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Poola et al.

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[45] **Date of Patent: May 2, 2000**

[54] **METHOD AND APPARATUS FOR REDUCING PARTICULATES AND NO_X EMISSIONS FROM DIESEL ENGINES UTILIZING OXYGEN ENRICHED COMBUSTION AIR**

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[73] Assignee: **The University of Chicago**, Chicago, Ill.

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[51] **Int. Cl.**[7] **F01N 3/00**

[52] **U.S. Cl.** **60/274**; 60/285; 60/289; 60/280; 123/585; 123/567; 123/26

[58] **Field of Search** 60/274, 285, 276, 60/303, 280, 286, 289; 123/302, 501, 503, 585, 567, 26, 316, 423, 669

[56] **References Cited**

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5,526,641	6/1996	Sekar et al.	60/274
5,636,619	6/1997	Poola et al.	123/585
5,640,845	6/1997	Ng et al.	60/274
5,649,517	7/1997	Poola et al.	123/585
5,709,196	1/1998	Coleman et al.	123/672
5,878,713	3/1999	Kadota	123/305

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Assistant Examiner—Binh Tran
Attorney, Agent, or Firm—Mason, Kolehmainen, Rathburn & Wyss

[57] **ABSTRACT**

An emission control system for reducing total particulates and NO_X emissions from the exhaust of a diesel engine includes an air supply system that supplies oxygen enriched air to an air intake of the engine. The air supply system may include a selectively permeable air separating membrane device for producing the oxygen enriched air. In order to effectively utilize the increase in the concentration level of oxygen in the intake air, the amount of fuel being supplied to the diesel engine also is increased at a minimum in proportion to the increased concentration level of oxygen in the intake air. The increase in the amount of such fuel being supplied to the diesel engine can be adjusted by an electronic fuel injection system used on such diesel engines. In addition, the electronic fuel injection system is used to retard the injection timing of the engine.

