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Poola, et al. **January 16, 2001**

METHOD TO REDUCE DIESEL ENGINE EXHAUST EMISSIONS

Abstract

A combustion air management and emission control system injects supplemental air directly into combustion chambers of a diesel engine in order to reduce total particulates in exhaust gases being emitted from the engine. A portion of intake air flowing toward an intake manifold of the engine is diverted to a compressor so that controlled quantities of pressurized supplemental air can be injected directly into each of the combustion chambers while the piston within the combustion chamber is in its expansion and/or exhaust strokes. At least a portion of the diverted intake air can be directed through a selectively permeable membrane device so that oxygen-enriched air and nitrogen-enriched air are produced. At least a portion of the oxygen-enriched air can be supplied to the compressor so that the supplemental air being injected into the combustion chambers will contain a desired, elevated amount of oxygen. In order to simultaneously reduce nitrogen oxides (NOx) from the exhaust gases of the engine, the nitrogen-enriched air can be mixed with intake air being supplied to the intake of the engine or can be introduced into a plasma device to generate monatomic nitrogen that is injected in the exhaust gases to react with NOx in the exhaust gases. Additionally, an exhaust gas recirculation (EGR) system can be provided to recirculate a portion of the exhaust gases into the intake of the engine, fuel injection timing can be retarded to delay the beginning of combustion in the combustion chambers or rate shaping of the fuel delivery can be used.

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Description

Background of the Invention

1. Field of the Invention

This invention relates to a method and apparatus for reducing undesirable emissions in the exhaust of a compression ignition (diesel) engine, and more particularly, to a new and improved method and apparatus for reducing the amount of total particulates in the exhaust of the diesel engine by injecting controlled quantities of supplemental air (that may include oxygen-enriched air) directly into combustion chambers of the engine during the portion of the combustion cycle of the engine when the piston in each such combustion chamber is in its expansion and/or exhaust strokes.

2. Background of the Invention

Compression ignition (diesel) engines typically have high exhaust emissions, such as particulates (for example, carbon soot and volatile organic compounds), visible smoke, and oxides of nitrogen (NOx). The United States Environmental Protection Agency (EPA) emissions standards for future automobiles, trucks and locomotive diesel engines require simultaneous reduction of NOx and total particulate emissions to very low levels. This tends to be difficult to achieve because of the inherent tradeoffs between lowering both total particulates and NOx emissions from a diesel engine while maintaining the engine's overall fuel economy and the engine's cost efficiency. Consequently, the reduction of total particulate emissions while still meeting NOx emission standards has been an ongoing problem. In order to overcome this ongoing problem, various different methods have been tried to reduce particulate emissions. These methods include high-pressure fuel injection, multiple-staged injection, oxygenated diesel fuels, oxidation catalysts, and particulate traps. While it is possible in a diesel engine to reduce total particulate emissions and to improve power density performance by using oxygen-enriched intake air, such oxygen-enriched intake air tends to also increase the amount of NOx in the exhaust being emitted from the diesel engine.

In the case of both diesel and spark ignition engines, exhaust gas recirculation (EGR) systems have been used as one method of decreasing NOx emissions. When the gases from the EGR system are about 50% of the intake air, oxygen concentration is decreased from about 21% to about 14%. The decrease of NOx by the use of EGR systems tends to vary depending on the rate, temperature and water content of the EGR gases, injection timing, and air-fuel ratio of the intake to the engine. However, there are limits as to the amount of exhaust gases that can be reintroduced into the engine before power output and fuel economy are adversely affected. Such reintroduction of exhaust gases can also cause an increase in particulates in exhaust gases being emitted from the engine because the recirculated gases include soot particles.

Other attempts have been made to control the amount of NOx being emitted from the exhaust of an engine. One such method involves the retarding of the fuel injection timing, but such retarding of the injection of fuel tends to increase the amount of particulate emissions and also tends to increase fuel consumption. Another method that has been developed to control the amount of NOx generated by the engine involves controlling the amount of oxygen and nitrogen included in the intake air of the engine (see, for example, U.S. Pat. No. 5,649,517 that is assigned to the same assignee of record as the present application). On the other hand, attempts have been made to lower the level of NOx in such exhaust gases or emissions of an engine by injecting into the exhaust gases of the engine monatomic nitrogen induced by a pulse arc (see, for example, U.S. Pat. Nos. 5,526,641 and 5,640,845 that are assigned to the same assignee of record as the present application). While these systems tend to decrease the level of NOx in engine exhaust gases, they do not tend to decrease the total particulates that are present in those exhaust gases.

Accordingly, it is an object of the present invention to provide a new and improved method and apparatus for reducing total particulates in the exhaust of a diesel engine while minimizing the amount of NOx emissions in the exhaust.

It is another object of the present invention to provide a new and improved method and apparatus for reducing total particulates in the exhaust of a diesel engine by introducing controlled quantities of supplemental air (that may include oxygen-enriched air) directly into combustion chambers of the engine while the piston in each such chamber is in its expansion and/or exhaust strokes during the time that the combustion is in a diffusion and/or tail end phases of the chamber's combustion cycle.

It is still another object of the present invention to provide a new and improved method and apparatus for reducing the amount of total particulates in the exhaust of a diesel engine by introducing controlled quantities of supplemental air, that includes, at least in part, oxygen-enriched air produced by a selectively permeable membrane, directly into combustion chambers of the engine while the piston in each such chamber is in its expansion and/or exhaust strokes during the time that the combustion is in a diffusion and/or tail end phases of the chamber's combustion cycle.

It is yet another object of the present invention to provide a new and improved method and apparatus for reducing simultaneously the amount of total particulates and NOx in the exhaust of a diesel engine by utilizing both oxygen-enriched air and nitrogen-enriched air produced by a selectively permeable membrane. The oxygen-enriched air may be combined with ambient air and is injected in controlled quantities as supplemental air directly into combustion chambers of the engine while the piston in each such chamber is in its expansion and/or exhaust strokes during the time that the combustion is in a diffusion and/or tail end phases of the chamber's combustion cycle whereas the nitrogen-enriched air either is used to form monatomic nitrogen that is injected in the exhaust being emitted by the engine or is used to mix with intake air being supplied to the intake of the engine to lower the oxygen purity of the intake air.

It is still a further object of the present invention to provide a new and improved method and apparatus for reducing total particulates in the exhaust of a diesel engine by introducing controlled quantities of supplemental air (which may include oxygen-enriched air) directly into combustion chambers of the engine while the piston in each such chamber is in its expansion and/or exhaust strokes during the time that the combustion is in a diffusion and/or tail end phases of the chamber's combustion cycle and to simultaneously minimize NOx in the exhaust of the engine by either retarding the beginning of fuel injection or multi-stage injection of the diesel fuel or by recirculating a portion of the exhaust gases from the engine back into the intake of the engine [commonly known as exhaust gas recirculation (EGR)].

Summary of the Invention

In accordance with these and many other objects of the present invention, a combustion air management control system for a diesel engine embodying the present invention includes an injector associated with each of the cylinders or combustion chambers within the diesel engine so that supplemental air, which has been compressed to an elevated pressure, can be injected directly into each combustion chamber during an appropriate phases of the chamber's combustion cycle. Preferably, the pressurized supplemental air is introduced into each of the combustion chambers while the piston within the combustion chamber is in its expansion and/or exhaust strokes during the diffusion and/or tail end phases of the chamber's combustion cycle.

