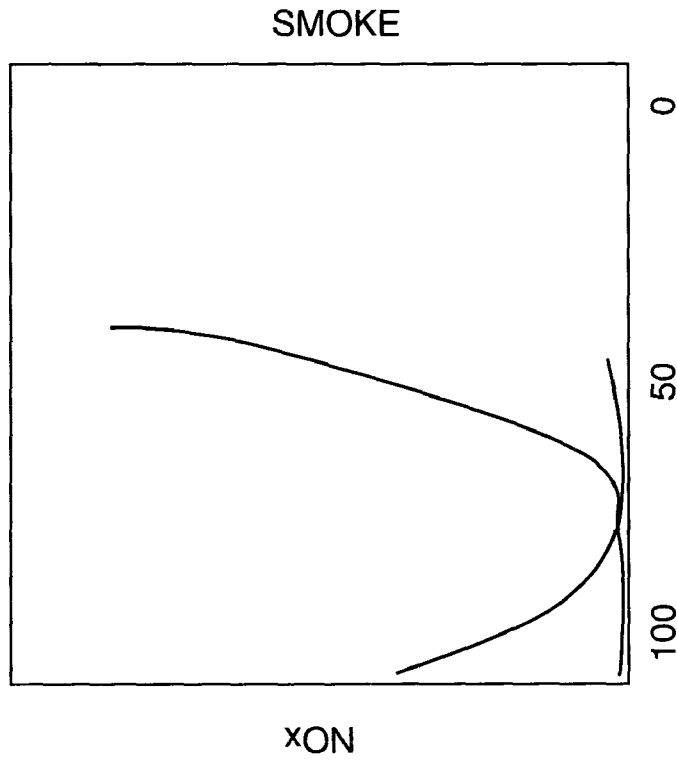


FIG. 6a.



INJECTION TIMING

FIG. 6b.



INJECTION TIMING

FIG. 7.

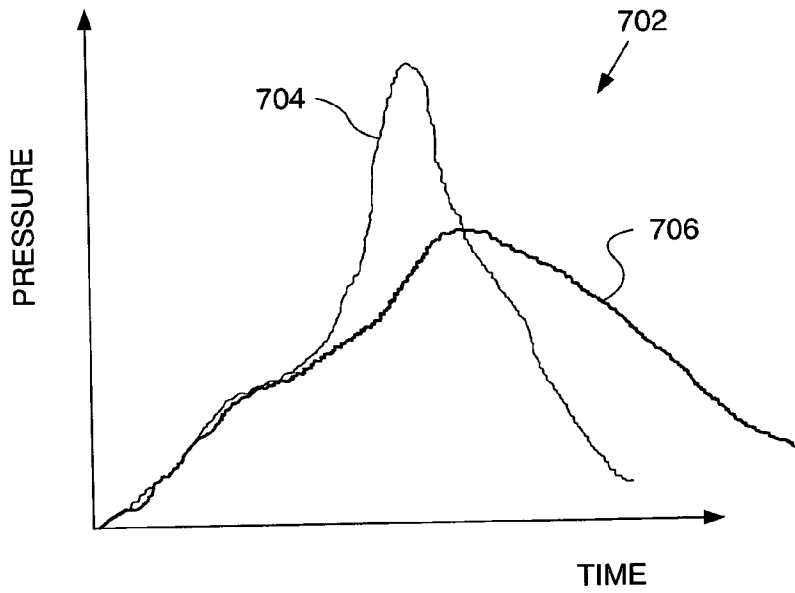
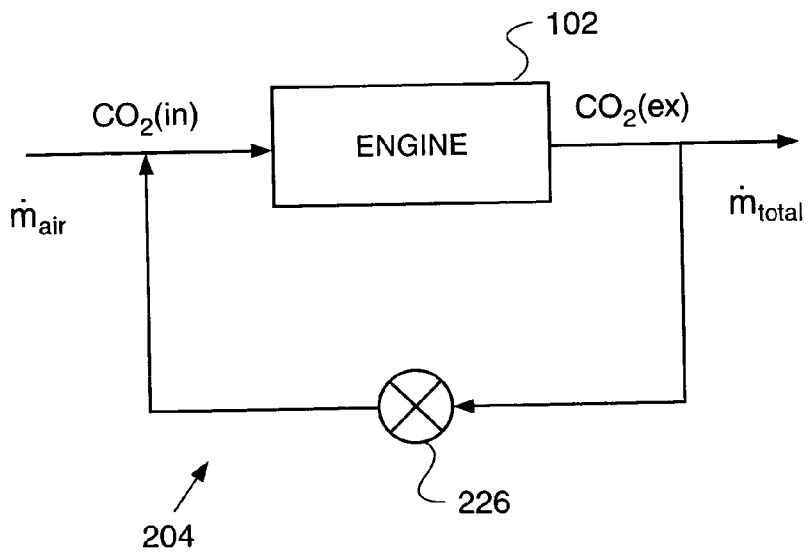
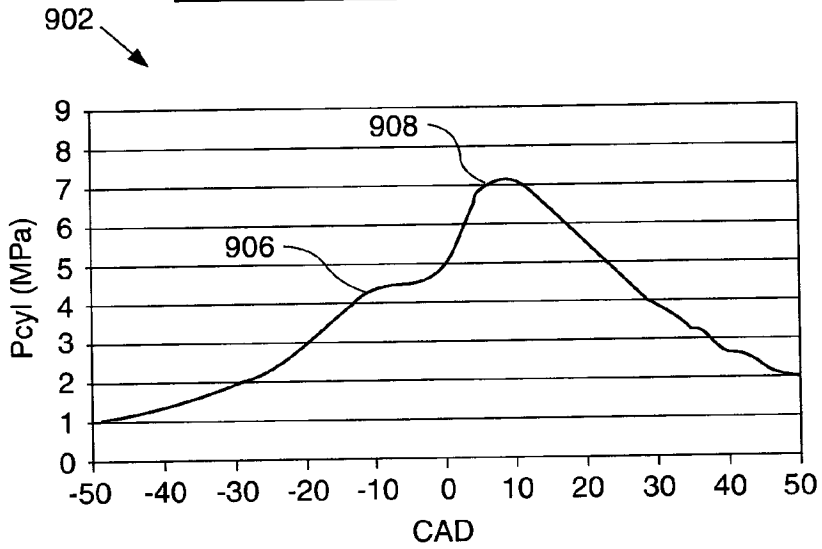


FIG. 8.





**FIG. 9a.**



**FIG. 9b.**

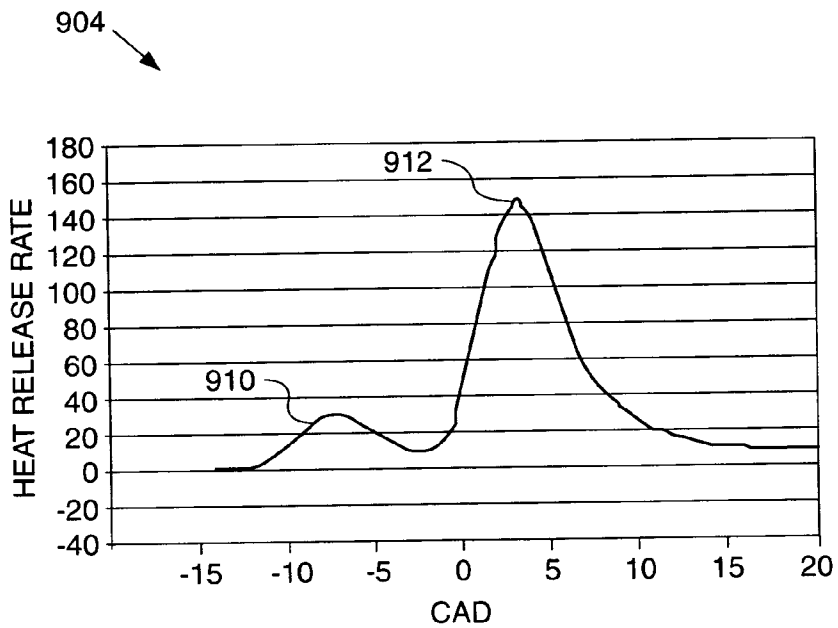
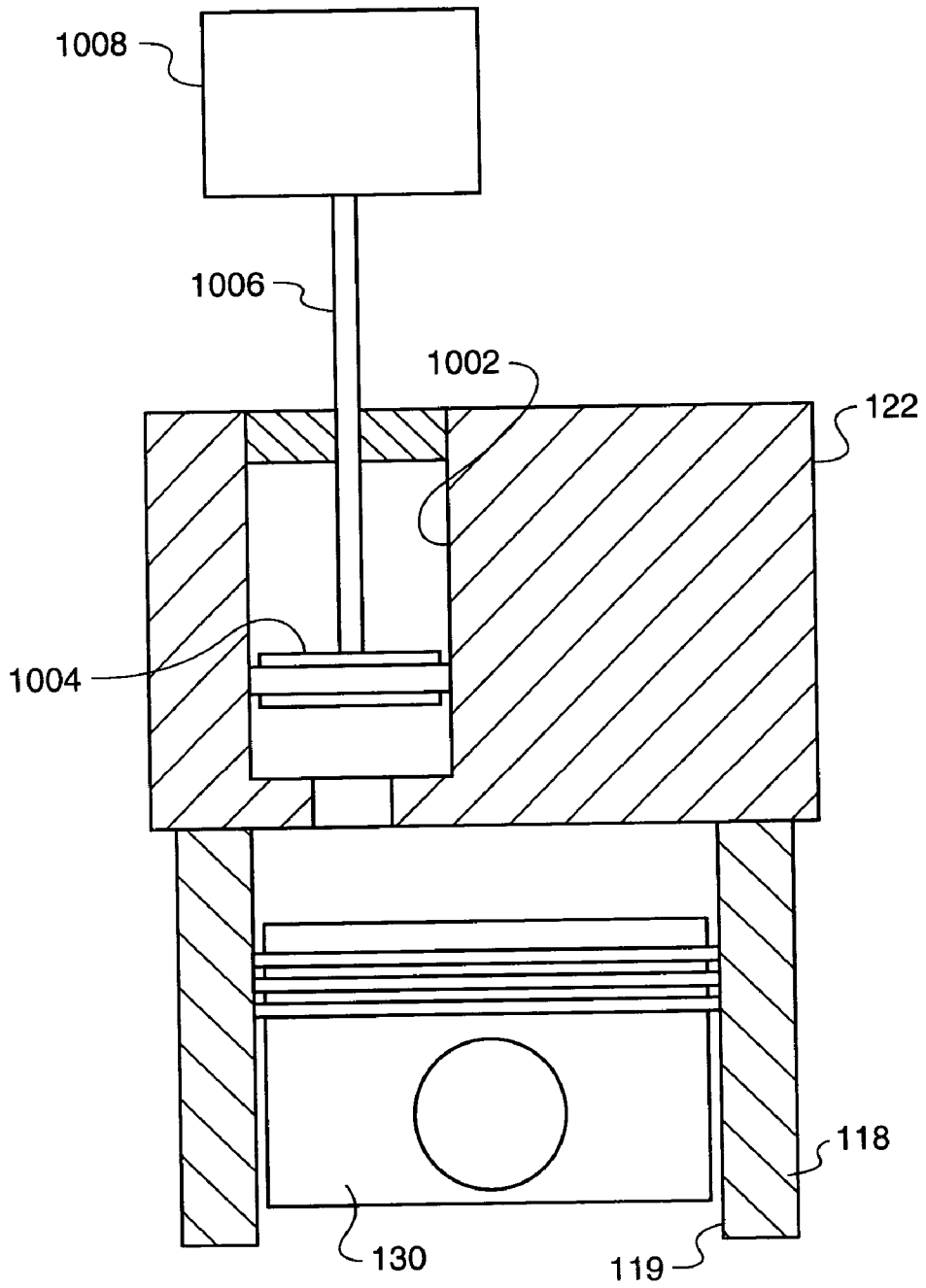


FIG. 10.