17 Claims, 4 Drawing Sheets

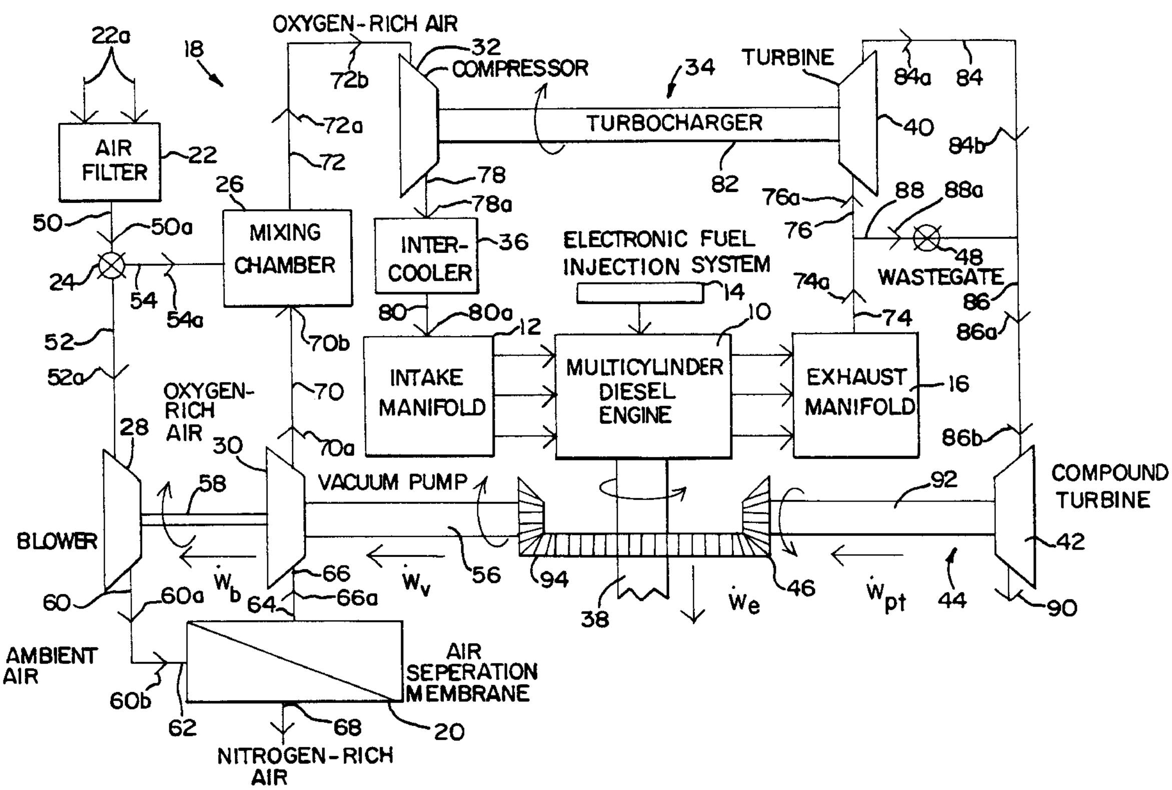


FIG. 1

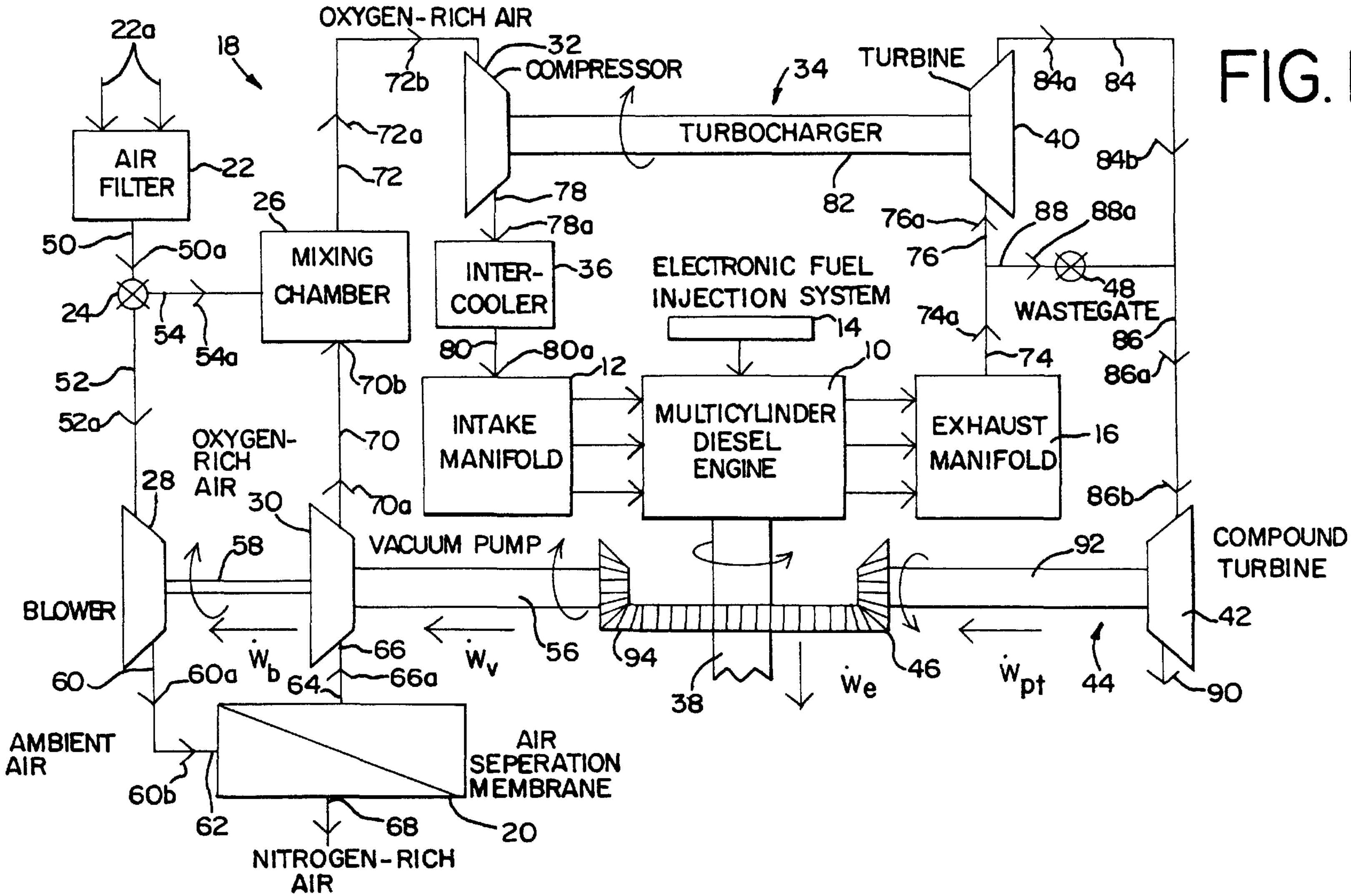

22a
18
OXYGEN-RICH AIR
72b
32
COMPRESSOR
34
TURBINE
84a
84
72a
TURBOCHARGER
40
84b
AIR FILTER
22
72
78
82
26
78a
76a
88
88a
50
50a
MIXING CHAMBER
INTER-COOLER
36
ELECTRONIC FUEL INJECTION SYSTEM
76
24
48
WASTEGATE
54
54a
14
74a
86
80
80a
10
74
86a
52
70b
12
52a
INTAKE MANIFOLD
MULTICYLINDER DIESEL ENGINE
EXHAUST MANIFOLD
16
OXYGEN-RICH AIR
70
28
70a
86b
30
COMPOUND TURBINE
58
VACUUM PUMP
92
BLOWER
42
56
$\dot{W}_b$
$\dot{W}_v$
94
46
$\dot{W}_e$
$\dot{W}_{pt}$
60
60a
64
66
66a
38
44
90
AMBIENT AIR
AIR SEPERATION MEMBRANE
60b
62
68
20
NITROGEN-RICH AIR