In one embodiment of the combustion air management control system embodying the present invention the supplemental air being injected into the combustion chambers includes at least in part oxygen-enriched air. A selectively permeable air separating membrane device is used for producing oxygen-enriched air and nitrogen-enriched air from air flowing towards an air intake manifold of the diesel engine. Depending on the engine design, the air being supplied to the intake manifold of the diesel engine from an air filter can be compressed by a compressor portion of a turbocharger and cooled by an inter-cooler. A portion of the air flowing toward the intake manifold is diverted through the permeable membrane device wherein a portion of the nitrogen in that air is separated from the air so that oxygen-enriched air (permeate) and nitrogen-enriched air (retentate) are produced at outlets of the permeable membrane device.

When the air is diverted directly from the air filter, the air flows through the permeable membrane device due to a pressure differential that is established across the permeable membrane device either by a compressor at an input of the permeable membrane device or a blower or pump at the input of the permeable membrane device and a vacuum pump at an output of the permeable membrane device. The oxygen-enriched air being produced at one of the outlets of the permeable membrane device may contain approximately 23-35% oxygen by volume (this is compared to ambient air which contains about 21% oxygen by volume). This oxygen-enriched air, either by itself or after being mixed with ambient air to control or vary the oxygen content of the air, can be considered supplemental air for the diesel engine. This supplemental air is pressurized to an elevated pressure [for example, to 500-2,000 psi (pounds per square inch)] by a compressor or pump. Controlled quantities of this pressurized supplemental, oxygen-enriched air is introduced directly into each of the combustion chambers of the diesel engine during an appropriate phases of the engine's combustion cycle. Preferably, the supplemental oxygen-enriched air is introduced into the combustion chamber while the piston within the combustion chamber is in its expansion and/or exhaust strokes during the diffusion and/or tail end phases of the chamber's combustion cycle.

The introduction of the supplemental oxygen-enriched air directly into the combustion chamber can be achieved using an injector (a nozzle with one or more orifices) on each of the cylinder heads at a geometrically feasible location to provide the appropriate mixing of the supplemental oxygen-enriched air with the igniting fuel. The timing of both the start of and duration of injecting the supplemental oxygen-enriched air, the flow rate of the air and fuel, and the purity of oxygen in the supplemental oxygen-enriched air can be optimized for a given engine and the operating conditions of that engine. By introducing the supplemental oxygen-enriched air directly into the cylinders of the diesel engine during the diffusion and/or tail end phases of the diesel combustion cycle while the piston within each cylinder of the diesel engine is in its expansion and/or exhaust strokes, turbulent mixing of the reactants in the cylinder occurs due to the jet momentum of the air being injected and also the oxygen concentration is increased in the gases surrounding burning fuel droplets. These changes in the mixing and chemical kinetics help to enhance soot and hydrocarbon oxidation reactions without adversely increasing NOx formation. This results in higher oxidation reaction rates being achieved such that smoke, unburned hydrocarbons, and particulate emissions can be reduced significantly. In addition, the retarding of the fuel injection timing (i.e., delaying the time in the engine cycle when fuel is injected into a cylinder--for example, the injection timing could be retarded between 4 and 10 degrees of crankshaft angle) tends to delay the beginning of combustion within the cylinder such that peak combustion temperatures can be lowered so that less NOx is formed and emitted from the engine. As a result, the total particulates and NOx in the diesel engine's exhaust can be reduced simultaneously.

The nitrogen-enriched air being produced at the another outlet of the permeable membrane device can be expelled to atmosphere. On the other hand, the nitrogen-enriched air can be used to further reduce NOx that tends to be formed in the diesel engine and that might be present in the exhaust of the diesel engine. For example, the nitrogen-enriched air can be mixed with air being supplied to the intake manifold of the engine (see, for example, the disclosure in U.S. Pat. No. 5,649,517) or alternatively, it can be introduced into a plasma device to generate monatomic nitrogen that is injected in the exhaust to react with NOx in the exhaust (see, for example, the disclosures in U.S. Pat. Nos. 5,526,641 and 5,640,845). In addition to the use of such nitrogen-enriched air in this manner to reduce NOx in the engine's exhaust or instead of using such nitrogen-enriched air, a portion of the exhaust gases can be recirculated back into the intake manifold of the diesel engine (this recirculation process is commonly known as exhaust gas recirculation or EGR). Such recirculated exhaust gases tend to lower the combustion temperatures within the combustion cylinders, which thereby reduces the formation of NOx in the combustion chamber. The formation of NOx also can be further reduced by electronically controlling the timing and delivery of the injection of diesel fuel into the engine's cylinders. In this regard, the fuel injection can be retarded to delay the beginning of combustion within each cylinder.

In an alternative embodiment of the present invention, the air flowing from the intake air filter is diverted to the permeable membrane device after the air has been compressed by the compressor portion of the turbocharger so as to be at slightly elevated pressure (for example, to 30-35 psi). The elevation of the pressure of this intake air is sufficient to establish a differential pressure across the permeable membrane device so that the diverted air will flow through the permeable membrane device. The oxygen-enriched air that is produced at one of the outlets of the permeable membrane device is used as the supplemental air that is further pressurized (for example, to 500-2,000 psi) by a compressor and injected directly into the combustion cylinders during the expansion and/or exhaust strokes of the piston within each of those cylinders. In order to reduce the NOx in the exhaust gases being emitted from the engine, the nitrogen-enriched air produced at another outlet of the permeable membrane device can be mixed with air being supplied to the intake manifold of the engine or can be introduced into a plasma device to generate monatomic nitrogen that is injected into the engine's exhaust to react with NOx in the exhaust gases.

In still another alternative embodiment of the present invention, no permeable membrane device is utilized. Instead, the air flowing from the intake air filter is compressed by the compressor portion of the turbocharger so as to be at slightly elevated pressure (for example, to 30-35 psi). This somewhat pressurized air is used as supplemental air that is further pressurized by a compressor (for example, to 500-2,000 psi) and injected directly into the combustion cylinders during the expansion and/or exhaust strokes of the piston within each of those cylinders. In order to minimize NOx in the exhaust gases being emitted from the engine, fuel injection timing can be retarded and/or an EGR system can be employed whereby exhaust gases from the engine can be recirculated back into the air flowing into the intake manifold.

Brief Description of the Drawings

These and many other objects and advantages of the present invention will become readily apparent from consideration of the following detailed description of the embodiments of the invention shown in the accompanying drawings wherein:

FIG. 1 is a diagrammatic illustration of a diesel engine with a combustion air management and emission control system which embodies the present invention, this particular embodiment employing a permeable membrane device to produce supplemental oxygen-enriched air that can be combined with intake air and injected under pressure directly into the combustion chambers of the diesel engine;

FIG. 2 is a diagrammatic illustration of a diesel engine with an alternate embodiment of a combustion air management and emission control system which embodies the present invention, this particular embodiment employing a permeable membrane device to produce supplemental oxygen-enriched air that is injected under pressure directly into the combustion chambers of the diesel engine; and

FIG. 3 is a diagrammatic illustration of a diesel engine with another alternate embodiment of a combustion air management and emission control system which embodies the present invention, this particular embodiment injects supplemental intake air under pressure directly into the combustion chambers of the diesel engine.