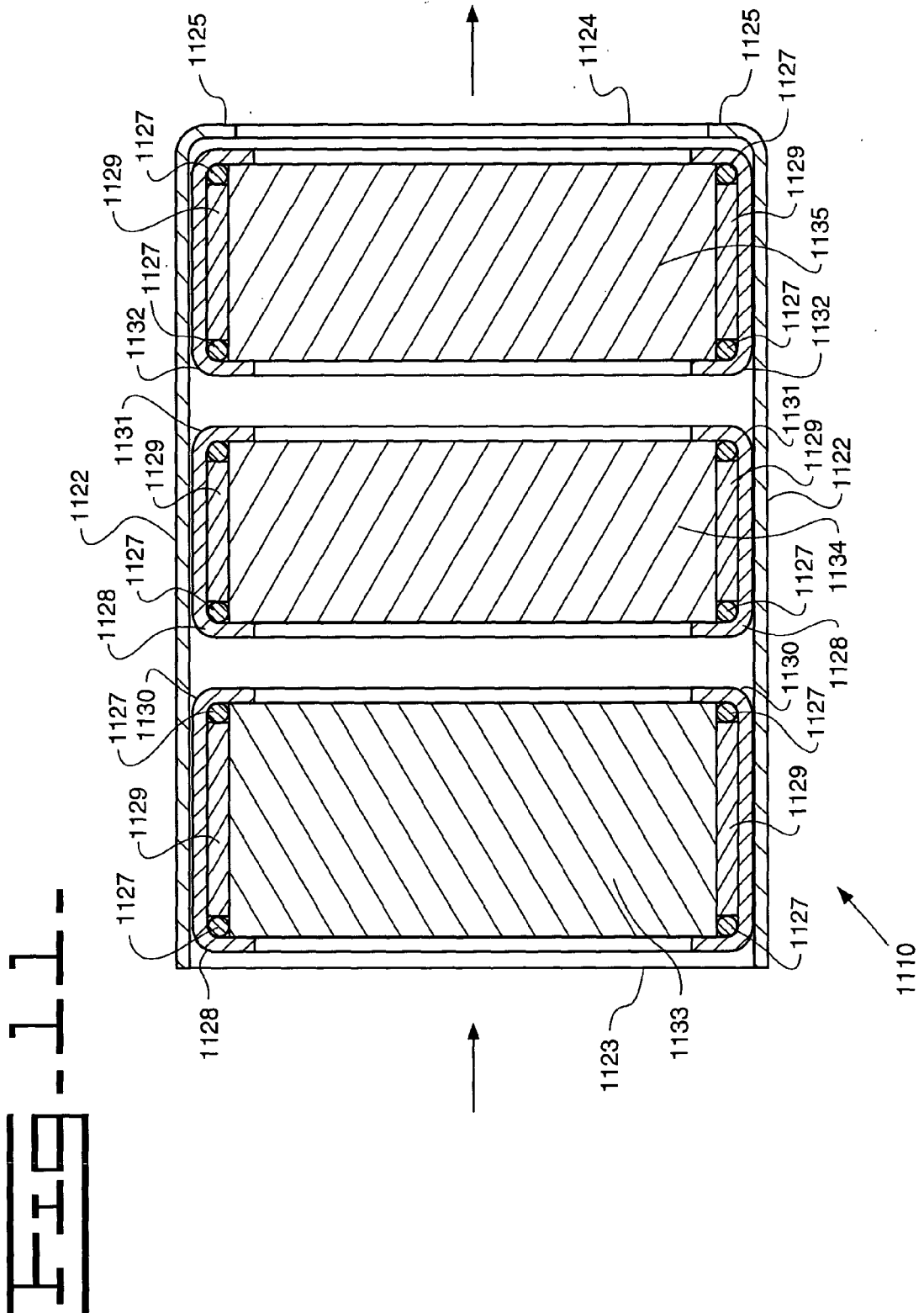
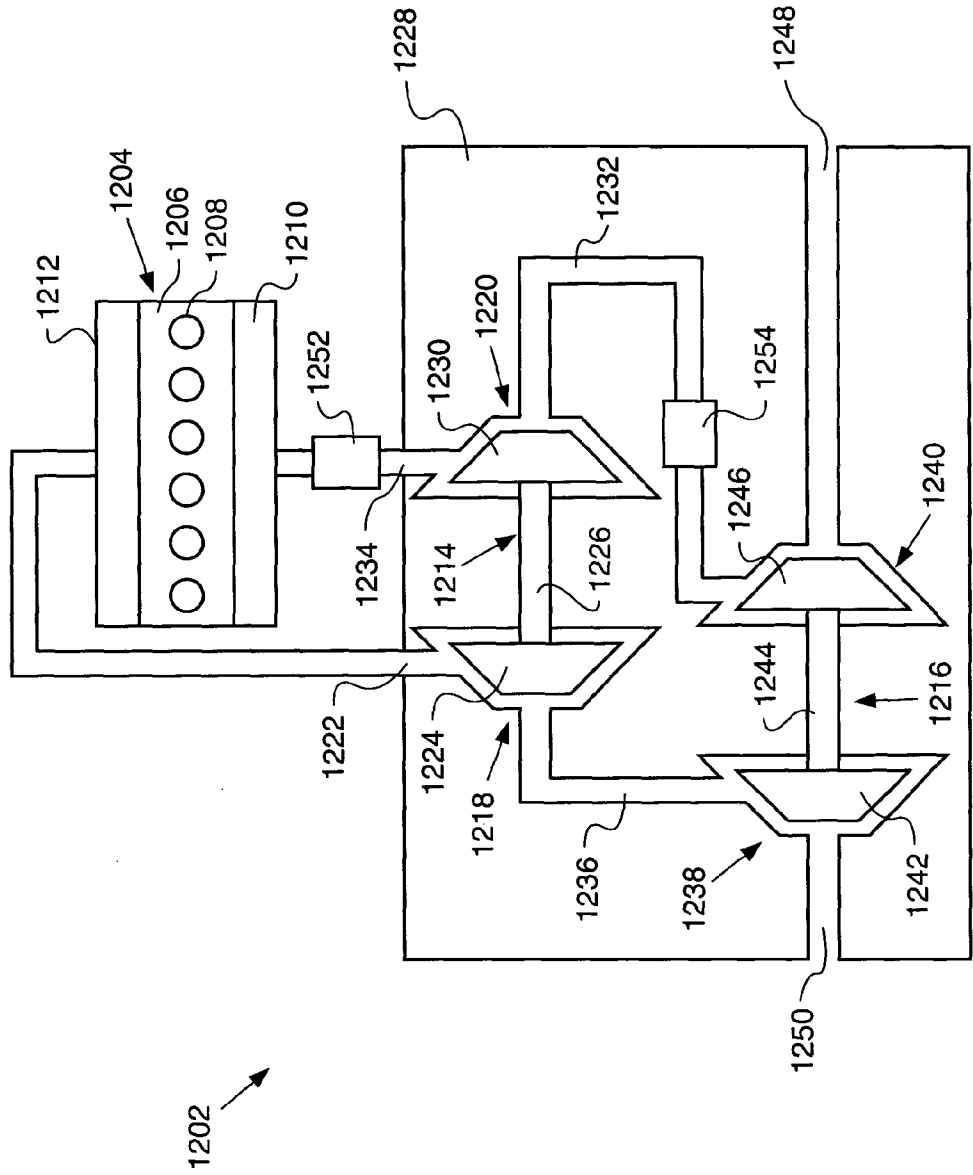
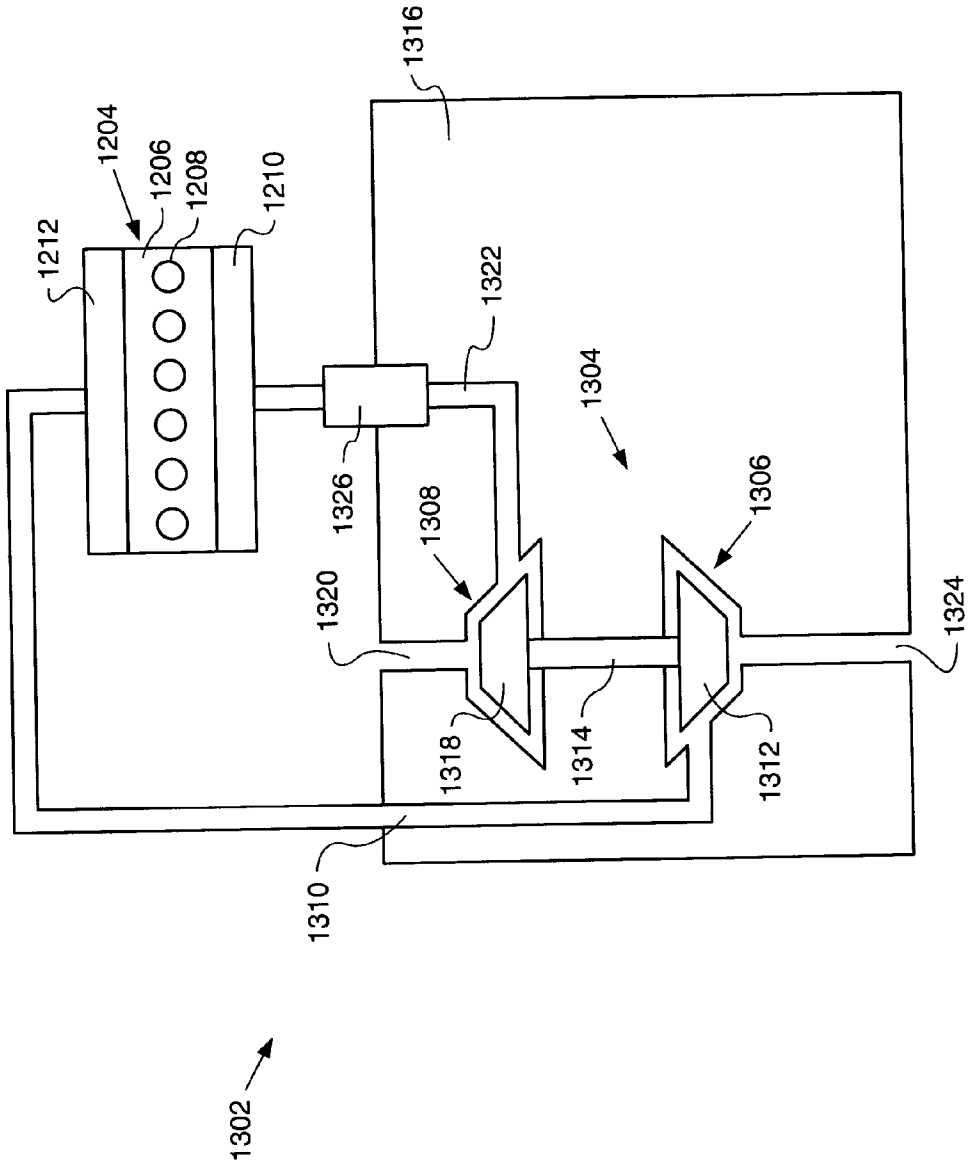