FIG. 2

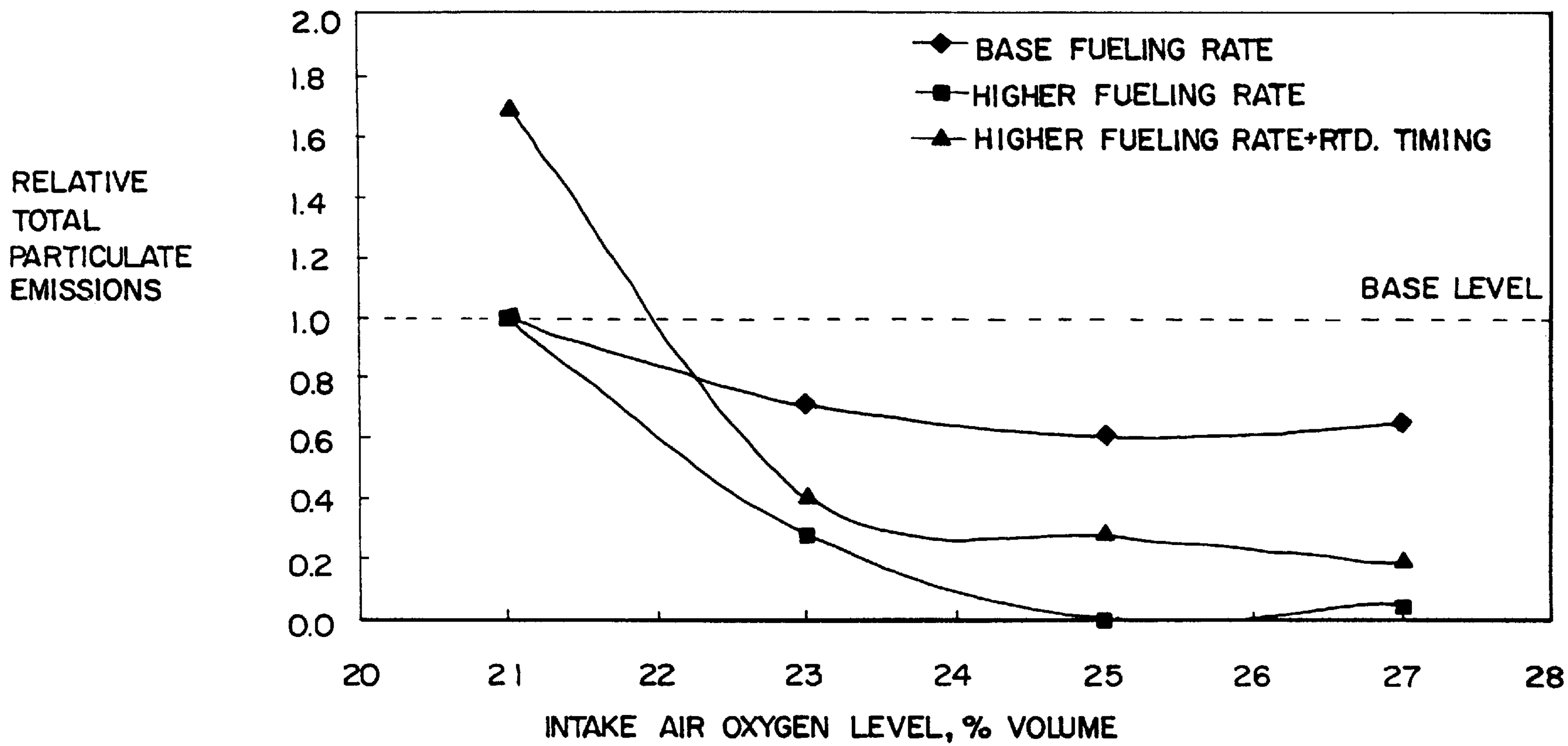

RELATIVE TOTAL PARTICULATE EMISSIONS
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
BASE FUELING RATE
HIGHER FUELING RATE
HIGHER FUELING RATE+RTD. TIMING
BASE LEVEL
20
21
22
23
24
25
26
27
28
INTAKE AIR OXYGEN LEVEL, % VOLUME