Detailed Description of the Preferred Embodiment

Referring now more specifically to FIG. 1, therein is disclosed a diagrammatic representation of a diesel engine (10) having an intake manifold (12) through which air is supplied to the engine (10) to be combined with combustible fuel in cylinders or combustion chambers (14A-4D) of the engine (10). When the intake air and the combustible fuel are combusted in the engine (10), exhaust gases are expelled from an exhaust manifold (16) in the engine (10). The exhaust gases flowing from the exhaust manifold (16) can contain a number of different pollutants including total particulates (carbon soot and volatile organics) and visible smoke and oxides of nitrogen (NOx). In order to limit the amount of these undesirable emissions that are present in the exhaust gases being emitted from the engine (10) through the exhaust manifold (16), the engine (10) is provided with a combustion air management or emission control system that is generally designated by the reference numeral (18) and that embodies the present invention.

The combustion air management control system (18) includes an air separation permeable membrane device (20) that separates nitrogen from air flowing through the air separation membrane device (20) such that oxygen-enriched air and nitrogen-enriched air are produced. During the operation of the engine (10), ambient or atmospheric air flows through an air filter (22) towards the intake manifold (12). When a blower (24) and a vacuum pump (26) are activated, a portion of the air flowing from the air filter (22) is diverted and flows to the air separation membrane (20). The diverted air flows through the air separation membrane (20) due to the pressure differential established across the membrane device (20) by the blower (24) and the vacuum pump (26) (a compressor can be used in place of the blower (24) in which case the vacuum pump (26) will not be necessary). The air separation membrane (20) separates nitrogen from the air flowing through the air separation membrane (20) such that oxygen-enriched air (permeate) flows to a mixing valve (28).

The oxygen-enriched air flowing to the mixing valve (28) can be mixed with ambient air from the air filter (22) so that supplemental air consisting of oxygen-enriched air from the air separation membrane (20) and if desired, ambient air from the air filter (22), flow to a high-pressure, supplemental air compressor or pump (30). The compressor (30) compresses the supplemental air to an elevated pressure which supplemental pressurized air is supplied to a high pressure air rail or air accumulator (32). The supplemental oxygen-enriched air then can be injected directly into the cylinders (14A-14D) of the diesel engine (10) through electronically controlled air injectors (34A-34D) associated respectively with each of the cylinders (14A-14D).

The timing of both the start of and duration of injecting the supplemental oxygen-enriched air, the flow rate of the air and fuel, and the purity of oxygen in the supplemental oxygen-enriched air can be optimized for the particular diesel engine (10) and the operating conditions of that engine (10). By introducing the supplemental oxygen-enriched air directly into the cylinders (14A-14D) during the diffusion and/or tail end phases of the diesel combustion cycle while pistons (36A-36D) within each of the cylinders (14A-14D) respectively are in their expansion and/or exhaust strokes, turbulent mixing of the reactants in the cylinders (14A-14D) occurs due to the jet momentum of the air being injected and also the oxygen concentration is increased in the gases surrounding burning fuel droplets. These changes in the mixing and chemical kinetics help to enhance soot and hydrocarbon oxidation reactions without adversely increasing NOx formation. This results in higher oxidation reaction rates being achieved such that smoke, unburned hydrocarbons, and particulate emissions can be reduced significantly. In addition, the retarding of the fuel injection timing tends to delay the beginning of combustion within each of the cylinders (14A-14D) such that peak combustion temperatures within the cylinders (14A-14D) can be lowered resulting in less NOx being formed and emitted from the exhaust manifold (16) of the engine (10). As a result, the total particulates and NOx in the engine's exhaust can be reduced simultaneously.

In order to further reduce the NOx in the exhaust gases being emitted from the exhaust manifold (16), the nitrogen-enriched air being produced by the permeable membrane (20) can be used. The nitrogen-enriched air may be supplied via a control valve (38) so as to be mixed with ambient air flowing from the air filter (22) to the intake manifold (12) of the engine (10) or so as to be introduced into a plasma device or monatomic nitrogen generator (40) to generate monatomic nitrogen that is injected into the exhaust of the engine (10) to react with NOx in the exhaust.

In addition to the use of such nitrogen-enriched air in this manner to reduce NOx in the engine's exhaust or instead of so using such nitrogen-enriched intake air, a portion of the exhaust gases can be recirculated back into the intake air flowing from the air filter (22) via a EGR control valve (42) (this recirculation process is commonly known as exhaust gas recirculation or EGR). Such recirculated exhaust gases tend to lower the combustion temperatures within the combustion cylinders (14A-14D) which thereby reduces the formation of NOx in the combustion chambers (14A-14D). The formation of NOx also can be further reduced by electronically controlling the timing and delivery of the injection of diesel fuel into the engine's cylinders (14A-14D). In this regard, the fuel injection can be retarded to delay the beginning of combustion within each of the cylinders (14A-14D) or rate shaping of the fuel delivery can be used.

As previously indicated, ambient air for use in the engine (10) flows through the air filter (22 as indicated by arrows 22A) to an air duct (44). As long as the blower (24) and the vacuum pump (26) are not activated, all of the air flowing in the air duct (44) and an air duct (46 as represented by an arrow 46A) will flow into a compressor portion (48) of a turbocharger (50). The compressor (48) of the turbocharger (50) compresses (i.e., elevates in pressure, for example, to a pressure of 30-35 psi) the air flowing into the compressor (48) from the duct (46). A turbine portion (52) of the turbocharger (50) is driven by the energy from the exhaust gases being emitted from the exhaust manifold (16) through an exhaust duct (54 as indicated by an arrow 54A). The exhaust gases within the exhaust duct (54) are at elevated temperatures so the energy from those gases can be used to drive the turbine portion (52) of the turbocharger (50) such that a shaft (56) is rotated thereby driving the compressor portion (48). The pressurized air from the compressor (48) flows out from the compressor portion (48) through an air duct (58 as indicated by arrow 58A) to an intercooler (60). The intercooler (60) is designed to act as a heat exchanger to cool the intake air flowing into the intake manifold (12). The cooling of the intake air tends to decrease the amount of NOx formed in the engine (10). Once the intake air is cooled by the intercooler (60), it flows out of the intercooler (60) via an air duct (62 as indicated by arrow 62A) and is supplied to the intake manifold (12) so that it can be combined with combustible fuel in the cylinders (14A-14D).

When the blower (24) and the vacuum pump (26) are activated, a portion of ambient air flowing out through the air filter (22) is diverted from the air duct (44) and flows along an air duct (64 as indicated by arrow 64A) and an air duct (66 as indicated by arrow 66A) to the blower (24). The flow of the diverted air along the air ducts (64 and 66) is caused by a pressure differential that is established across the air separation membrane (20) between an input (68) of the membrane device (20) and an outlet (70) (permeate) of the membrane device (20) [i.e., the pressure is higher at the input (68) as compared to the outlet (70)]. This differential in pressure across the membrane device (20) will result in air flowing from the blower (24) through an air duct (72 as indicated by arrow 72A) into the input (68) and through the membrane device (20) so that supplemental oxygen-enriched air will permeate from the higher pressure, upstream side of the membrane device (20) at the input (68) to the lower pressure, downstream side of the membrane device (20) at the outlet (70) and thereby to an outlet duct (74). On the other hand, nitrogen-enriched air will likewise flow out of another outlet (76) (retentate) of the membrane device (20) into an outlet duct (78).