FIG. 12-

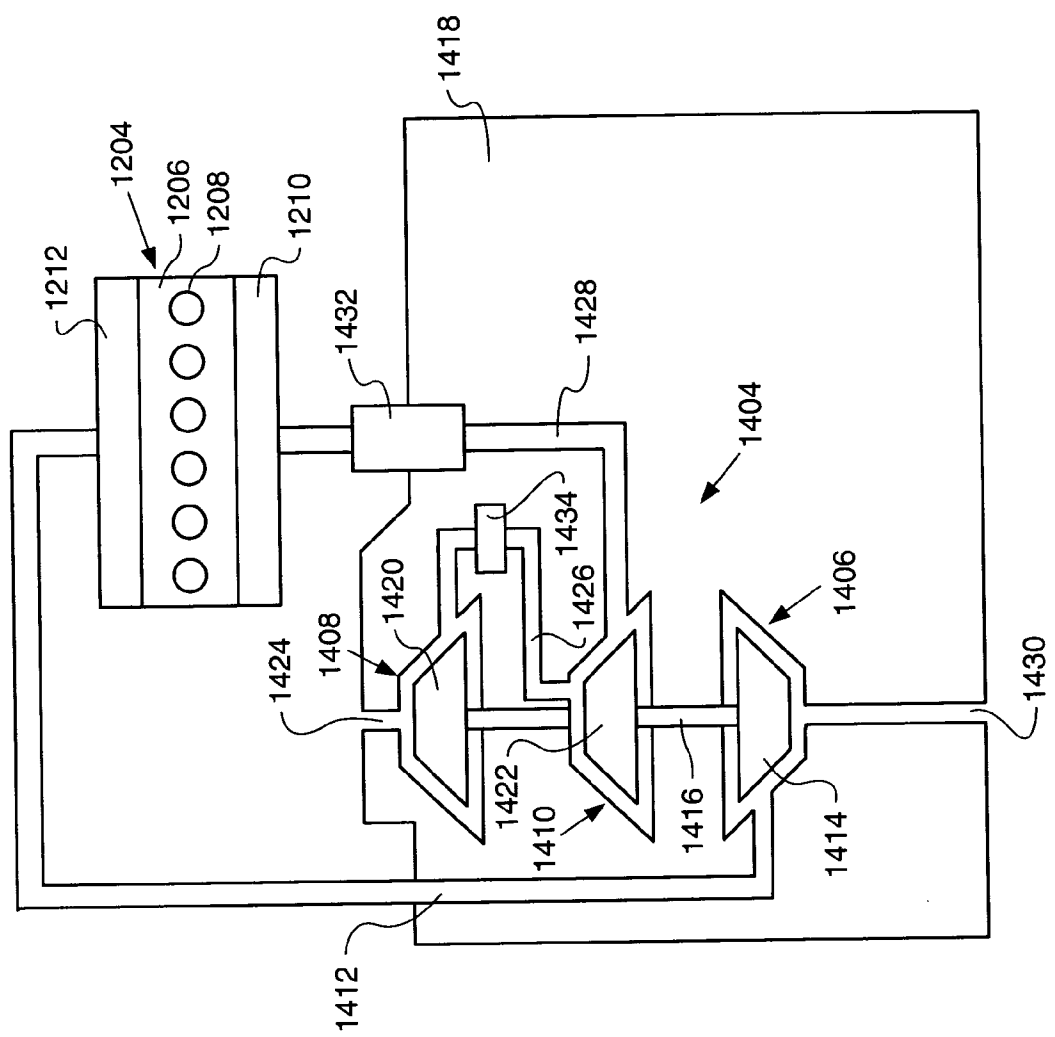


**FIG. 13.**

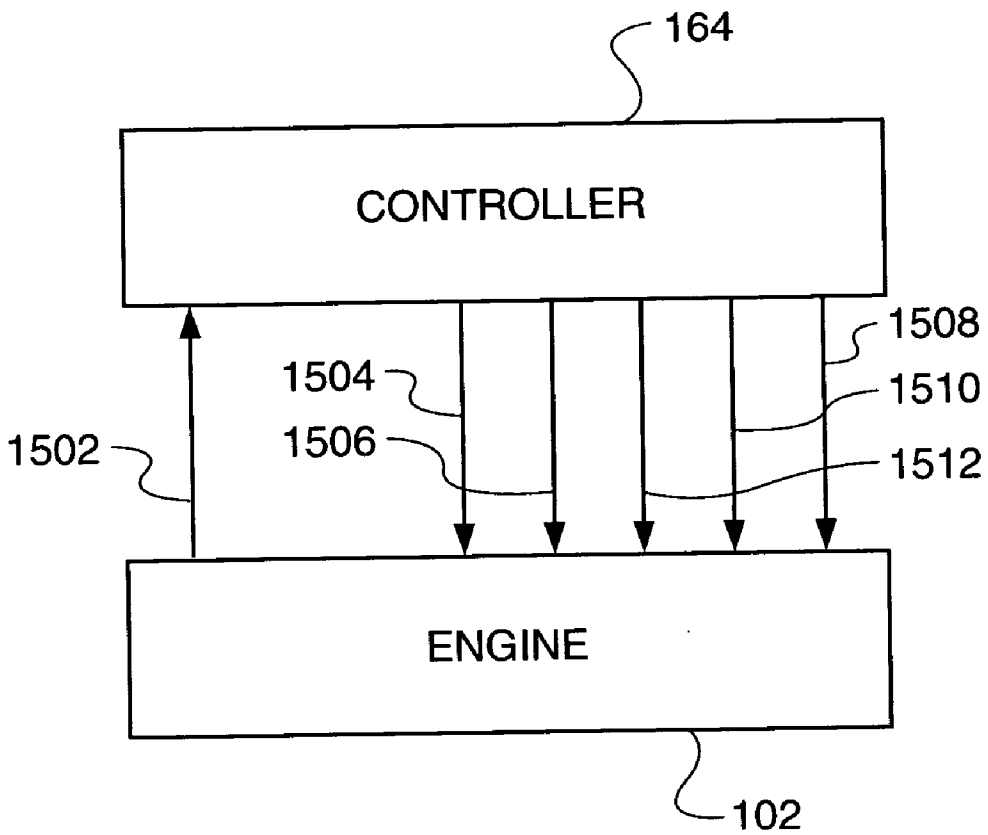


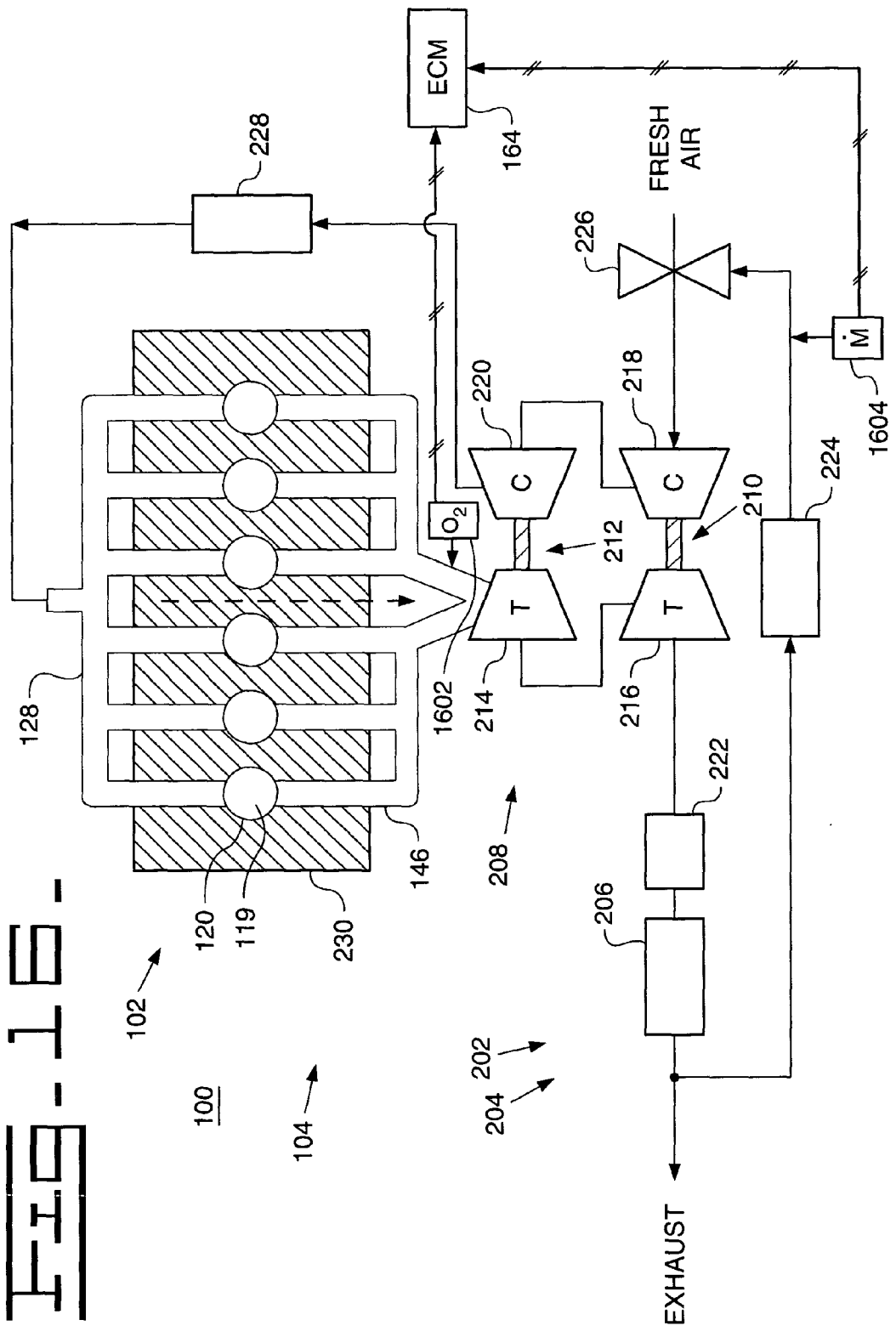
**FIG. 14**

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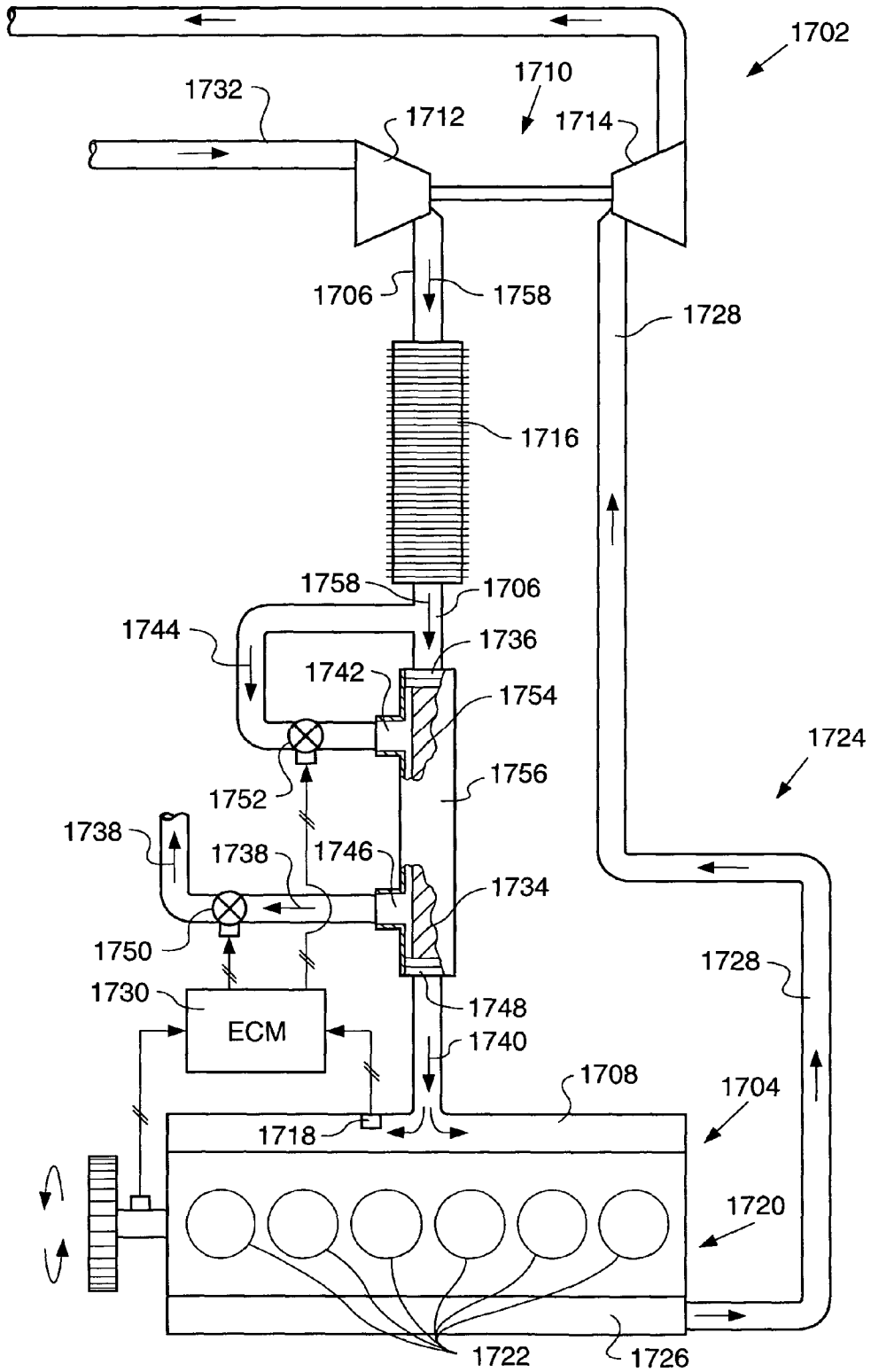
# FIG. 15.