FIG. 3

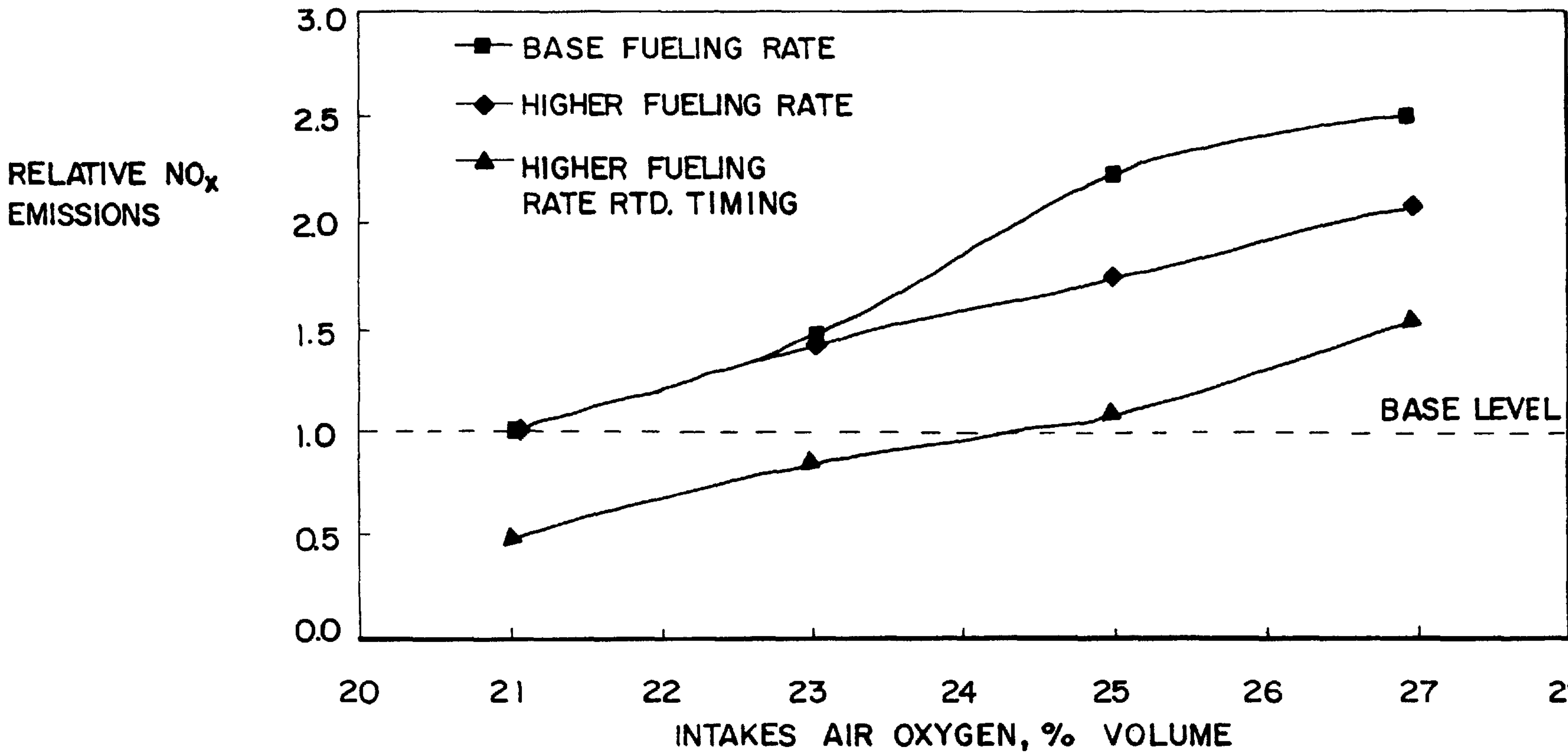
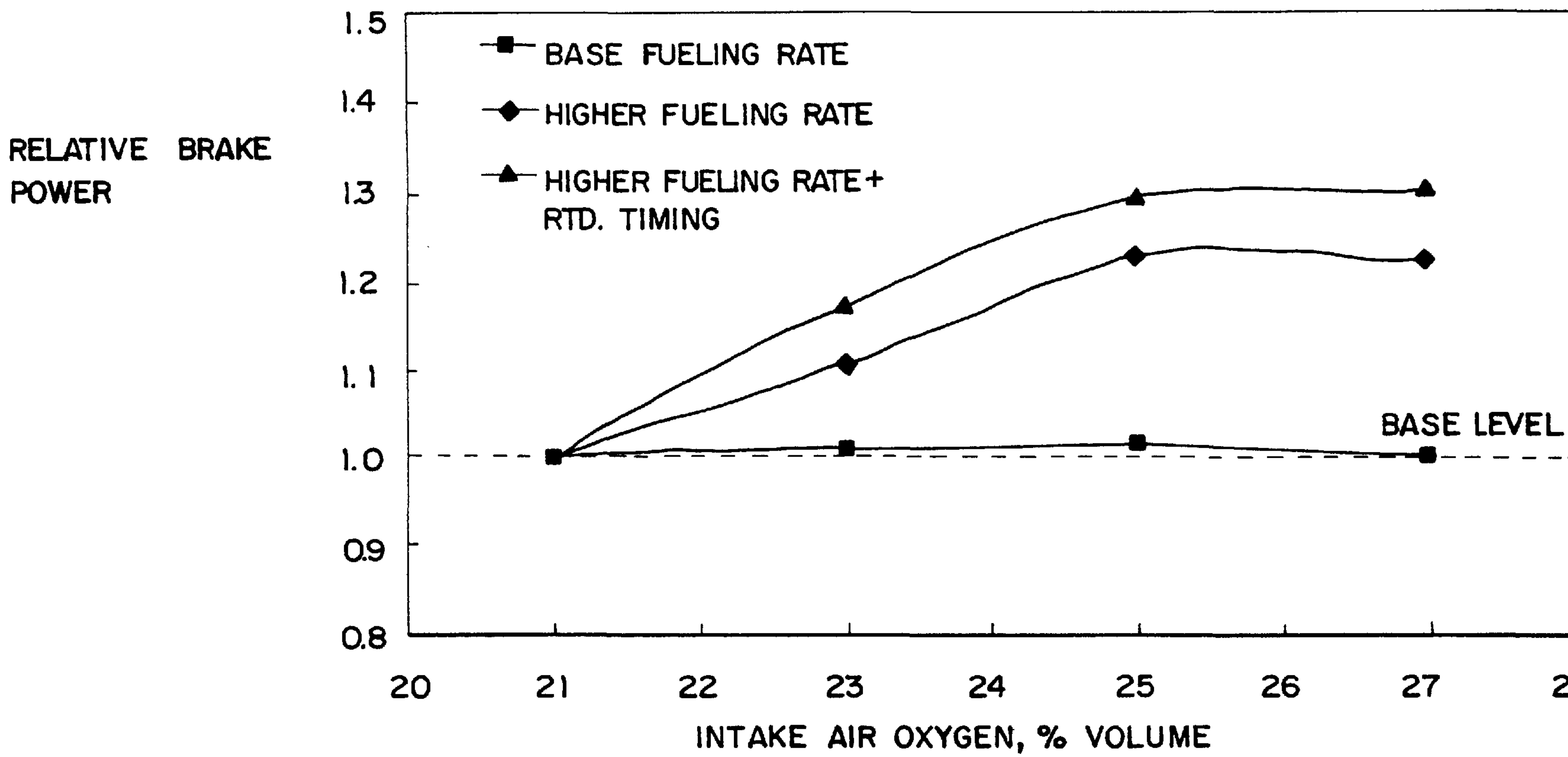