The membrane device (20) is adapted to separate oxygen and nitrogen present in the air being supplied through the input (68) so as to produce supplemental oxygen-enriched air (permeate) at the outlet (70) and nitrogen-enriched air (retentate) at the other outlet (76). The membrane device (20) can be of the type having a selectively permeable membrane that can separate or enrich gaseous mixtures. An example of such a membrane is disclosed in U.S. Pat. Nos. 5,051,113 and 5,051,114, both having been issued on Sep. 24, 1991. As indicated in those patents, such a membrane can be used to produce oxygen-enriched air by separating oxygen and nitrogen present in the air. An example of one possible configuration for such a membrane device (20) is illustrated in FIGS. 6 and 7A-7C of U.S. Pat. No. 5,636,619 and FIGS. 3 and 3A-3C of U.S. Pat. No. 5,649,517, both of which patents are assigned to the assignee of the present application. Alternatively, any other suitable source of oxygen-enriched air can be used in place of or in addition to the membrane device (20).

The particular percentage of oxygen contained within the supplemental oxygen-enriched air flowing out from the outlet (70) of the membrane device (20) and the particular percentage of nitrogen contained within the nitrogen-enriched air flowing out from the outlet (76) of the membrane device (20) can be adjusted by providing the proper membrane device (20). In this regard, the membrane properties, the coating thickness, the membrane surface area and the pressure differential across the membrane device (20) will in part determine the amount of nitrogen separated from the air flowing into the input (68) and thereby the percentage of oxygen within the air flowing out from the outlet (70). In general, the supplemental oxygen-enriched air flowing from the outlet (70) of a membrane device, like the membrane device (20), may contain about 23-35% oxygen concentration by volume (this is compared to ambient air, which contains about 21% oxygen by volume).

Once the supplemental oxygen-enriched air is produced by the membrane device (20), it will flow from the outlet (70) through the outlet duct (74 as indicated by arrow 74A) to the vacuum pump (26) and then through an air duct (80 as indicated by arrow 80A) to the mixing valve (28). The mixing valve (28) controls the amount of supplemental oxygen-enriched air flowing in the air duct (80) and the amount of ambient air that is flowing in an air duct 82 (as indicated by an arrow 82A) that is supplied as supplemental air through an air duct (84 as indicated by arrow 84A) to the compressor (30) and/or the amount of such air that is expelled to atmosphere through an air duct (86 as indicated by an arrow 86A).

The compressor or pump (30) will further pressurize the supplemental air flowing out from the mixing valve (28) so that it will be at a sufficiently elevated pressure that it can be injected directly into the cylinders (14A-14D) of the diesel engine (10). For example, the compressor (30) (which can be of a piston, diaphragm or rotary type and alternatively can be a pump) can be designed to pressurize the supplemental air flowing from the compressor (30) to a pressure of 500-2,000 psi. In general, the pressure should be sufficiently higher than the cylinder combustion pressure so that the supplemental air can be injected directly into the cylinders (14A-14D) during the appropriate time in the combustion cycle of the cylinders (14A-14D). This pressurized supplemental air containing oxygen-enriched air flows through an air duct (88 as indicated by the arrow 88A) to the high-pressure air rail or air accumulator (32).

The air rail (32) is in fluid communication with the air injectors (34A-34D) via air duct (90A-90D) respectively, so that the pressurized supplemental air from the air rail (32) will flow in the air duct (90A-90D) (as indicated by arrows 90AA, 90BA, 90CA and 90DA) to the air injectors (34A-34D). The air injectors (34A-34D) are in turn respectively associated with each of the cylinders (14A-14D). The air injectors (34A-34D) are adapted to inject controlled quantities of supplemental pressurized air from the air rail (32) directly into the cylinders (14A-14D) at the appropriate point or time in the combustion cycle of the each of those cylinders (14A-14D). The injectors (14A-14D) may have nozzles with one or more orifices and are located at the top of the cylinders (14A-14D) at a geometrically feasible location to inject the supplemental air that is to be mixed with fuel within the cylinders (14A-14D). The injectors (34A-34D) can be of the type for injecting both fuel and supplemental air in the same injectors into the cylinders (14A-14D), in which case the injectors (34A-34D) would each have separate inputs for the fuel and the supplemental air. One type of injector that possibly could be used for the injectors (14A-14D) is an injector similar to the one disclosed in an article entitled "Natural gas fueling of diesel engines" appearing in Automotive Engineering, November 1996, pages 87-90. While the injector disclosed in that article is designed to inject both diesel fuel and compressed natural gas, it also could be used to supply the diesel fuel and the pressurized supplemental air to the cylinders (14A-14D) in the engine (10).

The combustion cycle of a typical diesel engine, such as the depicted engine (10), can be described as having three combustion phases (i.e., pre-mix, diffusion and tail end). The pre-mix combustion phases is the portion of the combustion cycle during which diesel fuel and intake air are mixed within the cylinder (14A) as the piston (36A) is moving in its compression stroke toward its top dead center position. After certain physical and chemical delays, ignition of the fuel begins to occur. The actual beginning of the ignition of the fuel and air mixture can be controlled to some extent by when the fuel is injected into the cylinder (14A). Retarding the injection timing [i.e., delaying the time when the fuel is being injected into the cylinder (14A) with respect to the position of the piston (36A)] tends to delay the ignition of the fuel so that lower amounts of NOx are formed because the temperature generated within the cylinder (14A) during the pre-mix combustion phase tends to be lowered. For example, the injection timing could be retarded between 4 and 10 degrees of crankshaft angle. On the other hand, the fuel does not tend to be burned completely when the injection timing is retarded so that additional amounts of particulates such as soot can be formed.

Once the pre-mix combustion phase is completed, what can be termed the diffusion combustion phase of the combustion cycle occurs. During this phase, the piston (36A) reverses its direction of travel such that it begins its expansion stroke. As the piston (36A) is traveling in its expansion stroke, the electronically controlled air injector (34A) injects the highly pressurized supplemental oxygen-enriched air from the air rail (32) in small, controlled quantities into the cylinder (14A). At this point in the combustion cycle of the cylinder (14A), the temperature within the cylinder (14A) is still sufficiently high that the introduction of the small quantities of supplemental oxygen-enriched air will promote the further oxidation of any fuel or particulates still in the combustion chamber 14A, but the temperature is low enough that the formation of NOx is not significantly promoted.

Once this further combustion is accomplished, what can be termed the tail end combustion phase of the engine's combustion cycle will be occur. During this time, the piston (36A) will complete its expansion stroke and the gases within the cylinder (14A) will be exhausted through the exhaust manifold (16) to the exhaust duct (54). As a result of the additional oxidation that occurs due to the injection of supplemental oxygen-enriched air into the cylinder (14A) during the expansion stroke of the piston (36A), visible smoke, total particulates, hydrocarbons, and carbon monoxide being emitted from the exhaust manifold (16) into the exhaust duct (54) will be significantly reduced.