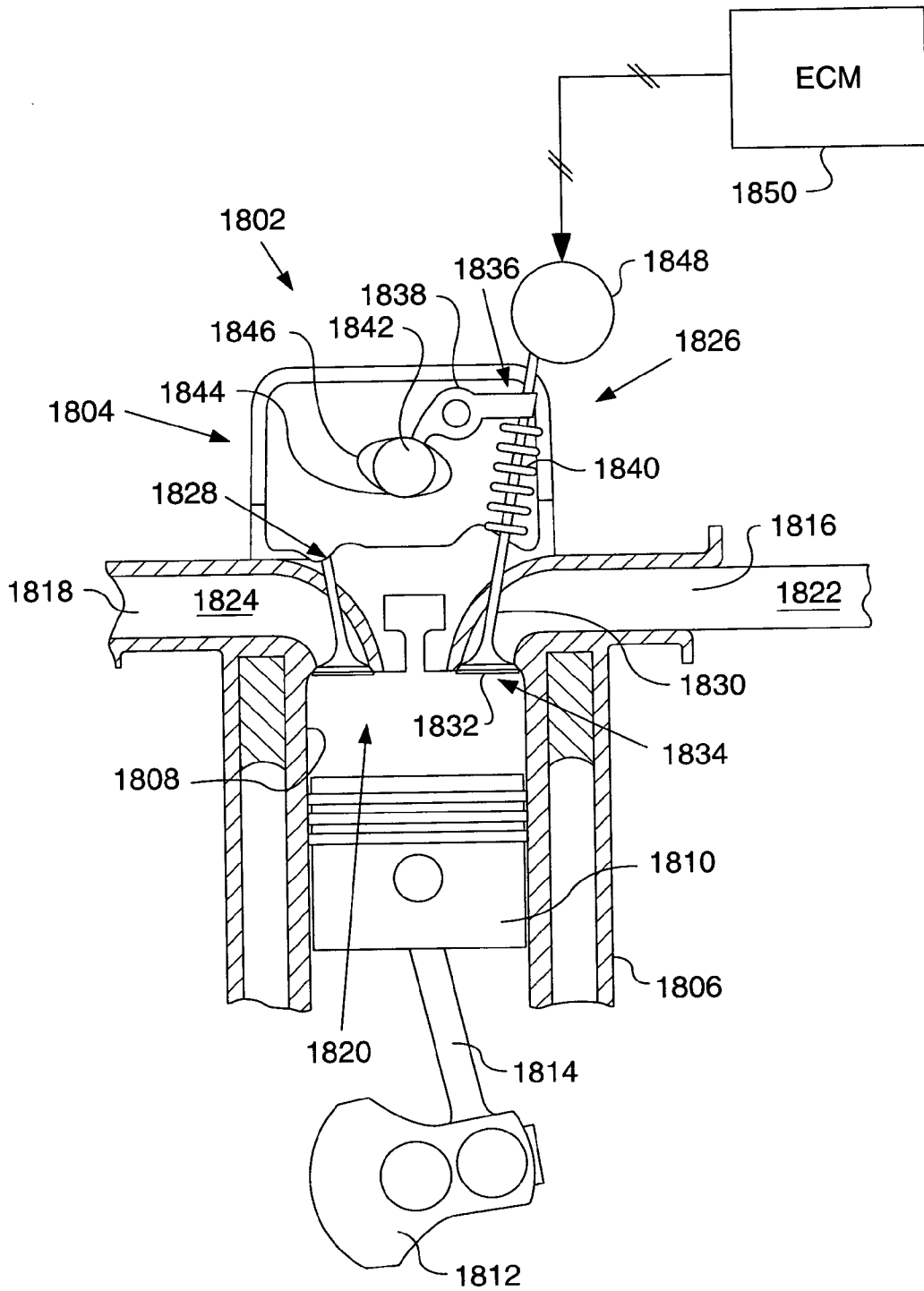




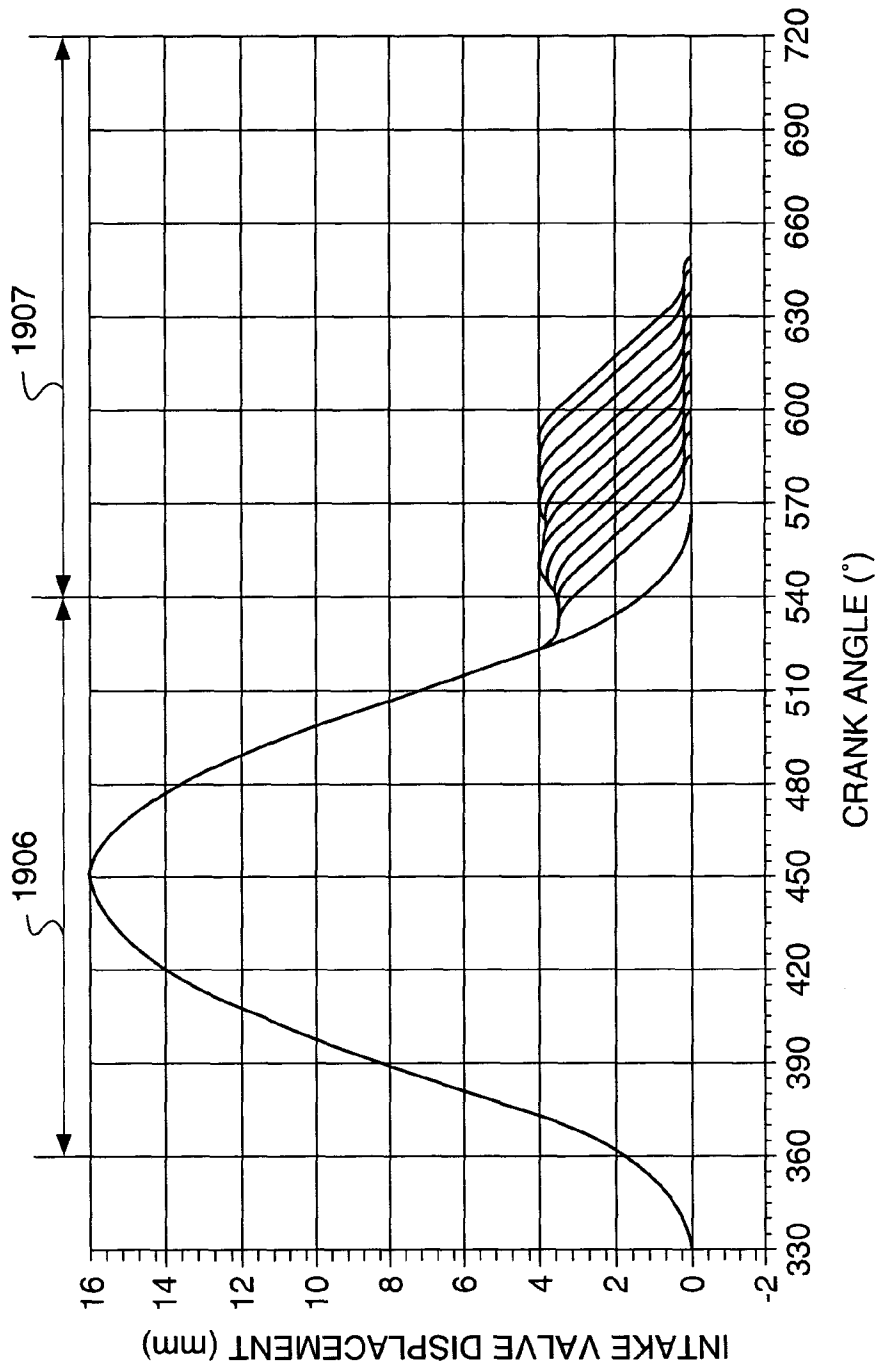
**FIG. 17.**

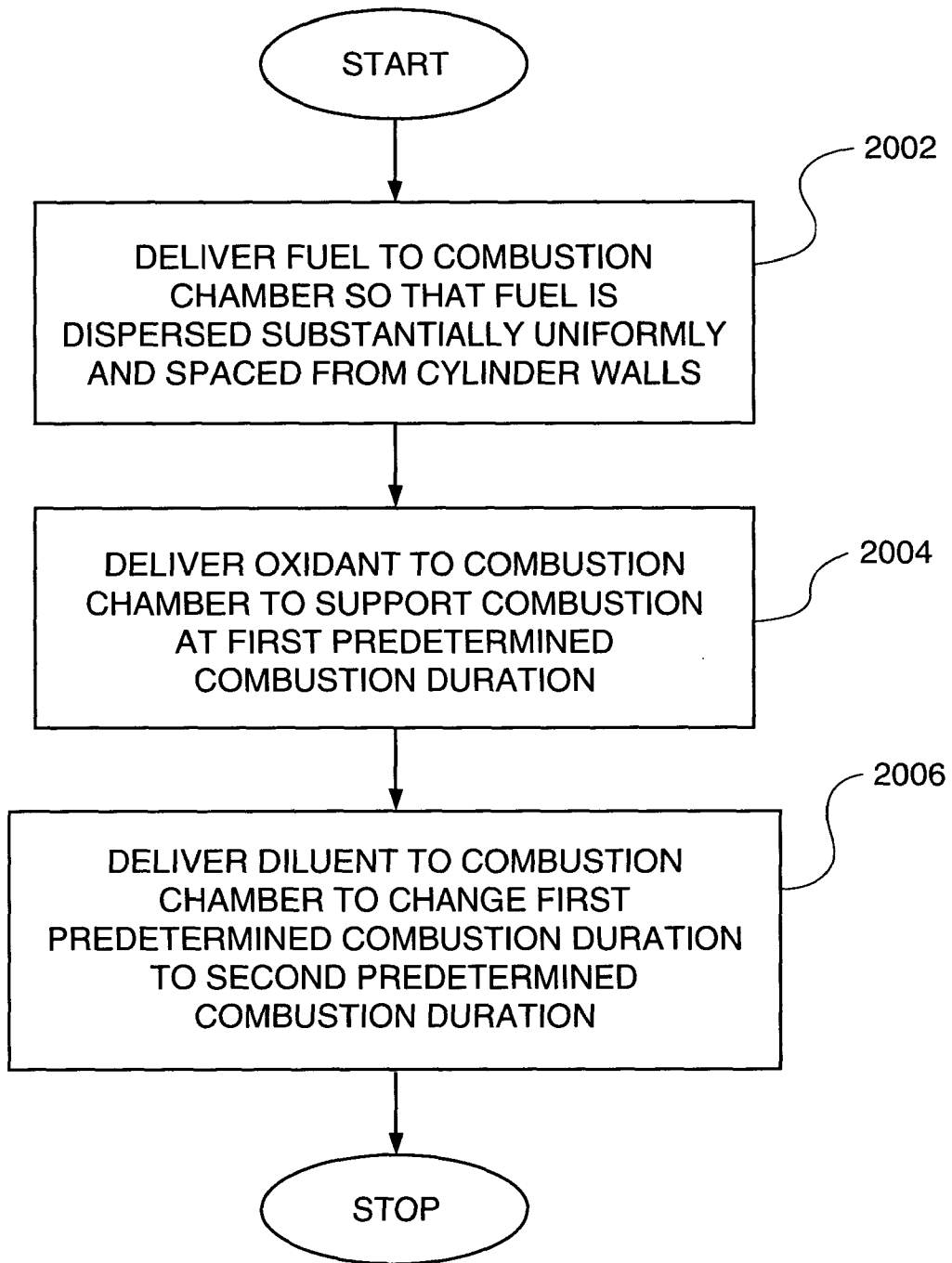
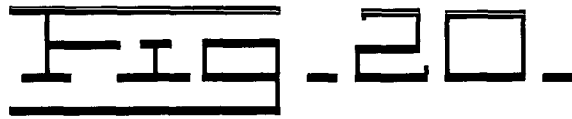


**FIG. 18.**



# FIG. 18.





## LOW EMISSIONS COMPRESSION IGNITED ENGINE TECHNOLOGY

### TECHNICAL FIELD

[0001] This invention relates generally to a method and apparatus for operating a compression ignition engine and, more particularly, to a method and apparatus for operating an engine in a homogeneous charge compression ignition mode to achieve low emissions during normal operating load conditions.

### BACKGROUND

[0002] Internal combustion engines are used extensively for a variety of purposes. The transportation infrastructure relies almost exclusively on the use of engines to provide power for mobility. Electrical power generation also relies heavily on internal combustion engines.

[0003] The prolific use of engines in our society has created a number of issues, one of which is the ever-increasing amounts of combustion by-products being emitted. Although today's engines operate with much lower emission levels than previous generations of engines, the rapidly increasing numbers of engines being used creates the need to reduce emission levels even more.

[0004] Governments around the world recognize this problem and are taking regulatory steps to address the emission levels of engines. For example, levels of oxides of nitrogen (NO<sub>x</sub>), hydrocarbons (HC), carbon monoxide (CO), and smoke, among others, must be reduced drastically to meet evolving government standards.

[0005] Spark ignition engines, by the nature of their operation and the types of fuel used, tend to produce low levels of NO<sub>x</sub> and particulate emissions. Compression ignition engines, for example diesel engines, generally produce high levels of NO<sub>x</sub> and particulate emissions. Diesel engines, however, are still popular in use because they provide higher thermal efficiency than their spark-ignition counterparts, and thus offer higher power output for work applications.

[0006] Engines that operate in homogeneous charge compression ignition (HCCI) mode have generated much interest due to the potential to operate at high fuel efficiency while generating low combustion emissions. HCCI engines differ from conventional diesel compression ignition engines in that diesel engines ignite fuel that is rich, i.e., highly concentrated in an area in a combustion chamber, while HCCI techniques create a dispersed homogeneous fuel/air mixture by the time of combustion. Combustion of a homogeneous fuel/air mixture allows an engine to operate such that emission by-products are significantly reduced.

[0007] The theory of HCCI mode operation has not been met by the reality, however. It has proven to be extremely difficult to create a desired homogeneous mixture of fuel and air and still control operation of the engine. For example, it is very difficult to control the timing of combustion when introducing a homogeneous mixture into a combustion chamber. Past attempts by others has only resulted in partial success under low load, e.g., one half load or less, conditions. In U.S. Pat. No. 6,286,482, Flynn et al. recognize this issue and only operate an engine in PCCI mode (which is equivalent to HCCI) under low to medium load conditions. Operation switches to spark ignition mode at high loads.

Yanagihara, in a paper entitled "Ignition Timing Control at Toyota 'UNIBUS' Combustion System", limits engine operation to one half load to enable operation in HCCI mode.

[0008] The present invention is directed to overcoming one or more of the problems as set forth above.

### SUMMARY OF THE INVENTION

[0009] In one aspect of the present invention a method for operating a compression ignition engine having a cylinder wall, a piston, and a head defining a combustion chamber is disclosed. The method includes the steps of delivering fuel substantially uniformly into the combustion chamber, the fuel being dispersed throughout the combustion chamber and spaced from the cylinder wall, delivering an oxidant into the combustion chamber sufficient to support combustion at a first predetermined combustion duration, and delivering a diluent into the combustion chamber sufficient to change the first predetermined combustion duration to a second predetermined combustion duration different from the first predetermined combustion duration.

[0010] In another aspect of the present invention a method for operating a compression ignition engine having a cylinder wall, a piston, and a head defining a combustion chamber is disclosed. The method includes the steps of delivering fuel substantially uniformly into the combustion chamber, the fuel being dispersed throughout the combustion chamber and spaced from the cylinder wall, delivering an oxidant into the combustion chamber sufficient to support combustion at a first predetermined pressure rise rate, and delivering a diluent into the combustion chamber sufficient to change the first predetermined pressure rise rate to a second predetermined pressure rise rate different from the first predetermined pressure rise rate.

[0011] In yet another aspect of the present invention a method for delivering fuel into a combustion chamber of a compression ignition engine, the combustion chamber being defined by a cylinder wall, a piston, and a head, is disclosed. The method includes the steps of delivering the fuel to a nozzle of an injector, the nozzle having a plurality of holes distributed in a desired pattern, and injecting the fuel through the nozzle holes into the combustion chamber in a predetermined spray pattern so that the fuel is dispersed throughout the combustion chamber and spaced from the cylinder wall.

[0012] In still another aspect of the present invention an apparatus for operating a compression ignition engine having a cylinder wall, a piston, and a head defining a combustion chamber is disclosed. The apparatus includes a fuel injector having a nozzle positioned to inject fuel in a dispersed pattern throughout the combustion chamber and spaced from the cylinder wall, and an air supply system for delivering at least one of an oxidant and a diluent into the combustion chamber.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1 is a diagrammatic illustration of an internal combustion engine suited for use with the present invention;

[0014] FIG. 2 is a block diagram illustrating an engine including an exhaust gas recirculation (EGR) system;

[0015] FIG. 3 is a block diagram illustrating a variation of the EGR system of FIG. 2;

[0016] FIG. 4a is a diagrammatic illustration of a fuel spray pattern;

[0017] FIG. 4b is another view of the fuel spray pattern of FIG. 4a;

[0018] FIG. 5a is a partial view of an exemplary fuel injector tip;

[0019] FIG. 5b is a diagram illustrating use of the fuel injector tip of FIG. 5a in a first mode;

[0020] FIG. 5c is a diagram illustrating use of the fuel injector tip of FIG. 5a in a second mode;

[0021] FIG. 6a is a graph depicting NOx and smoke emissions as a function of injection timing;

[0022] FIG. 6b is a graph depicting HC and CO emissions as a function of injection timing;

[0023] FIG. 7 is a graph depicting a combustion event as a function of pressure and time;

[0024] FIG. 8 is a block diagram illustrating exhaust gases being routed from the output of an engine to the input of the engine;

[0025] FIG. 9a is a graph depicting a combustion event as a function of cylinder pressure and crank angle degrees;

[0026] FIG. 9b is a graph depicting a combustion event as a function of a heat release rate and crank angle degrees;

[0027] FIG. 10 is a diagrammatic illustration of an exemplary variable compression ratio configuration;

[0028] FIG. 11 is a diagrammatic illustration of an exemplary 3-way catalyst;

[0029] FIG. 12 is a diagrammatic illustration of a first exemplary air assist system for an engine;

[0030] FIG. 13 is a diagrammatic illustration of a second exemplary air assist system;

[0031] FIG. 14 is a diagrammatic illustration of a third exemplary air assist system;

[0032] FIG. 15 is a block diagram illustrating an exemplary control system for an engine;

[0033] FIG. 16 is the block diagram of FIG. 2 including further features;

[0034] FIG. 17 is a diagrammatic illustration of an exemplary membrane technology system suited for use with the present invention;

[0035] FIG. 18 is a diagrammatic illustration of an engine having an exemplary variable valve actuation system;

[0036] FIG. 19 is a graph depicting displacement of an intake valve as a function of crank angle degrees; and

[0037] FIG. 20 is a flow diagram illustrating a preferred method of the present invention.

#### DETAILED DESCRIPTION

[0038] Referring to the drawings and the specification, a method and apparatus 100 for operating a compression ignition engine 102 is disclosed.

[0039] Referring to FIG. 1, there is shown an engine assembly 104. The engine assembly 104 depicts fundamental operation of a compression ignition engine 102. Additional features of the engine assembly 104 of FIG. 1, for example an exhaust gas recirculation assembly, are described below with reference to additional figures.

[0040] The engine assembly 104 includes a plenum member 106, and an air source 108. The plenum member 106 has an inlet opening 112, and an exit opening 110 defined therein. The air source 108 supplies air to the inlet opening 112. Air from the air source 108 advances into a plenum chamber 114 defined in the plenum member 106 via the inlet opening 112. It is noted that the description pertaining to FIG. 1 refers to air as being the medium being provided to the engine assembly 104. However, as described below, any suitable fluid medium may be used, for example, recirculated exhaust gases combined with air, and the like.

[0041] The engine assembly 104 further includes a cylinder assembly 116. The cylinder assembly 116 includes a block 118 having a cylinder 119 defined therein. The cylinder 119 is defined by a cylinder wall 120. An engine head 122 is secured to the block 118. The engine head 122 has an intake port 124, an exhaust port 126, and a fuel injector opening 154 defined therein. An intake conduit 128 places the intake port 124 in fluid communication with the exit opening 110 of the plenum member 106. An exhaust passage 146 places the exhaust port 126 in fluid communication with an exhaust manifold 148.

[0042] The engine assembly 104 further includes a piston 130 which translates in the cylinder 119 in the general direction of arrows 132 and 136. As the piston 130 moves downwardly in the general direction of arrow 136 to the position shown in FIG. 1, a connecting rod 134 urges a crankshaft 142 to rotate in the general direction of arrow 144. Subsequently, as the crankshaft 142 continues to rotate in the general direction of arrow 144, the crankshaft 142 urges the connecting rod 134 and the piston 130 in the general direction of arrow 132 to return the piston 130 to the uppermost position (not shown).

[0043] The piston 130, the cylinder wall 120, and the engine head 122 cooperate so as to define a combustion chamber 138. In particular, when the piston 130 is advanced in the general direction of arrow 132, the volume of the combustion chamber 138 is decreased. On the other hand, when the piston 130 is advanced in the general direction of arrow 136, the volume of the combustion chamber 138 is increased as shown in FIG. 1.

[0044] The engine assembly 104 further includes a fuel reservoir 158. A fuel pump 160 draws low pressure fuel from the fuel reservoir 158 and advances high pressure fuel to a fuel injector 156 via a fuel line 162. The fuel injector 156 is positioned in the injector opening 154 and is operable to inject a quantity of fuel into the combustion chamber 138 through the injector opening 154. In particular, the fuel injector 156 injects fuel into the combustion chamber 138 upon receipt of an injector control signal on a signal line 166. Furthermore, the fuel can be any one of the following group of fuels: diesel fuel, crude oil, lubricating oil, or an emulsion of water and diesel fuel. More generally, the fuel may be any type of fuel which has a high cetane number, thus having the property of combusting readily.

[0045] It should be appreciated that the amount of fuel injected by the fuel injector 156 controls the ratio of air to

fuel, or air/fuel ratio, advanced to the combustion chamber 138. Specifically, if it is desired to advance a leaner mixture to the combustion chamber 138, a fuel control signal received via signal line 166 causes the fuel injector 156 to operate so as to inject less fuel to the combustion chamber 138. On the other hand, if it is desired to advance a richer mixture of air and fuel to the combustion chamber 138, a fuel control signal received via signal line 166 causes the fuel injector 156 to operate so as to advance more fuel to the combustion chamber 138.