RELATIVE NO$_x$
EMISSIONS
3.0
2.5
2.0
1.5
1.0
0.5
0.0
BASE FUELING RATE
HIGHER FUELING RATE
HIGHER FUELING
RATE RTD. TIMING
BASE LEVEL
20
21
22
23
24
25
26
27
28
INTAKES AIR OXYGEN, % VOLUME

FIG. 4


RELATIVE BRAKE POWER
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
BASE FUELING RATE
HIGHER FUELING RATE
HIGHER FUELING RATE + RTD. TIMING
BASE LEVEL
20
21
22
23
24
25
26
27
28
INTAKE AIR OXYGEN, % VOLUME

METHOD AND APPARATUS FOR REDUCING PARTICULATES AND NO_X EMISSIONS FROM DIESEL ENGINES UTILIZING OXYGEN ENRICHED COMBUSTION AIR

CONTRACTUAL ORIGIN OF THE INVENTION

The United States Government has rights in this invention pursuant to Contract No. W-31-109-ENG-38 between the United States Government and The University of Chicago.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a method and apparatus for decreasing undesirable emissions in the exhaust of a compression ignition (diesel) engine, and more particularly, to a new and improved method and apparatus for decreasing total particulates and oxides of nitrogen (NO_X) from the exhaust of the diesel engine by introducing oxygen enriched air and an increased quantity of fuel and by retarding the injection timing of the diesel engine.

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 (NO_X). Environmental Protection Agency (EPA) emissions standards for future automobiles, trucks and locomotive diesel engines require simultaneous reduction of NO_X 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 NO_X emissions from a diesel engine. 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 NO_X 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 NO_X 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 NO_X 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 wear problems and oil contamination, particularly in the case of diesel engines where the recirculated gases include soot particles.

Other attempts have been made to control the amount of NO_X being emitted from the exhaust of an engine. In order to control the amount of NO_X actually generated by the engine, the amount of oxygen and nitrogen included in the intake of air of the engine has been controlled (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 NO_X 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 NO_X 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 decreasing both total particulates and NO_X emissions in the exhaust of a diesel engine.