While the amount of total particulates in the exhaust being emitted from the exhaust manifold (16) of the engine (10) are reduced, the amount of NOx in that exhaust flowing in the exhaust duct (54) may still be significant. In order to minimize the NOx present in that exhaust, the nitrogen-enriched air flowing from the outlet (76) of the membrane device (20) can be utilized by introducing the nitrogen-enriched air into the intake manifold (12) via the control valve (38) or by supplying the nitrogen-enriched air to the monatomic nitrogen generator (40) via the control valve (38) so that atomic nitrogen can be injected into the exhaust gases flowing from the exhaust duct (54).

As previously indicated, the nitrogen-enriched air (retentate) that is flowing from the outlet (76) flows through the outlet duct (78 as indicated by arrow 78A) to the flow control valve (38). If the nitrogen-enriched air is not to be used in controlling pollutants being generated by the engine (10), the control valve (38) can be actuated to release the nitrogen-enriched air to atmosphere via an air duct (92 as indicated by arrow 92A). On the other hand, the nitrogen-enriched air flowing in the outlet duct (78) from the outlet (76) can be directed by the control valve (38) either into the air duct (46) where it becomes mixed with the intake air from the air filter (22) or to the monatomic nitrogen generator (40).

In the case where the nitrogen-enriched air or at least a part of the nitrogen-enriched air flowing in the outlet duct (78) to the control valve (38) is to be directed to the intake manifold (12), the control valve (38) is actuated so that at least a portion of that nitrogen-enriched air flows through an air duct (94 as indicated by arrow 94A) into the air duct (46). The nitrogen-enriched air becomes combined with or mixed with the intake air flowing in the air duct from the air filter (22) and becomes part of the intake air being supplied to the intake manifold (12). As is in part disclosed in U.S. Pat. No. 5,649,517, the addition of nitrogen-enriched air into the air being introduced into the engine (10) through the intake manifold (12) tends to act as a diluent to reduce the combustion temperatures within the cylinders (14A-14D) of the engine (10) so as to lower the amount of NOx that is formed in the engine (10).

In the case where the nitrogen-enriched air being produced at the outlet (76) of the membrane device (20) and flowing in the outlet duct (78) is to be supplied to the monatomic nitrogen generator (40), the control valve (38) is actuated to divert at least a portion of that nitrogen-enriched air through an air duct (96 as indicated by arrow 96A) to the monatomic nitrogen generator (40).

The nitrogen-enriched air flowing in the air duct (96) is supplied to the monatomic nitrogen generator (40). As is disclosed in U.S. Pat. No. 5,526,641 and 5,640,845, the monatomic nitrogen generator (40) converts into atomic nitrogen the molecular nitrogen present in the nitrogen-enriched air flowing in the air duct (96). In order to accomplish this conversion, the monatomic nitrogen generator (40) includes one or more arc creating devices so that a corona or arc discharge is produced to create a plasma within the monatomic nitrogen generator (40). One type of such arc creating device is a spark plug type of a device (an example of such a device is disclosed in U.S. Pat. No. 5,640,845) and more than one spark plug (for example, four spark plugs) can be used to generate a sufficient arc that results in a plasma being produced such that the molecular nitrogen will be transformed into atomic nitrogen. Alternatively, a corona charge along the elongated axis of a cylindrical wire placed in the middle of a round tube can be used. The wire in the center of the tube is either positively or negatively charged while the tube is oppositely charged to create a corona charge.

The atomic nitrogen formed in the monatomic nitrogen generator (40) is supplied through an air duct 98 (as indicated by an arrow 98A) to an exhaust duct (100) through which flows (as indicated by an arrow 100A) the exhaust gas stream that is being expelled from the engine (10) and that flows through the exhaust duct (54) and the turbine portion (52) of the turbocharger (50). The injection of atomic nitrogen into a stream of gases containing NOx will result in the reduction of the NOx to nitrogen and oxygen. Consequently, the injection of the atomic nitrogen being supplied from the monatomic nitrogen generator (40) into the exhaust duct (100) will decrease the amount of NOx in the exhaust gases flowing in the exhaust duct (100) due to the reduction of such NOx to nitrogen and oxygen. As a result, the amount of NOx in the exhaust gases being expelled into the atmosphere from the exhaust duct (100) will tend to be at more acceptable levels.

As indicated above, the level of NOx in the exhaust gases flowing to atmosphere through the exhaust duct (100) can further be reduced by utilizing the EGR control valve (42). When the EGR control valve (42) is actuated, a portion of the exhaust gases flowing in the exhaust duct (100) will flow through ducts (102 and 104 as indicated by arrow 104) into the air duct (46) wherein the exhaust gases will become mixed with the intake air flowing from the air filter (22) to the intake manifold (12). The injection of such recirculated exhaust gases into the intake air tends to lower the combustion temperatures within the combustion cylinders (14A-14D) and the formation of NOx in the combustion chambers (14A-14D) tends to be retarded. The use of such recirculated exhaust gases to control the level of NOx in the exhaust gases flowing in the exhaust duct (100) can be used in addition to or instead of the injection into the exhaust duct (100) of monatomic nitrogen produced by the monatomic nitrogen generator (40) from the nitrogen-enriched air produced at the outlet (76) of the membrane device (20) or the injection of such nitrogen-enriched air into the air duct (46) so as to be combined with intake air flowing to the intake manifold (12). The formation of NOx also can be further reduced by electronically controlling the timing and delivery of the injection of diesel fuel into the engine's cylinders (14A-14D). In this regard, the fuel injection can be retarded to delay the beginning of combustion within each cylinder (14A-14D).

An alternate embodiment of the present invention is disclosed in FIG. 2 of the drawings. In that FIG. 2, therein is disclosed a diagrammatic representation of a diesel engine (210) having an intake manifold (212) through which air is supplied to the engine (210) to be combined with combustible fuel in cylinders or combustion chambers (214A-214D) of the engine (210). In order to limit the amount of undesirable emissions that are present in the exhaust gases being emitted from the engine (210) through an exhaust manifold (216), the engine (210) also is provided with a combustion air management or emission control system that is generally designated by the reference numeral (218) and that embodies the present invention. The engine (210) and the combustion air management and emission control system (218) include many of the same components included in the engine (10) and the combustion air management and emission control system (18). Consequently, the components of the engine (210) and the combustion air management and emission control system (218) that are specifically referred to herein are referenced by the same reference numerals as the corresponding components in the engine

(10) and the combustion air management and emission control system (18) except that the quantity 200 has been added to the reference numerals.

In the case of the combustion air management and emission control system (218), supplemental oxygen-enriched air and nitrogen-enriched air are produced by a permeable membrane device (220) in essentially the same manner as such supplemental air is produced by the permeable membrane device (20). In the case of the combustion air management and emission control system (18), a pressure differential across the membrane device (20) was established by the blower (24) and the vacuum pump (26). In the case of the combustion air management and emission control system (218), such a blower and vacuum pump are not necessary because the intake air is diverted to an input (268) of the membrane device (220) after the intake air has been somewhat elevated in pressure by a compressor portion (248) of a turbocharger (250). In this regard, ambient air flows through an air filter (222 as indicated by arrows 222A) and an air duct (244 as indicated by arrow 244A) so as to be compressed by a compressor (248) of a turbocharger (250) (i.e., the air is elevated in pressure, for example, to a pressure of 30-35 psi). This pressurized intake air flows from the compressor (248) through an air duct (320 as indicated by arrow 320A) to an air diverter valve (322). The valve (322) can be actuated to allow all of the intake air flowing in the air duct (320) to flow through an air duct (324 as indicated by arrow 324A) and then through an intercooler (260) and an air duct (262 as indicated by arrow 262A) to the intake manifold (212) so that it can be combined with combustible fuel in the cylinders (14A-14D).