[0046] It is noted that other methods of introducing the fuel and air mixture to the combustion chamber 138 may be used without deviating from the spirit and scope of the present invention. For example, the fuel may be mixed with air at any point from the air source 108 through the intake conduit 128, including upstream of a turbocharger (not shown).

[0047] An intake valve 140 selectively places the plenum chamber 114 in fluid communication with the combustion chamber 138. The intake valve 140 may be actuated in a known manner by a camshaft (not shown), a pushrod (not shown), and a rocker arm (not shown) driven by rotation of the crankshaft 142. Alternatively, the intake valve 140 may be actuated by other means, such as hydraulically, electronically, a combination of electro-hydraulically, and the like. When the intake valve 140 is placed in the open position (shown in FIG. 1), air is advanced from the intake conduit 128 to the combustion chamber 138 via the intake port 124. When the intake valve 140 is placed in the closed position (not shown), air is prevented from advancing from the intake conduit 128 to the combustion chamber 138 since the intake valve 140 blocks fluid flow through the intake port 124.

[0048] An exhaust valve 152 selectively places the exhaust manifold 148 in fluid communication with the combustion chamber 138. The exhaust valve 152 may be actuated in a known manner by a camshaft (not shown), a pushrod (not shown), and a rocker arm (not shown) each of which are driven by the rotation of the crankshaft 142. Alternatively, the exhaust valve 152 may be actuated by other means, such as hydraulically, electronically, a combination of electro-hydraulically, and the like. When the exhaust valve 152 is placed in the open position (not shown), exhaust gases are advanced from the combustion chamber 138 to the exhaust manifold 148 via a fluid path that includes the exhaust port 126 and the exhaust passage 146. From the exhaust manifold 148, exhaust gases are advanced to an exhaust conduit 150. When the exhaust valve 152 is placed in the closed position (shown in FIG. 1), exhaust gases are prevented from advancing from the combustion chamber 138 to the exhaust manifold 148 since the exhaust valve 152 blocks fluid flow through the exhaust port 126.

[0049] Combustion of the mixture of fuel and air in the combustion chamber 138 produces a number of exhaust gases. After the mixture of fuel and air is combusted in the combustion chamber 138, exhaust gases are advanced through the exhaust conduit 150. Included among the exhaust gases are quantities of oxides of nitrogen (NO<sub>x</sub>), hydrocarbons (HC), carbon monoxide (CO), smoke, and the like.

[0050] The engine assembly 104 further includes a controller 164. The controller 164 is preferably a microprocessor-based engine control unit (ECU).

[0051] The controller 164 may perform a variety of functions, including, as described above, controlling actuation of the fuel injector 156.

[0052] Referring to FIG. 2, a schematic representation of an engine 102 having an intake conduit 128 and an exhaust passage 146 is shown. An engine block 230 provides housing for at least one cylinder 119. FIG. 2 depicts six cylinders 119. However, any number of cylinders 119 could be used, for example, one, three, six, eight, ten, twelve, or any other number. The intake conduit 128 provides an intake path for each cylinder 119 for air, recirculated exhaust gases, or a combination thereof. The exhaust passage 146 provides an exhaust path for each cylinder 119 for exhaust gases.

[0053] In the embodiment shown in FIG. 2, a two-stage turbocharger system 208 is illustrated. The turbocharger system 208 includes a first turbocharger stage 210 having a low pressure turbine 216 and a first stage compressor 218. The turbocharger system 208 also includes a second turbocharger stage 212 having a high pressure turbine 214 and a second stage compressor 220. The two-stage turbocharger system 208 operates to increase the pressure of the air and exhaust gases being delivered to the cylinders 119 via the intake conduit 128, and to maintain a desired air to fuel ratio during an extended open duration of an intake valve, which is described in more detail below. It is noted that a two-stage turbocharger system 208 is not required for operation of the present invention. Other types of turbocharger systems, such as a high pressure ratio single-stage turbocharger system, a variable geometry turbocharger system, and the like, may be used instead.

[0054] The engine assembly includes an exhaust system 202, which in turn includes an exhaust gas recirculation (EGR) system 204. The EGR system 204 shown in FIG. 2 is typical of a low pressure EGR system in an internal combustion engine. Variations of the EGR system 204 shown may also be used with the present invention. Furthermore, other types of EGR systems, for example, by-pass, venturi, piston-pumped, peak clipping, and back pressure, could be used as well.

[0055] An oxidation catalyst 222 receives exhaust gases from the low pressure turbine 216. The oxidation catalyst 222 may also be coupled with a De-NO<sub>x</sub> catalyst to further reduce NO<sub>x</sub> emissions. A particulate matter (PM) filter 206 receives exhaust gases from the oxidation catalyst 222. Although the oxidation catalyst 222 and the PM filter 206 are shown as separate items, they may alternatively be combined into one package.

[0056] Some of the exhaust gases are delivered out the exhaust from the PM filter 206. However, a portion of exhaust gases are rerouted to the intake conduit 128 through an EGR cooler 224, through an EGR valve 226, and through the turbocharger system 208.

[0057] FIG. 3 shows a variation of the EGR system 204 of FIG. 2. In FIG. 3, some of the exhaust gases are routed from the low pressure turbine 216, through the oxidation catalyst 222, and through the PM filter 206. However, a portion of exhaust gases are rerouted to the intake conduit 128 from the low pressure turbine 216, i.e., before entering the oxidation catalyst 222, through an additional PM filter 302, then through the EGR cooler 224, EGR valve 226, and the turbocharger system 208. The additional PM filter 302

may be smaller in size than the PM filter 206 in the main exhaust stream since only a portion of the exhaust gases need be filtered. In addition, by installing the additional PM filter 302 in the return path of the EGR system 204, the packaging and routing of the filter 302 and the associated input and output ductwork becomes more compact and manageable around the vicinity of the engine 102.

[0058] Referring to FIGS. 4a and 4b, operation of a fuel injector 156 suited for use with the present invention is shown. In FIG. 4a, the fuel injector nozzle 154, i.e., the tip of the injector 156, is shown in more detail. The fuel injector nozzle 154 includes a plurality of micro-sized holes 401, e.g., 10, 16, 24, 32 and the like, arranged in a pattern such that a desired fuel spray 402 is achieved. The exemplary fuel injector opening 154 of FIGS. 4a and 4b reflects a 24 hole "showerhead" design, arranged such that a first set of holes injects fuel spray at a first angle of dispersion  $\alpha$  and a second set of holes injects fuel spray at a second angle of dispersion  $\beta$ . For example, a first set of 8 holes injects fuel spray at an angle  $\alpha$  equal to about 50 degrees and a second set of 16 holes injects fuel spray at an angle  $\beta$  equal to about 90 degrees. It is noted that any number and combination of holes, sets of holes, and angles of dispersion may be used as well without deviating from the scope of the present invention.

[0059] The design of the fuel injector nozzle 154 of FIGS. 4a and 4b offers the advantage of distributing the fuel spray 402 uniformly throughout desired portions of the combustion chamber 138, in particular with respect to a particular geometry of the piston 130. This control over the fuel spray 402 allows for fuel injection in advance of normal injection timing to allow sufficient time for the fuel and air, i.e., fluid medium, to mix homogeneously without fuel being allowed to deposit on the cylinder wall 120 prior to combustion. Preferably, the fuel spray 402 is configured to inject the fuel such that the fuel is dispersed substantially uniformly into the combustion chamber 138 and spaced from the cylinder wall 120. More specifically, the fuel spray 402 is intended to disperse throughout the combustion chamber 138 without any fuel contacting the cylinder wall 120, thus preventing fuel from quenching on the cylinder wall 120, which may be at a lower temperature than the remainder of the combustion chamber 138, and thus may result in increased levels of HC and CO during combustion.

[0060] Alternative fuel injection techniques may be used with the present invention. For example, FIGS. 5a-5c illustrate the function of a fuel injector 156 suited for use in mixed-mode operations. More specifically, the fuel injector opening 154 includes at least one HCCI nozzle outlet 504 and at least one conventional nozzle outlet 506. The HCCI nozzle outlet 504 is configured at an angle  $\theta$  from a longitudinal axis 502 of the fuel injector 156 to inject fuel spray 504 in a pattern represented by FIG. 5b. The conventional nozzle outlet 506 is configured at an angle  $\lambda$  from the longitudinal axis 502 to inject fuel spray 504 in a pattern represented by FIG. 5c.

[0061] During HCCI mode operations, the fuel spray 402 is directed downward toward the piston 130. Injection takes place more in advance of top dead center, as can be seen by the relative position of the piston 130 in FIG. 5b compared to FIG. 5c, which allows more time for the fuel and fluid medium, e.g., air, to combine into a homogeneous mixture.

[0062] During conventional mode operations, e.g., diesel compression mode, the fuel spray 402 is directed more toward the sides of the cylinder 119 and injection takes place closer to top dead center, as evidenced by the position of the piston 130 in FIG. 5c.

[0063] It is noted that variations of the injector configuration of FIG. 5a may be used without deviating from the scope of the present invention. For example, a showerhead type of output nozzle may be used in place of the HCCI nozzle outlet 504 for HCCI operations, while the conventional nozzle outlet 506 may be employed during conventional diesel operations. Furthermore, in the fuel injector 156 of FIG. 5a, the angles  $\theta$  and  $\lambda$  of the nozzle outlets 504, 506 may be varied over a wide range to suit particular applications. Alternatively, the HCCI injection may be accomplished with port injection, i.e., the fuel is injected for example in the intake conduit 128 to provide for a homogeneous mixture of fuel and air in the combustion chamber 138. This method, however, may result in fuel condensing on the cylinder wall 120, thus contributing to oil degradation.

[0064] The timing of fuel injection may be varied to improve performance during HCCI operation. A timing range from about 50 degrees before top dead center (TDC) to about 180 degrees before TDC is typically used to insure a near complete homogeneous mixture of fuel and fluid medium. However, it is preferred to inject fuel as late as possible, i.e., closer to TDC, since excessive time for fuel presence in the cylinder 119 results in fuel condensing on the cylinder walls 120, which in turn contaminates and degrades the engine oil. It has been shown, as depicted in FIGS. 6a and 6b, that with a 24 hole showerhead fuel injector and no EGR an optimal injection timing of about 70 degrees before TDC may be achieved. More specifically, at about 70 degrees before TDC, levels of NOx and smoke are minimal and levels of HC and CO are greatly reduced. It has been further found that the addition of EGR may retard the optimal injection timing to about 60 degrees before TDC, thus alleviating fuel condensation even more. Further refinements in operating conditions, such as injector tip geometry, fuel dispersion patterns, EGR quantity, air intake, and the like, have enabled fuel injection in the range of from about 30 degrees before TDC to about 90 degrees before TDC, with optimal emissions reported when fuel injection occurs at about 40 degrees before TDC.

[0065] It is desired during HCCI operations to maintain a low combustion temperature. One reason is that levels of NOx are reduced at low combustion temperatures. One method for achieving low combustion temperatures is to introduce a high level of excess mass, i.e., large amounts of a fluid medium such as air, EGR, water, inert gas and the like, into the combustion chamber 138. Using air, i.e., fresh air, as the excess mass medium requires very large amounts of air to be delivered to the combustion chamber 138 to achieve desired excess mass levels. For example, an air to fuel ratio of about 36 to 1 or greater may be desired, corresponding to an equivalence ratio of 0.4 or less.

[0066] Alternatively, some other type of fluid medium may be used to achieve excess mass. For example, the use of EGR in place of at least a portion of fresh air may enable operation of the engine 102 at a near stoichiometric equivalence ratio, i.e., with an air to fuel ratio of about 14.5 to 1.



[0067] EGR may also be used to control a heat release rate and a pressure rise rate within the combustion chamber 138. For example, as the graph 702 shown in FIG. 7 depicts, a first plot 704 is indicative of a pressure rise rate during combustion in HCCI mode without the addition of EGR. The plot 704 illustrates a sharp rise in pressure in the combustion chamber 138. This sharp rise in pressure creates stresses in components such as the engine head 122. A second plot 706 is indicative of the pressure rise rate with EGR added. First, it is noted that the duration of combustion, i.e., the time for combustion to take place, has changed. More specifically, the combustion duration is extended. Second, it is noted that the peak pressure has changed. More specifically, the peak pressure is reduced. It has been found that the addition of EGR enables brake mean effective pressure (BMEP) levels to approach 1600 kPa. Without EGR, BMEP is limited to about 1100 kPa, i.e., about one half load.

[0068] The fluid added does not necessarily have to be EGR. More generally, the addition of a diluent such as EGR, water, carbon dioxide, nitrogen, and the like performs the function of lowering combustion temperature, limiting peak combustion pressure, and extending the duration of combustion. The diluent affects combustion by lowering the heat release rate in the combustion chamber 138 and creating a number of interim chemical reactions during combustion which serves to extend the combustion event. It is noted that the mass of the diluent contributes to the total fluid mass in the combustion chamber 138, the other portion of fluid mass being the oxidant, e.g., air, introduced to support combustion.

[0069] Referring to FIG. 8, the amount of EGR added is preferably quantified as a volumetric percentage, as exemplified by the following equation:

$$\% \text{ EGR} = \frac{\text{CO}_2(\text{in})}{\text{CO}_2(\text{ex})} \times 100 \quad (\text{Eq. 1})$$

[0070] where  $\text{CO}_2(\text{in})$  is an amount of carbon dioxide being returned to the engine by way of the EGR system 204, and  $\text{CO}_2(\text{ex})$  is an amount of carbon dioxide exhausted from the engine 102. The amount of EGR may be a significant percentage, for example 40% to 60%, under certain operating conditions. It is noted that the percentage of EGR may be quantified by some other method such as, for example, the mass of the EGR divided by the total mass in the combustion chamber 138.

[0071] Referring to FIG. 9a, a graph 902 of cylinder pressure vs. crank angle degrees (CAD) is shown. The plot indicates a first pressure rise portion 906 having a rise slope which levels off, then increases in slope to a second pressure rise portion 908. The "double-humped" curve is indicative of a homogeneous mixture during combustion, and thus defines an HCCI mode. In like manner, in FIG. 9b, a graph 904 of heat release rate vs. CAD is shown. The plot includes a first heat release peak portion 910, followed by a second heat release peak portion 912. As noted, the second heat release peak portion 912 is much larger in value than the first heat release peak portion 910. The curve serves to define an HCCI mode as well.

[0072] The excess mass may be provided by the use of high boost pressure at the intake conduit 128, i.e., intake manifold, of the engine 102. Exemplary techniques for providing high boost pressure are described below.