It is another object of the present invention to provide a new and improved method and apparatus for decreasing both total particulates and NO_X emissions in the exhaust of a diesel engine while enhancing the power generated by the engine by introducing oxygen enriched air into the air intake of the engine and by increasing the quantity of fuel injected into the engine while simultaneously controlling (retarding) the engine injection timing.

It is yet another object of the present invention to provide a new and improved method and apparatus for reducing the amount of total particulates and NO_X in the exhaust of a diesel engine while enhancing the power generated by the engine by introducing oxygen enriched air into the air intake of the diesel engine by diverting at least a portion of the intake air through a selectively permeable membrane so that ambient air and oxygen enriched air can be selectively supplied to the engine intake manifold, by increasing the amount of fuel introduced into the engine and by retarding the engine injection timing.

SUMMARY OF THE INVENTION

In accordance with these and many other objects of the present invention, an emission control system for a diesel engine embodying the present invention includes an air supply system that supplies oxygen enriched air to the intake of the engine. At least a portion of ambient air flowing from an air intake device is diverted so that the diverted air flows through a selectively permeable air separating membrane device. The ambient air being so diverted flows through the permeable membrane device due to a pressure differential established across the membrane device. This pressure differential can be established by a blower at the input of the membrane device and a vacuum pump at the output of the membrane device or alternatively, with a compressor at the input of the membrane device.

As the air flows from the blower through the permeable membrane device, a portion of the nitrogen in the ambient air is separated from the air so that oxygen enriched air (permeate) and nitrogen enriched air (retentate) are produced. The oxygen enriched air is supplied through the vacuum pump to the air intake of the engine along with ambient air from the air intake device. The nitrogen enriched air can be expelled to atmosphere. Depending on the engine design, the air being supplied to the intake manifold of the engine can be compressed by a compressor of a turbocharger and cooled by an inter-cooler. As a result, the air being supplied to the intake of the engine can be regulated so that an increased concentration level of oxygen is supplied to the air intake of the engine (for example, 23% to 25% oxygen by volume instead of ambient air which contains about 21% oxygen by volume).

In order to effectively utilize the increase concentration level of oxygen in the intake air, the amount of fuel being supplied to the diesel engine also should be increased. The increase in the amount of such fuel being supplied to the diesel engine can be adjusted by an electronic fuel injection system used on such diesel engines. For example, the amount of fuel being supplied can be increased at a minimum in proportion to the increase by weight of the oxygen in the intake air. While such increases in the oxygen in the intake air and the fuel tends to reduce the amount of total particulates in the exhaust being emitted from the diesel engine in part due to the increase temperature of combustion within the engine and also tends to increase the power being generated by the engine in part due the increase of fuel being combusted, the level of NO_X being emitted from the engine tends to be undesirably increased. However, the level of NO_X can be controlled by having the electronic fuel injection system retard the injection timing of the engine. By retarding the injection timing (i.e., delaying the time in the engine cycle when the fuel is injected into a cylinder), the length or duration of combustion is decreased resulting in less NO_X being formed and emitted from the engine. For example, the injection timing could be retarded between 4 and 10 degrees of crankshaft angle. This retarding of the engine injection timing also tends to maintain the temperature within the cylinder at a more typical level and therefore pressure in the cylinder also is maintained at a typical level.

In one embodiment of the present invention, the intake air is supplied to the intake manifold of a diesel engine at an elevated pressure by means of a turbocharger driven by the energy obtained from the gases being exhausted from the exhaust manifold of the engine. In addition, a compound turbine can be driven by the energy obtained from the exhaust gases which are at an elevated temperature (higher energy state) due to the elevated amount of oxygen in the intake air. The energy generated by such a turbine can be supplied to the output shaft of the diesel engine thereby at least partially offsetting any energy used to operate the blower and vacuum pump that are used in connection with the permeable separation membrane. As a result, there will be only possibly a small increase in the fuel consumption and a small decrease in the power output of the engine due to the use of the permeable separation membrane.