The valve (322) also can be activated such that a portion of the intake air flowing in the air duct (320) is diverted to and flows along an air duct (326 as indicated by arrows 326A and 326B) to the input (268) of the membrane device (220). The flow of the diverted air along the air duct 326 occurs because the air flowing out of the compressor (248) is sufficiently pressurized to establish a pressure differential across the air separation membrane (220) between the input (268) and an outlet (270) of the membrane device (220) [i.e., the pressure is higher at the input (268) as compared to the outlet (270)]. This differential in pressure across the membrane device (220) will result in air flowing from the input (268) through the membrane device (220) so that supplemental oxygen-enriched air will permeate from the higher pressure, upstream side of the membrane device (220) at the input (268) to the lower pressure, downstream side of the membrane device (220) at the outlet (270) and thereby to an outlet duct 328. On the other hand, nitrogen-enriched air will likewise flow out of another outlet (276) of the membrane device (220) into an outlet duct 278.

As is discussed with respect to the membrane device (20), the membrane device (220) is adapted to separate oxygen and nitrogen present in the air being supplied through the input (268) so as to produce supplemental oxygen-enriched air (permeate) at the outlet (270) and nitrogen-enriched air (retentate) at the other outlet (276). The membrane device (220) can be of the same type as permeable membrane device (20). Once the supplemental oxygen-enriched air is produced by the membrane device (220), it will flow through the outlet duct (328 as indicated by arrow 328A) to a control valve (330). The control valve (330) controls the amount of supplemental oxygen-enriched air that will flow through an air duct (284 as indicated by arrow 284A) to a compressor (230). In this regard, a portion of the supplemental oxygen-enriched air flowing through the outlet duct (328) can be expelled to atmosphere through an air duct (332 as indicated by arrow 332A).

The remaining portion of the supplemental oxygen-enriched air will flow through the air duct (284) and will be further pressurized by the compressor (230) so that the supplemental oxygen-enriched air will be at a sufficiently elevated pressure that it can be injected directly into the cylinders (214A-214D) of the diesel engine (210). For example, the compressor (230) can be designed to pressurize the supplemental air flowing from the compressor (230) to a pressure of 500-2,000 psi. In general, the pressure should be sufficiently higher than the cylinder combustion pressure so that the supplemental air can be injected directly into the cylinders (214A-214D) during the appropriate time in the combustion cycle of the cylinders (214A-214D). This pressurized supplemental air containing oxygen-enriched air flows through an air duct (288 as indicated by arrow 288A) to a high pressure air rail or air accumulator (232).

The air rail (232) is in fluid communication with air injectors (234A-234D) via air ducts (290A-290D) respectively, so that the pressurized supplemental oxygen-enriched air from the air rail (232) will flow in the air ducts (290A-290D as indicated by arrows 290AA, 290BA, 290CA and 290DA) to the air injectors (234A-234D). The air injectors (234A-234D) are in turn respectively associated with each of the cylinders (214A-214D). As with the air injectors (34A-34D), the air injectors (234A-234D) are adapted to inject controlled quantities of supplemental pressurized oxygen-enriched air from the air rail (232) directly into the cylinders (214A-214D) at the appropriate point or time in the combustion cycle of the each of those cylinders (214A-214D). As is discussed above with respect to the combustion air management and emission control system (18), controlled quantities of the supplemental oxygen-enriched air from the air rail (232) are injected into the cylinders (214A-214D) during the time in the combustion cycle of those cylinders (214A-214D) when pistons 236A-236D are in their expansion and/or exhaust strokes. The injection of supplemental oxygen-enriched air directly into the combustion chambers (214A-214D) during the diffusion and/or tail end phases of the combustion cycle provides turbulent mixing of the reactants in the cylinders (214A-214D) due to the jet momentum of the air being injected and also increases the oxygen concentration in the gases surrounding burning fuel droplets. These changes in the mixing and chemical kinetics help to enhance soot and hydrocarbon oxidation reactions without adversely increasing NOx formation. As a result of the enhanced oxidation reactions that occur due to the injection of the supplemental oxygen-enriched air into the cylinders (214A-214D) during the expansion and/or exhaust strokes of the pistons (236A-236D), visible smoke, total particulates, hydrocarbons, and carbon monoxide being emitted from the exhaust manifold (216) into the exhaust duct (254) will be significantly reduced.

The amount of NOx in the exhaust flowing in the exhaust duct (254) can be minimized in the same manner that the NOx flowing in the exhaust duct (100) is minimized in the case of the combustion air management control system (18). More specifically, the NOx present in the exhaust gases flowing in the exhaust duct (254) can be reduced by utilizing the nitrogen-enriched air flowing from the outlet (276) of the membrane device (220) either by introducing the nitrogen-enriched air into the intake manifold (212) via a control valve (238) or by supplying the nitrogen-enriched air to a monatomic nitrogen generator (240) via the control valve (238) so that atomic nitrogen can be injected into the exhaust gases flowing in the exhaust duct (254). In this regard, the control valve (238) can be actuated to expel the nitrogen-enriched air flowing in the air duct (278 as indicated by arrow 278A) to atmosphere through an air duct (292 as indicated by arrow 292A); to supply the nitrogen-enriched air via an air duct (296 as indicated by arrow 296A) to the monatomic nitrogen generator (240) which converts into atomic nitrogen the molecular nitrogen present in the nitrogen-enriched air so that the atomic nitrogen can be injected into the exhaust duct (254) via an air duct (298 as indicated by arrow 298A); or to supply the nitrogen-enriched air into the air duct (262) via an air duct (294 as indicated by arrow 294A) so that it becomes combined with or mixed with the intake air flowing in the air duct (262) and becomes part of the intake air being supplied to the intake manifold (212).

This utilization of the nitrogen-enriched air to inject monatomic nitrogen into the exhaust duct (254) or to become part of the intake air being supplied to the intake manifold (212) are ways to minimize the amount of NOx flowing from the exhaust duct (300 as indicated by arrow 300A). As is discussed in connection with the combustion air management or emission control system (18), the NOx flowing from the exhaust duct (300) also can be reduced by using an EGR system or by retarding the fuel injection timing to delay the beginning of the combustion within the cylinders (214A-214D).

In certain instances, it is not practical or suitable to provide a source of oxygen-enriched air such as the membrane devices (20) and (220) in the case of the combustion air management or emission control systems (18) and (218) respectively. Some of the benefits derived from those systems (18) and (218) nevertheless can be attained by an combustion air management or emission control system (418) disclosed in FIG. 3. In that FIG. 3, therein is disclosed a diagrammatic representation of a diesel engine (410) having an intake manifold (412) through which air is supplied to the engine (410) to be combined with combustible fuel in cylinders or combustion chambers (414A-414D) of the engine (410). In order to limit the amount of undesirable emissions that are present in the exhaust gases being emitted from the engine (410) through an exhaust manifold (416), the engine (410) also is provided with the combustion air management or emission control system that is generally designated by the reference numeral (418) and that embodies the present invention. The engine (410) and the combustion air management and emission control system (418) include many of the same components included in the engine (10) and the combustion air management and emission control system (18). Consequently, the components of the engine (410) and the combustion air management and emission control system (418) that are specifically referred to herein are referenced by the same reference numerals as the corresponding components in the engine (10) and the combustion air management and emission control system (18) except that the quantity 400 has been added to the reference numerals.