[0073] Although the introduction of excess mass serves to control the pressure rise rate in the combustion chamber 138, it is also desired to control a peak pressure during combustion. As FIG. 7 illustrates, the first plot 704 has a peak pressure that is higher in value than the peak pressure of the second plot 706. One method of controlling the peak pressure is by use of a variable compression ratio (VCR).

[0074] There are many techniques in use which provide VCR of an engine. One common strategy is to employ variable valve timing, in particular variable intake valve timing. For example, an intake valve may be kept open for a period of time into a compression cycle, for example from about 20 to about 50 degrees into compression. Variable valve timing may be accomplished by several means. Exemplary techniques may include mechanical, e.g., control of cam actuation, hydraulic, electric, electro-hydraulic, and the like.

[0075] Another common strategy, and one that may be more effective than variable valve timing, is to vary the geometric characteristics of a cylinder. For example, as depicted in FIG. 10, a secondary cylinder 1002 may be used in cooperation with a secondary piston 1004 to vary the effective volume of the cylinder 119. A rod 1006 connected to the secondary piston 1004 is also connected to an actuator 1008, such as a cam actuator, a hydraulic actuator, a solenoid actuator, or other actuation device. As the position of the secondary piston 1004 is varied in the secondary cylinder 1002, the effective compression ratio of the piston 130 and cylinder 119 is varied. It is noted that the example of FIG. 10 is but one of many methods by which the compression ratio of a cylinder may be varied using geometric techniques.

[0076] Preferably, to enable combustion to occur at a desired time, the VCR is varied as a function of engine speed and engine load. Typically, as speed and load increases, more fuel is delivered to the combustion chamber 138. This additional fuel causes an increase in pressure. The VCR may be lowered as speed and load increases to help compensate for this pressure increase. An exemplary range for compression ratio may be from about 8:1 to about 16:1. For example, a compression ratio of 10:1 was used in a test engine running at about 75% load. Preferably, compression ignition rather than spark ignition is maintained during the above-referenced lower compression ratios.

[0077] Although the engine 102 may be operating in HCCI mode and may be using a fuel such as diesel, the addition of EGR as described above, for example about 40% to about 60% EGR, enables operation at near stoichiometric. Under these conditions, it is possible to use a 3-way catalyst for further reductions in HC, CO and NOx. For example, referring to FIG. 11, an exemplary 3-way catalyst suited for use with the present invention is shown.

[0078] FIG. 11 shows a series combination catalytic converter 1110 in which three different catalytic substrates 1133, 1134 and 1135 are mounted in series within an individual tubular housing 1122. The inner structure includes mounting each of the catalytic substrates in its own sub-can 1130, 1131

and **1132**, respectively. Tubular housing **1122** may be formed from thin stainless steel and may be formed on the outlet end **1124** with an annular retaining lip **1125** that prevents the individual sub-cans from escaping through the outlet. In addition, the curvature of the bend which creates retaining lip **1125** may be useful as a guide when mounting the converter **1110** in an opening having a diameter very close to that of the housing **1122**. Each of the sub-cans **1130**, **1131** and **1132** may be held within the tubular housing **1122** by a peripheral seam weld at corners **1128**.

[**0079**] The substrate **1133** may be coated with a typical deNOx catalyst, such as a combination precious metal and zeolite catalyst. The substrate **1134** may be coated with a catalyst appropriate to target secondary undesirable nitrogen compounds existing in the exhaust after exiting the substrate **1133**. After emerging from the substrate **1134**, the exhaust contains very low levels of NOx compounds and even less undesirable secondary nitrogen compounds which would otherwise become NOx compounds after proceeding through an oxidation catalyst. The substrate **1135** may be coated with an oxidation catalyst to promote the conversion of any existing HC and CO into carbon dioxide and water. Only small amounts of the exhaust are turned back into undesirable NOx compounds after passing through oxidation catalyst substrate **1135**. Upon exiting the converter **1110** at the outlet **1124**, the exhaust has acceptable levels of both HC and NOx.

[**0080**] The sub-cans **1130**, **1131** and **1132** are preferably made from relatively thin stainless steel that is rolled on both ends to create an annular retaining lip that traps the individual ceramic substrates **1133**, **1134** and **1135** within the sub-cans. A matting material **1129** may be mounted between the inner surface of each sub-can and the outer surface of each substrate. The edges of the individual strips of matting **1129** may be shielded from the corrosive effects of the exhaust by end rings **1127**. Each of the sub-cans may be fixed within the tubular housing **1122** via a peripheral seam weld at the annular corners **1128**.

[**0081**] It is noted that the above example of a 3-way catalyst is for exemplary purposes only, and that variations of the above catalyst may be used as well. Furthermore, other types of catalysts, e.g., deNOx catalysts only, oxidation catalysts only, and the like, may be used as well.

[**0082**] The large amounts of excess mass, e.g., EGR, will require a significant level of boost pressure, i.e., intake manifold pressure, to deliver the excess mass into the combustion chamber **138**. For example, a boost pressure value of about 4.5 to 1 or higher may be required under full load operating conditions. That is, the pressure at the intake manifold will need to be at least 456 kPa. The achievement of this high boost pressure requires an air system capable of generating sufficient pressure. For example, the 2-stage turbocharger system **208** of FIGS. 2 and 3 illustrates one possible air system capable of generating sufficient boost pressure.

[**0083**] Referring to FIGS. 12-14, exemplary variations of the turbocharger system **208** are shown. Discussion of the components of FIGS. 12-14 is provided below, with new element labeling to provide further clarification of various air systems.

[**0084**] Referring to FIG. 12, an exemplary air supply system **1202** for an internal combustion engine **1204**, for

example, a four-stroke, diesel engine, is provided. The internal combustion engine **1204** includes an engine block **1206** defining a plurality of combustion cylinders **1208**, the number of which depends upon the particular application. For example, a 4-cylinder engine would include four combustion cylinders, a 6-cylinder engine would include six combustion cylinders, etc. In the exemplary embodiment of FIG. 12, six combustion cylinders **1208** are shown.

[**0085**] The internal combustion engine **1204** also includes an intake manifold **1210** and an exhaust manifold **1212**. The intake manifold **1210** provides fluid, for example, air or a fuel/air mixture, to the combustion cylinders **1208**. The exhaust manifold **1212** receives exhaust fluid, for example, exhaust gas, from the combustion cylinders **1208**. The intake manifold **1210** and the exhaust manifold **1212** are shown as a single-part construction for simplicity in the drawing. However, it should be appreciated that the intake manifold **1210** and/or the exhaust manifold **1212** may be constructed as multi-part manifolds, depending upon the particular application.

[**0086**] The air supply system **1202** includes a first turbocharger **1214** and may include a second turbocharger **1216**. The first and second turbochargers **1214**, **1216** may be arranged in series with one another such that the second turbocharger **1216** provides a first stage of pressurization and the first turbocharger **1214** provides a second stage of pressurization. For example, the second turbocharger **1216** may be a low pressure turbocharger and the first turbocharger **1214** may be a high pressure turbocharger. The first turbocharger **1214** includes a turbine **1218** and a compressor **1220**. The turbine **1218** is fluidly connected to the exhaust manifold **1212** via an exhaust duct **1222**. The turbine **1218** includes a turbine wheel **1224** carried by a shaft **1226**, which in turn may be rotatably carried by a housing **1228**, for example, a single-part or multi-part housing. The fluid flow path from the exhaust manifold **1212** to the turbine **1218** may include a variable nozzle (not shown) or other variable geometry arrangement adapted to control the velocity of exhaust fluid impinging on the turbine wheel **1224**.

[**0087**] The compressor **1220** includes a compressor wheel **1230** carried by the shaft **1226**. Thus, rotation of the shaft **1226** by the turbine wheel **1224** in turn may cause rotation of the compressor wheel **1230**.

[**0088**] The first turbocharger **1214** may include a compressed air duct **1232** for receiving compressed air from the second turbocharger **1216** and an air outlet line **1234** for receiving compressed air from the compressor **1220** and supplying the compressed air to the intake manifold **1210** of the engine **1204**. The first turbocharger **1214** may also include an exhaust duct **1236** for receiving exhaust fluid from the turbine **1218** and supplying the exhaust fluid to the second turbocharger **1216**.

[**0089**] The second turbocharger **1216** may include a turbine **1238** and a compressor **1240**. The turbine **1238** may be fluidly connected to the exhaust duct **1236**. The turbine **1238** may include a turbine wheel **1242** carried by a shaft **1244**, which in turn may be rotatably carried by the housing **1228**. The compressor **1240** may include a compressor wheel **1246** carried by the shaft **1244**. Thus, rotation of the shaft **1244** by the turbine wheel **1242** may in turn cause rotation of the compressor wheel **1246**.

[**0090**] The second turbocharger **1216** may include an air intake line **1248** providing fluid communication between the

atmosphere and the compressor 1240. The second turbocharger 1216 may also supply compressed air to the first turbocharger 1214 via the compressed air duct 1232. The second turbocharger 1216 may include an exhaust outlet 1250 for receiving exhaust fluid from the turbine 1238 and providing fluid communication with the atmosphere. In an embodiment, the first turbocharger 1214 and second turbocharger 1216 may be sized to provide substantially similar compression ratios. For example, the first turbocharger 1214 and second turbocharger 1216 may both provide compression ratios of between 2 to 1 and 3 to 1, resulting in a system compression ratio of at least 4:1 with respect to atmospheric pressure. Alternatively, the second turbocharger 1216 may provide a compression ratio of 3 to 1 and the first turbocharger 1214 may provide a compression ratio of 1.5 to 1, resulting in a system compression ratio of 4.5 to 1 with respect to atmospheric pressure.

[0091] The air supply system 1202 may include an air cooler 1252, for example, an aftercooler, between the compressor 1220 and the intake manifold 1210. The air cooler 1252 may extract heat from the air to lower the intake manifold temperature and increase the air density. Optionally, the air supply system 1202 may include an additional air cooler 1254, for example, an intercooler, between the compressor 1240 of the second turbocharger 1216 and the compressor 1220 of the first turbocharger 1214. Alternatively, the air supply system 1202 may optionally include an additional air cooler (not shown) between the air cooler 1252 and the intake manifold 1210. The optional additional air cooler may further reduce the intake manifold temperature.

[0092] FIG. 13 is a block diagram illustrating another exemplary air supply system 1302 for the internal combustion engine 1204. The air supply system 1302 may include a turbocharger 1304, for example, a high-efficiency turbocharger capable of producing at least about a 4.5 to 1 compression ratio with respect to atmospheric pressure. The turbocharger 1304 may include a turbine 1306 and a compressor 1308. The turbine 1306 may be fluidly connected to the exhaust manifold 1212 via an exhaust duct 1310. The turbine 1306 may include a turbine wheel 1312 carried by a shaft 1314, which in turn may be rotatably carried by a housing 1316, for example, a single-part or multi-part housing. The fluid flow path from the exhaust manifold 1212 to the turbine 1306 may include a variable nozzle (not shown), which may control the velocity of exhaust fluid impinging on the turbine wheel 1312.

[0093] The compressor 1308 may include a compressor wheel 1318 carried by the shaft 1314. Thus, rotation of the shaft 1314 by the turbine wheel 1312 in turn may cause rotation of the compressor wheel 1318. The turbocharger 1304 may include an air inlet 1320 providing fluid communication between the atmosphere and the compressor 1308 and an air outlet 1322 for supplying compressed air to the intake manifold 1210 of the engine 1204. The turbocharger 1304 may also include an exhaust outlet 1324 for receiving exhaust fluid from the turbine 1306 and providing fluid communication with the atmosphere.

[0094] The air supply system 1302 may include an air cooler 1326 between the compressor 1308 and the intake manifold 1210. Optionally, the air supply system 1302 may include an additional air cooler (not shown) between the air cooler 1326 and the intake manifold 1210.

[0095] FIG. 14 is a block diagram illustrating another exemplary air supply system 1402 for the internal combustion engine 1204. The air supply system 1402 may include a turbocharger 1404, for example, a turbocharger 1404 having a turbine 1406 and two compressors 1408, 1410. The turbine 1406 may be fluidly connected to the exhaust manifold 1212 via an inlet duct 1412. The turbine 1406 may include a turbine wheel 1414 carried by a shaft 1416, which in turn may be rotatably carried by a housing 1418, for example, a single-part or multi-part housing. The fluid flow path from the exhaust manifold 1212 to the turbine 1406 may include a variable nozzle (not shown), which may control the velocity of exhaust fluid impinging on the turbine wheel 1414.

[0096] The first compressor 1408 may include a compressor wheel 1420 carried by the shaft 1416, and the second compressor 1410 may include a compressor wheel 1422 carried by the shaft 1416. Thus, rotation of the shaft 1416 by the turbine wheel 1414 in turn may cause rotation of the first and second compressor wheels 1420, 1422. The first and second compressors 1408, 1410 may provide first and second stages of pressurization, respectively.

[0097] The turbocharger 1404 may include an air intake line 1424 providing fluid communication between the atmosphere and the first compressor 1408 and a compressed air duct 1426 for receiving compressed air from the first compressor 1408 and supplying the compressed air to the second compressor 1410. The turbocharger 1404 may include an air outlet line 1428 for supplying compressed air from the second compressor 1410 to the intake manifold 1210 of the engine 1204. The turbocharger 1404 may also include an exhaust outlet 1430 for receiving exhaust fluid from the turbine 1406 and providing fluid communication with the atmosphere.

[0098] For example, the first compressor 1408 and second compressor 1410 may both provide compression ratios of between 2 to 1 and 3 to 1, resulting in a system compression ratio of at least 4:1 with respect to atmospheric pressure. Alternatively, the second compressor 1410 may provide a compression ratio of 3 to 1 and the first compressor 1408 may provide a compression ratio of 1.5 to 1, resulting in a system compression ratio of 4.5 to 1 with respect to atmospheric pressure.

[0099] The air supply system 1402 may include an air cooler 1432 between the second compressor 1410 and the intake manifold 1210. Optionally, the air supply system 1402 may include an additional air cooler 1434 between the first compressor 1408 and the second compressor 1410 of the turbocharger 1404. Alternatively, the air supply system 1402 may optionally include an additional air cooler (not shown) between the air cooler 1432 and the intake manifold 1210.

[0100] It is noted that other types of air supply systems could be used as well. For example, an air-to-EGR cooler, a blower and turbocharger arrangement, and an electric turbocharger assist are a few of the types of air supply systems which may provide the needed boost pressure for the present invention.

[0101] Referring to FIG. 15, a block diagram illustrating an embodiment of a control system for the present invention is shown. The engine 102 is monitored and controlled by the

controller **164**, e.g., an electronic control module (ECM) typically used for engine monitoring and control.

[**0102**] A signal indicative of cylinder pressure feedback is delivered to the controller **164** by way of signal line **1502** and may be used to determine an event such as a start of combustion. The cylinder pressure feedback may be sensed directly, for example by a cylinder pressure sensor (not shown), or may be derived from other sensed parameters. For example, engine speed and load parameters may be monitored and used to determine a start of combustion event.

[**0103**] The controller **164** may, upon receipt of the cylinder pressure feedback signal, determine that some control of engine operations is needed. For example, it may be determined that the timing of the start of combustion should be changed. The controller **164** may have several options to use for controlling engine operations. For example, the controller **164** may deliver a control signal via signal line **1504** to modulate an intake manifold temperature, the controller **164** may deliver a control signal via signal line **1506** to modulate a timing of actuation of an intake valve, a control signal may be delivered via signal line **1508** to modulate a rate at which EGR is being delivered, a control signal may be delivered via signal line **1510** to modulate a timing of injection of fuel, or a control signal may be delivered via signal line **1512** to modulate a boost pressure value. It is understood that any combination of the above control strategies may be employed. Furthermore, other control strategies may be incorporated as well.

[**0104**] The complexities of engine operation due to the interactions of many variables indicates that it may be desired to configure the controller **164** to use advanced techniques for data analysis and engine control. For example, it may be desired to incorporate a neural network (not shown) into the controller **164** to make control decisions based on an historical database of engine operations.

[**0105**] Referring to **FIG. 16**, the block diagram of **FIG. 2** is reproduced with the addition of an oxygen sensor (O<sub>2</sub>) **1602** and a mass airflow sensor (MAF) **1604**. The O<sub>2</sub> sensor **1602** may be located at some position suitable for sensing an amount of oxygen in the exhaust gases after combustion, for example at the exhaust passage **146**. The MAF sensor **1604** may be located at some position suitable for sensing the mass of EGR gases, for example prior to the EGR valve **226**. Alternatively, the MAF sensor **1604** may be located elsewhere, for example after the EGR valve **226** to sense a total flow of mass, e.g., EGR plus fresh air, being delivered to the engine **102**.

[**0106**] The O<sub>2</sub> and MAF sensors **1602,1604** may be used separately or in combination, and may deliver sensed values to the controller **164** for processing to further determine and control a rate of EGR being delivered to the engine **102**.

[**0107**] In an alternate embodiment, it may be desired to incorporate membrane technology to use nitrogen as an inert gas in place of, or in combination with, EGR as the excess mass used to control heat release rates in the combustion chamber **138**. For example, **FIG. 17** depicts an exemplary intake air separation system **1702** suited for use with the present invention.

[**0108**] Referring to **FIG. 17**, a diagrammatic illustration of an intake air separation system **1702** for an engine **1704**

is shown. The intake side of the engine **1704** includes an intake air conduit **1706**, an intake manifold **1708**, intake air pressurizing device **1710**, e.g., a turbocharger, and an inter-cooler or an air-to-air aftercooler **1716**. The intake air pressurizing device **1710** may include an exhaust gas driven turbine **1714**, which in turn drives a compressor **1712**. The engine **1704** also includes a main combustion section **1720**, and an exhaust system **1724**. Although not shown in great detail, the typical main combustion section **1720** includes, among other elements, an engine block and a cylinder head forming a plurality of combustion cylinders **1722** therein. Associated with each of the cylinders **1722** is a fuel injector, a cylinder liner, at least one air intake port and corresponding intake valves, at least one exhaust gas port and corresponding exhaust valves, and a reciprocating piston movable within each cylinder to define, in conjunction with the cylinder liner and cylinder head, the combustion chamber. The exhaust system **1724** of the engine **1704** includes an exhaust manifold **1726** or split exhaust manifolds, one or more exhaust conduits **1728**, and the turbine **1714**. Optionally, the exhaust system **1724** may include one or more aftertreatment devices (not shown) such as particulate traps, NO<sub>x</sub> adsorbers, oxidation and/or lean NO<sub>x</sub> catalysts, or other recent advances in exhaust gas aftertreatment. Finally, the engine **1704** includes an electronic control module (ECM) **1730**, i.e., a controller, for operatively controlling the fuel injection timing and air system valve operations in response to one or more measured or sensed engine operating parameters, used as inputs to the ECM **1730**.

[**0109**] The intake air conduit **1706** is in flow communication with intake air input **1732**, the compressor **1712** of the intake air pressurizing device **1710**, and the aftercooler **1716**. Although the intake air separation system **1702** is shown and described in conjunction with a conventional turbocharged diesel engine, the disclosed system **1702** is equally useful on engines with a variable geometry turbocharger (VGT) or other supercharged engines, including engines with pressure wave supercharging devices. The intake manifold **1708** is connected to an end of the intake air conduit **1706**. An inlet pressure sensor **1718** is shown located somewhere in the intake air separation system **1702**, e.g., shown proximate the intake manifold **1708**, and provides intake air pressure data to the ECM **1730**. Other sensors such as temperature sensors, oxygen sensors (not shown), and the like may also be incorporated within the intake air separation system **1702** and likewise coupled as inputs to the ECM **1730**. In addition, various other devices such as filters, valves, actuators, bypass conduits, etc., although not shown, may also be incorporated within the intake air separation system **1702**. Any such electronically operative components such as valves and/or actuators are preferably operatively coupled to the ECM **1730** and operate in response to selected engine operating parameters or conditions, including engine speed, engine load, boost pressure conditions, etc.

[**0110**] The illustrated intake air separation system **1702** includes an intake air separation device **1734** disposed within the intake air separation system **1702** of the engine **1704**. The intake air separation device **1734** may be adapted for receiving substantially all of the engine combustion air at an air separation device inlet **1736**, i.e., an intake air inlet, and separating the same into a flow **1738** of oxygen enriched air, i.e., a permeate flow, and a flow **1740** of nitrogen enriched air, i.e., a retentate flow. The illustrated intake air

separation device **1734** includes two inlets and two outlets. The first inlet is the intake air inlet **1736** that receives the air to be separated into an oxygen rich stream and a nitrogen rich stream. The second inlet is a purge air inlet **1742** that is adapted to receive a flow **1744** of sweep air or purge air which enhances the permeation effectiveness of the intake air separation device **1734**. The purge air **1744** may be taken from a flow of intake air **1758** from the compressor **1712** and the aftercooler **1716**. Alternatively, the flow of purge air **1744** may be a separate flow of filtered ambient air. The first outlet, or permeate outlet **1746** of the intake air separation device **1734** is adapted to receive the permeate flow **1738** of oxygen enriched air combined with the flow of purge air **1744**.

[**0111**] The second outlet, or retentate outlet **1748** is adapted to receive the retentate flow **1740** of nitrogen enriched air. Preferably, the intake air separation device **1734** is a full flow separation unit and thus there is no need for subsequent mixing of the nitrogen enriched air flow **1740** exiting the retentate outlet **1748** with more intake air. The retentate outlet **1748** is further in flow communication with the intake manifold **1708** of the engine **1704**. A permeate flow valve **1750** may be disposed proximate the permeate outlet **1746**. The permeate flow valve **1750** is preferably actuated in response to signals received from ECM **1730** which controls the permeate flow **1738** away from the intake air separation device **1734**, and thereby controls the flow **1740** from the retentate outlet **1748** to the intake manifold **1708**. More specifically, the permeate flow valve **1750** located proximate the permeate outlet **1746** controls both the permeate flow **1738** and the flow of purge air **1744** away from intake air separation device **1734** and thus controls the relative concentrations of nitrogen and oxygen in the air directed to the intake manifold **1708** and to the combustion cylinders **1722**.

[**0112**] The location of the permeate flow valve **1750** is preferably at or proximate to the permeate outlet **1746**. Such an arrangement aids the responsiveness of the engine **1704** based on a relatively fast change in oxygen and nitrogen content of the air exiting the retentate outlet **1748** into the intake manifold **1708** when the permeate flow valve **1750** is actuated, e.g., opened or closed, during transient operating conditions. Selective operation of the permeate flow valve **1750** allows the engine **1704** to operate in essentially three different charge air modes, namely nitrogen enriched mode, i.e., valve partially or fully open, standard intake air mode, i.e., valve closed for selected length of time, and transient oxygen enriched mode, which occurs for a short period or duration as the permeate flow valve **1750** is first closed. The exact location of the permeate flow valve **1750** is preferably optimized to take advantage of the different modes of charge air, and in particular the transient charge of oxygen enriched air that occurs when the permeate flow valve **1750** is first closed.

[**0113**] The intake air separation device **1734** preferably uses a plurality of selectively permeable separation membranes **1754** that separates ambient intake air into streams of oxygen enriched air and nitrogen enriched air. Such membranes **1754** are well known in the art.

[**0114**] The intake air separation device **1734** may include a housing or shell **1756**, having the intake air inlet **1736**, the purge air inlet **1742**, the permeate outlet **1746**, and the

retentate outlet **1748**. A plurality of selectively permeable membrane elements or fibers are disposed in a general longitudinal or helical, i.e., spiral, orientation within the housing **1756** and potted or sealed at each end. The air separation membranes **1754** are preferably hollow, porous, coated tubes through which selected gases such as hydrogen, helium, water vapors, carbon dioxide, and oxygen tend to permeate outwardly through the membranes at a relatively fast rate while other gases such as carbon monoxide, argon and nitrogen permeate less rapidly and are mostly retained and transported along the membrane tubes. Different gases present in the flow **1758** of intake air tend to permeate through the membrane **1754** at different relative permeation rates and generally through the sidewalls of the membrane **1754**. The rate of permeation is also dependent in part on the membrane temperature, and therefore altering or controlling the temperatures of gases entering the intake air separation device **1734** ultimately controls permeability.

[**0115**] The intake air is introduced into the housing **1756** and membranes **1754** of the intake air separation device **1734** in an orientation or direction that is generally along the length of the membranes **1754**. In this manner the flow **1758** of intake air is transported or flows generally along the length of the intake air separation device **1734**. Conversely, the flow **1744** of purge air is introduced into the housing **1756** and membranes **1754** in a cross flow orientation or direction such that the flow **1744** of purge air flows generally across outer surfaces of the membranes **1754**. The flow **1744** of purge air then exits the housing **1756** via the permeate outlet **1746** as part of the permeate flow **1738** and together with the permeated oxygen rich air. The retentate flow **1740** of nitrogen rich air exits from the housing **1756** via retentate outlet **1748**.

[**0116**] The above description of an intake air separation device **1734** illustrate only one example of sweep or purge air flow configurations that produce good separation results. Various other flow configurations can also be employed. The various purge flow configurations offer differences in separation performance and packaging issues and can be tailored to the specific application in which the air separation device is used.

[**0117**] The compressor **1712** of the intake air pressurizing device **1710** is used to forcibly move intake air through the membrane-based intake air separation device **1734** in what is often referred to as the pressure mode. In like manner, the flow **1744** of purge air is received or diverted from the flow **1758** of boosted, cooled intake air and delivered to the purge air inlet **1742**. A purge air valve **1752** operatively coupled to the ECM **1730** may be used to control the flow **1744** of purge air under various operating conditions. Thus, the flow **1744** of purge air and the flow of intake air **1758** are typically pressurized while the permeate flow **1738** of oxygen enriched air and purge air exiting the intake air separation device **1734** is preferably at a somewhat lower pressure, due to pressure losses incurred by flowing through the intake air separation device **1734**. This pressure gradient across the membranes **1754** enables air separation to occur. As illustrated, the permeate flow **1738** is preferably vented to the atmosphere or otherwise fed to other parts of the engine **1704**, including, but not limited to the exhaust system **1724**. However, the permeate flow **1738** may also be delivered to the combustion cylinders **1722** to provide at least a portion of a supply of oxidant to support combustion. The retentate

flow **1740** of nitrogen enriched air is fed to the intake manifold **1708** in a generally pressurized condition, albeit at a lower pressure than the feed or intake air pressure due to losses caused by the membrane-based intake air separation device **1734**.

[0118] Referring briefly to **FIG. 1**, it may be desired to utilize variable valve timing to aid in performance of the present invention. For example, the temperature in the cylinder **119** may be increased, thus assisting in control of combustion, by varying the timing of the exhaust valve **152**. More specifically, by varying the timing of closing of the exhaust valve **152**, some of the hot residual gases from combustion are trapped in the combustion chamber **138** and the start of combustion for the next cycle is advanced.

[0119] It may also be desired to vary the timing of the intake valve **140** to modulate the air to fuel ratio during acceleration of the engine **102**, thus further controlling combustion. Varying the timing of closing of the intake valve **140** serves to operate the engine **102** in a Miller cycle which lowers the effective compression ratio which in turn retards the start of combustion. Varying the timing of opening of the intake valve **140** allows hot exhaust gases to flow into the intake port **124**, which advances the start of combustion.

[0120] **FIGS. 18 and 19** illustrate operation of an exemplary technique for achieving variable valve timing. Although the description below and **FIGS. 18 and 19** depict variable valve operation of the intake valve, similar principles apply to varying the timing of an exhaust valve.

[0121] Referring to **FIG. 18**, a diagrammatic and cross-sectional illustration of a portion of an internal combustion engine **1802** is shown. A cylinder head **1804** is connected to an engine block **1806**. The cylinder head **1804** houses one or more cylinders **1808**. For purposes of illustration, **FIG. 18** is described below with reference to one cylinder **1808**.

[0122] The cylinder **1808** contains a piston **1810** slidably movable in the cylinder **1808**. A crankshaft **1812** is rotatably disposed within the engine block **1806**. A connecting rod **1814** couples the piston **1810** to the crankshaft **1812** so that sliding motion of the piston **1810** within the cylinder **1808** results in rotation of the crankshaft **1812**. Similarly, rotation of the crankshaft **1812** results in a sliding motion of the piston **1810**. For example, an uppermost position of the piston **1810** in the cylinder **1808** corresponds to a top dead center position of the crankshaft **1812**, and a lowermost position of the piston **1810** in the cylinder **1808** corresponds to a bottom dead center position of the crankshaft **1812**.

[0123] As one skilled in the art will recognize, the piston **1810** in a conventional, four-stroke engine cycle reciprocates between the uppermost position and the lowermost position during a combustion (or expansion) stroke, an exhaust stroke, an intake stroke, and a compression stroke. Meanwhile, the crankshaft **1812** rotates from the top dead center position to the bottom dead center position during the combustion stroke, from the bottom dead center to the top dead center during the exhaust stroke, from top dead center to bottom dead center during the intake stroke, and from bottom dead center to top dead center during the compression stroke. Then, the four-stroke cycle begins again. Each piston stroke correlates to about 180° of crankshaft rotation, or crank angle. Thus, the combustion stroke may begin at

about 0° crank angle, the exhaust stroke at about 180°, the intake stroke at about 360°, and the compression stroke at about 540°.