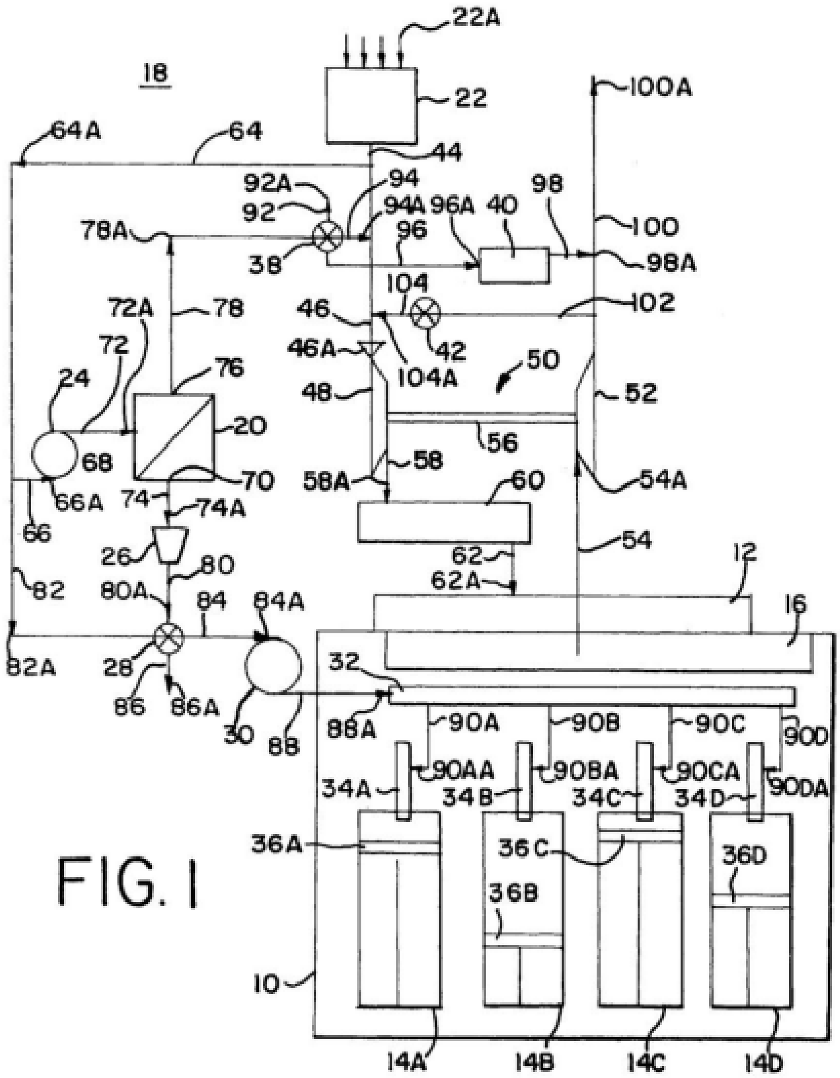
In connection with the engine (410), ambient air flows through an air filter (422 as indicated by arrows 422A) and an air duct (444 as indicated by an arrow 444A) so as to be compressed by a compressor (448) of a turbocharger (450) (i.e., the air is elevated in pressure, for example, to a pressure of 30-35 psi). This pressurized intake air flows from the compressor (448) through an air duct (520 as indicated by arrow 520A) to an air diverter valve (522). The valve (522) can be actuated to allow all of the intake air flowing in the air duct (520) to flow through an air duct (524 as indicated by arrow 524A) and then through an intercooler (460) and an air duct (462 as indicated by arrow 462A) to the intake manifold (412) so that it can be combined with combustible fuel in the cylinders (414A-414D).

The valve (522) also can be activated such that a portion of the intake air flowing in the air duct (520) is diverted to and flows along an air duct (526 as indicated by arrow 526A) to a compressor (430). The air flowing to the compressor (430) will be further pressurized by the compressor (430) so that this pressurized supplemental air will be at a sufficiently elevated pressure that it can be injected directly into the cylinders (414A-414D) of the diesel engine (410). For example, the compressor (430) can be designed to pressurize the supplemental air flowing from the compressor (230) to a pressure of 500-2,000 psi. In general, the pressure should be sufficiently higher than the cylinder combustion pressure so that the supplemental air can be injected directly into the cylinders (414A-414D) during the appropriate time in the combustion cycle of the cylinders (414A-414D). This pressurized supplemental air flows through an air duct (488 as indicated by arrow 488A) to a high pressure air rail or air accumulator (432).

The air rail (432) is in fluid communication with air injectors (434A-434D) via air ducts (490A-490D) respectively, so that the pressurized supplemental air from the air rail (432) will flow in the air ducts (490A-490D as indicated by arrows 490AA, 490BA, 490CA and 490DA) to the air injectors (434A-434D). The air injectors (434A-434D) are in turn respectively associated with each of the cylinders (414A-414D). As with the air injectors (34A-34D), the air injectors (434A-434D) are adapted to inject controlled quantities of supplemental pressurized air from the air rail (432) directly into the cylinders (414A-414D) at the appropriate point or time in the combustion cycle of the each of those cylinders (414A-414D). As is discussed above with respect to the combustion air management and emission control system (18), controlled quantities of the supplemental air from the air rail (432) are injected into the cylinders (414A-414D) during the time in the combustion cycle of those cylinders (414A-414D) when pistons (436A-436D) are in their expansion and/or exhaust strokes. Even though the supplemental air being injected into the cylinders (414A-414D) does not have increased quantities of oxygen, oxidation within the cylinders (414A-414D) during the expansion and/or exhaust strokes of the pistons (436A-436D) nevertheless tends to be promoted. The injection of supplemental air directly into the combustion chambers (414A-414D) during the diffusion and/or tail end phases of the combustion cycle provides turbulent mixing of the reactants in the cylinders (414A-414D) due to the jet momentum of the air being injected. These changes in the mixing kinetics help to enhance soot and hydrocarbon oxidation reactions without adversely increasing NOx formation. As a result, visible smoke, total particulates, hydrocarbons, and carbon monoxide being emitted from the exhaust manifold (416) into an exhaust duct (454) will be reduced.

While the injection of supplemental air directly into the cylinders (414A-414D) of the engine (410) tends to reduce the particulates in the exhaust gases flowing through the exhaust ducts (454 and 500), the level of NOx in the exhaust gases flowing to atmosphere through the exhaust duct (500) can be reduced by utilizing an EGR system. In this regard, an EGR control valve (442) is used to control the amount, if any, of the exhaust gases flowing in the exhaust duct (500) that is to be fed back into the intake duct (444). When the EGR control valve (442) is actuated, a portion of the exhaust gases flowing in the exhaust duct (500) will flow through ducts (402 and 404 as indicated by an arrow 404) into the air duct (444) wherein the exhaust gases will become mixed with the intake air flowing from the air filter (422) to the intake manifold (412). The injection of such recirculated exhaust gases into the intake air tends to lower the combustion temperatures within the combustion cylinders (414A-414D) and the formation of NOx in the combustion chambers (414A-414D) can be reduced. The formation of NOx can be further reduced by electronically controlling the timing and delivery of the injection of diesel fuel into the engine's cylinders (414A-414D). In this regard, the fuel injection can be retarded to delay the beginning of combustion within each cylinder (414A-414D) or rate shaping of the fuel delivery can be used.