[0124] The cylinder **1808** includes at least one intake port **1816** and at least one exhaust port **1818**, each opening to a combustion chamber **1820**. The intake port **1816** is coupled to an intake passageway **1822** and the exhaust port **1818** is coupled to an exhaust passageway **1824**. The intake port **1816** is opened and closed by an intake valve assembly **1826**, and the exhaust port **1818** is opened and closed by an exhaust valve assembly **1828**. The intake valve assembly **1826** includes, for example, an intake valve **1830** having a head **1832** at a first end **1834**, with the head **1832** being sized and arranged to selectively close the intake port **1816**. A second end **1836** of the intake valve **1830** is connected to a rocker arm **1838** or any other conventional valve-actuating mechanism. The intake valve **1830** is movable between a first position permitting flow from the intake port **1816** to enter the cylinder **1808** and a second position substantially blocking flow from the intake port **1816** to the cylinder **1808**. Preferably, a spring **1840** is disposed about the intake valve **1830** to bias the intake valve **1830** to the second, closed position.

[0125] A camshaft **1842** carrying a cam **1844** with one or more lobes **1846** is arranged to operate the intake valve assembly **1826** cyclically based on the configuration of the cam **1844**, the lobes **1846**, and the rotation of the camshaft **1842** to achieve a desired intake valve timing. The exhaust valve assembly **1828** is configured in a manner similar to the intake valve assembly **1826** and is preferably operated by one of the lobes **1846** of the cam **1844**. In one embodiment, the intake lobe **1846** is configured to operate the intake valve **1830** in a conventional Otto or diesel cycle, whereby the intake valve **1830** moves to the second, closed position from between about 10° before bottom dead center of the intake stroke and about 10° after bottom dead center of the compression stroke. Alternatively, the intake valve assembly **1826** and/or the exhaust valve assembly **1828** may be operated hydraulically, pneumatically, electronically, or by any combination of mechanics, hydraulics, pneumatics, and/or electronics.

[0126] In the preferred embodiment, the intake valve assembly **1826** includes a variable intake valve closing mechanism **1848** structured and arranged to selectively interrupt cyclical movement of and extend the closing timing of the intake valve **1830**. The variable intake valve closing mechanism **1848** may be operated hydraulically, pneumatically, electronically, mechanically, or any combination thereof. For example, the variable intake valve closing mechanism **1848** may be selectively operated to supply hydraulic fluid, for example, at a low pressure or a high pressure, in a manner to resist closing of the intake valve **1830** by the bias of the spring **1840**. That is, after the intake valve **1830** is lifted, i.e., opened, by the cam **1844**, and when the cam **1844** is no longer holding the intake valve **1830** open, the hydraulic fluid may hold the intake valve **1830** open for a desired period. The desired period may change depending on the desired performance of the engine **1802**. Thus, the variable intake valve closing mechanism **1848** enables the engine **1802** to operate under a conventional Otto or diesel cycle or under a variable late-closing Miller cycle. In alternative embodiments, the intake valve **1830**

may be controlled by a camless system (not shown), such as an electrohydraulic system, as is well known in the art.

[0127] As shown in FIG. 19, the intake valve 1830 may begin to open at about 360° crank angle, that is, when the crankshaft 1812 is at or near a top dead center position of an intake stroke 1906. The closing of the intake valve 1830 may be selectively varied from about 540° crank angle, that is, when the crankshaft 1812 is at or near a bottom dead center position of a compression stroke 1907, to about 650° crank angle, that is, about 700 before top center of the combustion stroke. Thus, the intake valve 1830 may be held open for a majority portion of the compression stroke 1907, that is, for the first half of the compression stroke 1907 and a portion of the second half of the compression stroke 1907.

[0128] A controller 1850, e.g., an electronic control module (ECM), may be electrically connected to the variable intake valve closing mechanism 1848. Preferably, the controller 1850 is configured to control operation of the variable intake valve closing mechanism 1848 based on one or more engine conditions, for example, engine speed, load, pressure, and/or temperature in order to achieve a desired engine performance. It should be appreciated that the functions of the controller 1850 may be performed by a single controller or by a plurality of controllers.

[0129] Referring back to FIG. 1, it is noted that, under some operating conditions such as engine start-up and light load operation, it may be desired to operate the engine 102 using a spark ignition system (not shown), as is well known in the art.

#### INDUSTRIAL APPLICABILITY

[0130] As an example of an application of the present invention, reference is made to FIG. 20 in which a flow diagram illustrating a method for operating a compression ignition engine 102 having a cylinder wall 120, a piston 130, and a head 122 defining a combustion chamber 138 is shown.

[0131] In a first control block 2002, fuel is delivered to the combustion chamber 138 so that the fuel is dispersed substantially uniformly throughout the combustion chamber 138 and is spaced from the cylinder wall 120. More particularly, the fuel is dispersed throughout the combustion chamber 138 to provide a substantially homogeneous distribution, yet the fuel dispersion is controlled such that fuel does not impinge on the cylinder wall 120, which would result in fuel condensation and subsequent degradation of the lubricating oil in the engine 102.

[0132] In a second control block 2004, sufficient oxidant is delivered to the combustion chamber 138 to support combustion at a first predetermined combustion duration. Typically, the oxidant includes a supply of fresh air, as is well known in the art. However, the oxidant could be at least in part a supply of oxygen obtained from such means as use of membrane technology, as described above.

[0133] In a third control block 2006, a supply of diluent is delivered to the combustion chamber 138 sufficient to change the first predetermined combustion duration to a second predetermined combustion duration. Preferably, the second predetermined combustion duration differs from the first predetermined combustion duration. For example, the second predetermined combustion duration may be greater

than the first predetermined combustion duration so that combustion is controlled over a longer period of time.

[0134] The diluent may be EGR, air, an inert gas such as nitrogen, and the like. For example, as described above, the diluent may be a gas which includes up to 40-60% EGR. As another example, the diluent may include a quantity of nitrogen obtained by means such as membrane technology, as described above. The diluent may also include a combination of gases.

[0135] In combination with the combustion duration being changed by the addition of diluent, the diluent may also serve to change a first predetermined pressure rise rate in the combustion chamber 138 to a second predetermined pressure rise rate. For example, the pressure rise rate during combustion may decrease from the addition of diluent. As described above, FIG. 7 serves to illustrate the change in both combustion duration and combustion pressure rise rate (and peak pressure) by the addition of a diluent.

[0136] Other aspects can be obtained from a study of the drawings, the disclosure, and the appended claims.

What is claimed is:

1. A method for operating a compression ignition engine having a cylinder wall, a piston, and a head defining a combustion chamber, comprising the steps of:

delivering fuel substantially uniformly into the combustion chamber, the fuel being dispersed throughout the combustion chamber and spaced from the cylinder wall;

delivering an oxidant into the combustion chamber sufficient to support combustion at a first predetermined combustion duration; and

delivering a diluent into the combustion chamber sufficient to change the first predetermined combustion duration to a second predetermined combustion duration different from the first predetermined combustion duration.

2. A method, as set forth in claim 1, wherein delivering fuel substantially uniformly into the combustion chamber includes the step of delivering a substantially homogeneous distribution of fuel into the combustion chamber.

3. A method, as set forth in claim 1, wherein delivering fuel substantially uniformly into the combustion chamber includes the step of delivering fuel into the combustion chamber such that fuel does not impinge on the cylinder wall.

4. A method, as set forth in claim 1, wherein delivering fuel substantially uniformly into the combustion chamber includes the step of injecting fuel in at least one pattern indicative of a desired angle of dispersion.

5. A method, as set forth in claim 4, wherein injecting fuel in at least one pattern includes the step of injecting fuel in at least one pattern with respect to a geometry of the piston.

6. A method, as set forth in claim 4, wherein injecting fuel in at least one pattern includes the step of injecting a first portion of fuel at a first angle of dispersion and injecting a second portion of fuel at a second angle of dispersion.

7. A method, as set forth in claim 4, wherein injecting fuel in at least one pattern includes the step of injecting fuel through a nozzle of an injector having a plurality of holes arranged to inject fuel in at least one pattern.

**8.** A method, as set forth in claim 4, wherein injecting fuel in at least one pattern includes the step of injecting fuel in a plurality of predetermined patterns.

**9.** A method, as set forth in claim 8, wherein injecting fuel in a plurality of predetermined patterns includes the step of injecting fuel at a plurality of predetermined angles of dispersion.

**10.** A method, as set forth in claim 7, wherein injecting fuel through a nozzle of an injector includes the step of injecting fuel through a plurality of micro-sized holes arranged on the nozzle such that fuel is injected in a plurality of predetermined patterns.

**11.** A method, as set forth in claim 1, wherein delivering fuel substantially uniformly into the combustion chamber includes the step of delivering fuel into the combustion chamber in the range of about 50 degrees before top dead center to about 180 degrees before top dead center.

**12.** A method, as set forth in claim 11, wherein delivering fuel substantially uniformly into the combustion chamber includes the step of delivering fuel into the combustion chamber in the range of about 60 degrees before top dead center to about 70 degrees before top dead center.

**13.** A method, as set forth in claim 1, wherein delivering fuel substantially uniformly into the combustion chamber includes the step of delivering fuel into the combustion chamber in the range of about 30 degrees before top dead center to about 90 degrees before top dead center.

**14.** A method, as set forth in claim 13, wherein delivering fuel substantially uniformly into the combustion chamber includes the step of delivering fuel into the combustion chamber in the range of about 40 degrees before top dead center.

**15.** A method, as set forth in claim 1, wherein delivering an oxidant includes the step of delivering a quantity of fresh air into the combustion chamber.

**16.** A method, as set forth in claim 1, wherein delivering an oxidant includes the step of delivering a quantity of oxygen into the combustion chamber.

**17.** A method, as set forth in claim 16, wherein delivering a quantity of oxygen includes the steps of:

providing a quantity of fresh air;

separating a quantity of oxygen from the fresh air; and

delivering the oxygen into the combustion chamber.

**18.** A method, as set forth in claim 1, wherein delivering a diluent into the combustion chamber includes the step of delivering a diluent comprised of at least one of air, nitrogen, and recirculated exhaust gas.

**19.** A method, as set forth in claim 1, wherein delivering a diluent into the combustion chamber includes the step of delivering a diluent having at least a portion of recirculated exhaust gas.

**20.** A method, as set forth in claim 19, wherein delivering a diluent having at least a portion of recirculated exhaust gas includes the step of delivering a diluent which includes recirculated exhaust gas from about 40 to about 60 percent of a total quantity of exhaust gas.

**21.** A method, as set forth in claim 1, wherein delivering a diluent into the combustion chamber includes the step of delivering a diluent having at least a portion of nitrogen.

**22.** A method, as set forth in claim 21, wherein delivering a diluent having at least a portion of nitrogen includes the steps of:

providing a quantity of fresh air;

separating a quantity of nitrogen from the fresh air; and

delivering the nitrogen into the combustion chamber.

**23.** A method, as set forth in claim 1, wherein delivering a diluent sufficient to change the first predetermined combustion duration to a second predetermined combustion duration includes the step of delivering a diluent sufficient to change the first predetermined combustion duration to a second predetermined combustion duration having a value greater than the first predetermined combustion duration.

**24.** A method, as set forth in claim 1, wherein delivering a diluent into the combustion chamber includes the step of delivering a diluent into the combustion chamber sufficient to change a first predetermined pressure rise rate to a second predetermined pressure rise rate different from the first predetermined pressure rise rate.

**25.** A method, as set forth in claim 24, wherein delivering a diluent into the combustion chamber sufficient to change a first predetermined pressure rise rate to a second predetermined pressure rise rate includes the step of delivering a diluent into the combustion chamber sufficient to change a first predetermined pressure rise rate to a second predetermined pressure rise rate having a value less than the first predetermined pressure rise rate.

**26.** A method for operating a compression ignition engine having a cylinder wall, a piston, and a head defining a combustion chamber, comprising the steps of:

delivering fuel substantially uniformly into the combustion chamber, the fuel being dispersed throughout the combustion chamber and spaced from the cylinder wall;

delivering an oxidant into the combustion chamber sufficient to support combustion at a first predetermined pressure rise rate; and

delivering a diluent into the combustion chamber sufficient to change the first predetermined pressure rise rate to a second predetermined pressure rise rate different from the first predetermined pressure rise rate.

**27.** A method, as set forth in claim 26, wherein delivering a diluent into the combustion chamber includes the step of delivering a diluent into the combustion chamber sufficient to change a first predetermined combustion duration to a second predetermined combustion duration different from the first predetermined combustion duration.

**28.** A method, as set forth in claim 26, wherein the second predetermined pressure rise rate is less than the first predetermined pressure rise rate.

**29.** A method, as set forth in claim 27, wherein the second predetermined combustion duration is greater than the first predetermined combustion duration.

**30.** A method for delivering fuel into a combustion chamber of a compression ignition engine, the combustion chamber being defined by a cylinder wall, a piston, and a head, comprising the steps of:

delivering the fuel to a nozzle of an injector, the nozzle having a plurality of holes distributed in a desired pattern; and

injecting the fuel through the nozzle holes into the combustion chamber in a predetermined spray pattern so that the fuel is dispersed throughout the combustion chamber and spaced from the cylinder wall.



**31.** An apparatus for operating a compression ignition engine having a cylinder wall, a piston, and a head defining a combustion chamber, comprising:

a fuel injector having a nozzle positioned to inject fuel in a dispersed pattern throughout the combustion chamber and spaced from the cylinder wall; and

an air supply system for delivering at least one of an oxidant and a diluent into the combustion chamber.

**32.** An apparatus, as set forth in claim 31, wherein the fuel injector nozzle includes a plurality of holes configured to inject a substantially homogeneous distribution of fuel into the combustion chamber such that fuel does not impinge on the cylinder wall.

**33.** An apparatus, as set forth in claim 31, wherein the air supply system is configured to deliver an oxidant into the combustion chamber sufficient to support combustion at a first predetermined combustion duration and at a first predetermined pressure rise rate.

**34.** An apparatus, as set forth in claim 33, wherein the air supply system is configured to deliver a diluent into the combustion chamber sufficient to change the first predetermined combustion duration to a second increased predeter-

mined combustion duration, and to change the first predetermined pressure rise rate to a second decreased pressure rise rate.

**35.** An apparatus, as set forth in claim 31, wherein the air supply system includes:

an air source; and

a turbocharger system for receiving air from the air source and providing at least one of the oxidant and the diluent at boost pressures sufficient for substantially homogeneous combustion.

**36.** An apparatus, as set forth in claim 35, wherein a sufficient boost pressure is at least about 4 to 1.

**37.** An apparatus, as set forth in claim 36, wherein a sufficient boost pressure is at least about 4.5 to 1.

**38.** An apparatus, as set forth in claim 35, wherein the air supply system includes an intake air separation system for receiving a supply of air and responsively providing a supply of oxygen and nitrogen as a respective oxidant and diluent.

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