Obviously, many modifications and variations of the present invention are possible in light of the above teachings. Thus, it is to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described above.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90BA
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14A
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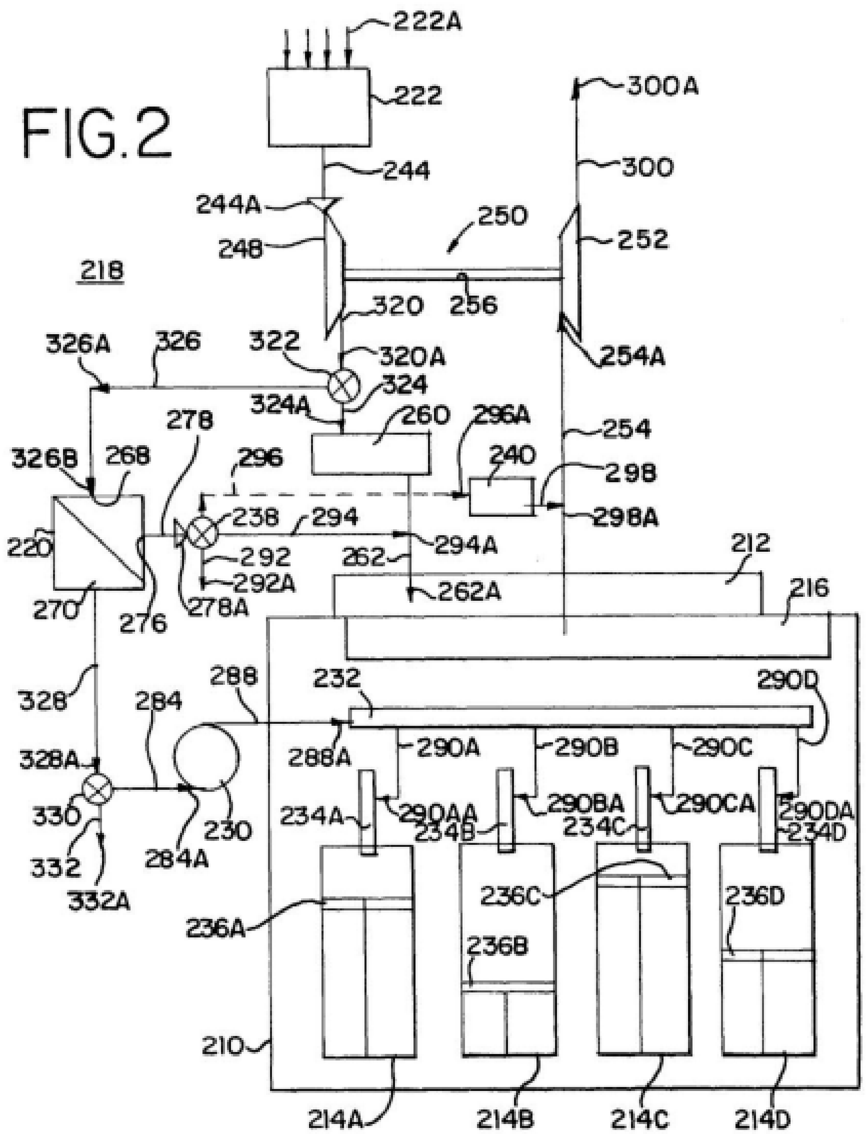
14D

FIG. 1

FIG.2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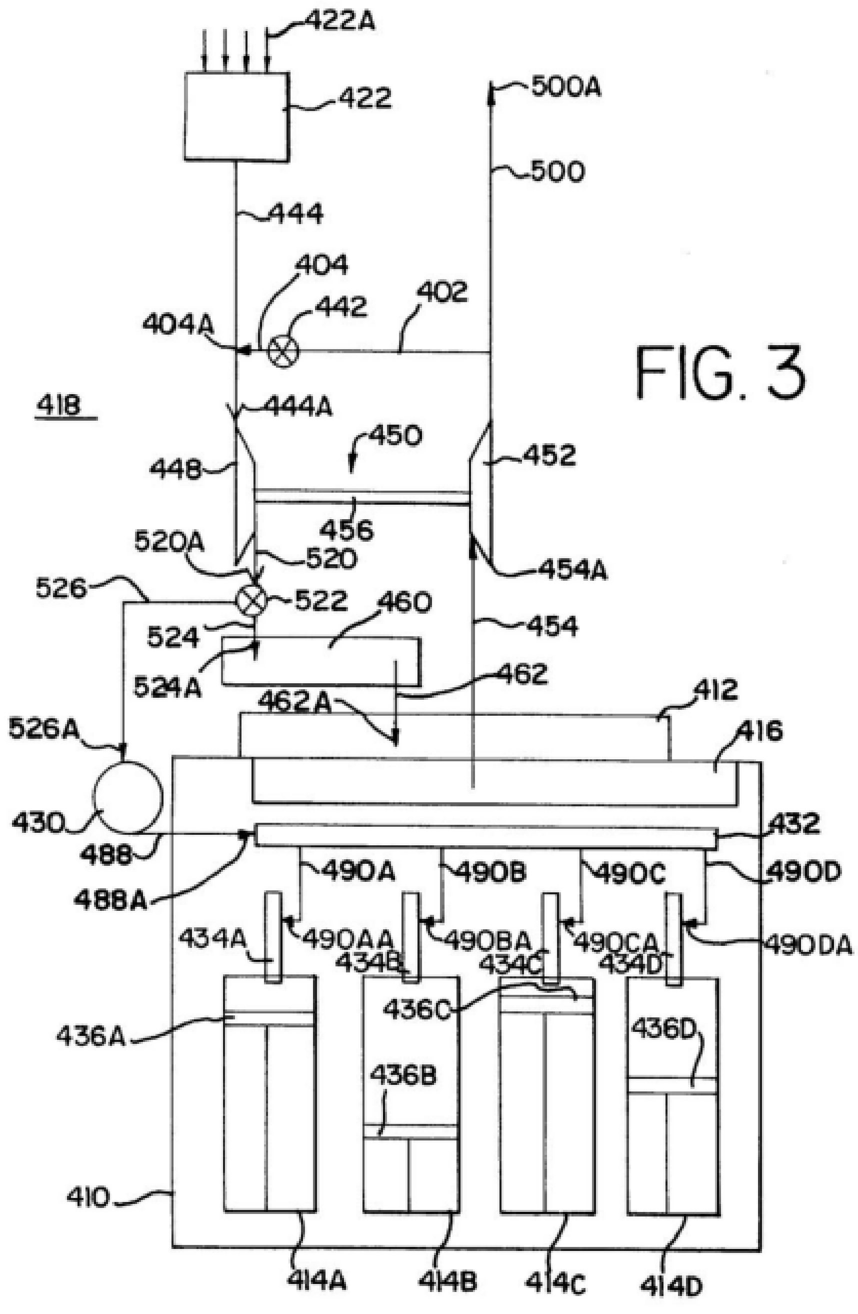
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526A
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414C
414D

FIG. 3