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 embodiment of the invention shown in the accompanying drawing wherein:

FIG. **1** is a diagrammatic illustration of a diesel engine with an emission control system which embodies the present invention.

FIG. **2** is a graph showing how the level of total particulates in the exhaust of a typical diesel engine is affected by adjusting the level of oxygen in the air intake of the engine, adjusting the engine's fuel rate and adjusting the engine's injection timing;

FIG. **3** is a graph showing how the level of NO_X in the exhaust of a typical diesel engine is affected by adjusting the level of oxygen in the air intake of the engine, adjusting the engine's fuel rate and adjusting the engine's injection timing;

FIG. **4** is a graph showing how the power output from a typical diesel engine is affected by adjusting the level of oxygen in the air intake of the engine, adjusting the engine's fuel rate and adjusting the engine's injection timing.

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 in the engine **10** with combustible fuel supplied through an electronic fuel injection system **14**. When the intake air and the 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 (NO_X). 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 an emission control system that is generally designated by the reference numeral **18** and that embodies the present invention.

The emission control system **18** includes an oxygen enrichment or air separation membrane device **20** that separates nitrogen from ambient 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 flowing through an air filter or air intake device **22** flows through an air intake bypass valve **24** to a mixing chamber **26**. In order to supply a mixture of oxygen enriched air and ambient air to the air intake manifold **12** during the operation of the engine **10**, at least a portion of the ambient air flowing through the air filter **22** is diverted by the air intake bypass valve **24** so that such diverted air will flow to the air separation membrane **20** when a blower **28** and a vacuum pump **30** are actuated. A portion of the nitrogen in the ambient air diverted through the permeable membrane device **20** due to a pressure differential established across the membrane device **20** by the blower **28** and the vacuum pump **30** is separated from the ambient air so that oxygen enriched air (permeate) flows through the vacuum pump **30** to the mixing chamber **26**.

The oxygen enriched air is mixed with ambient air within the mixing chamber **26** to the extent determined by the air intake bypass valve **24** such that oxygen enriched air is supplied to the intake manifold **12** of the engine **10** through a compressor portion **32** of a turbocharger **34** and an intercooler cooler **36**. While the emission control system **18** is shown in FIG. **1** as utilizing the mixing chamber **26** for combining the oxygen enriched air from the membrane device **20** and ambient air, the emission control system **18** does not necessarily need to utilize such a mixing chamber **26**. Instead, the oxygen enriched air generated by the membrane device **20** and ambient air can be supplied to the intake manifold **12** of the engine **10** in such proportions that the air entering the engine **10** will have the correct concentration of oxygen.

In either case, the oxygen enriched air is mixed with fuel supplied through the electronic fuel injection system **14** in the engine **10** so as to be combusted in the cylinders of the engine **10**. The timing of the combustion is controlled by the electronic fuel injection system **14** and the combustion results in the rotation of an output shaft **38** with the exhaust gases being expelled from the engine **10** through the exhaust manifold **16**. The exhaust gases being so expelled are at elevated temperatures and the energy of those exhaust gases are used to drive a turbine portion **40** of the turbocharger **34**. The exhaust gases also can be used to drive a turbine portion **42** of a compound turbine **44**, the output **46** of which supplies energy to the output shaft **38** of the engine **10** or alternatively to the blower **28** and the vacuum pump **30**. A wastegate control valve **48** can be used to control the extent to which the exhaust gases flow to the turbine **40** and/or the turbine **42**.

The oxygen level within the air being supplied to the intake manifold **12** of the engine **10** is at an increased concentration level as compared to the concentration of oxygen in ambient air. In order to effectively utilize this increased concentration level of oxygen in the intake air, the amount of fuel being supplied to the diesel engine **10** also is increased at a minimum in proportion to the increased level of oxygen in the intake air. The increase in the quantity of such fuel being supplied to the diesel engine **10** can be regulated by the electronic fuel injection system **14**. While such increases in the oxygen in the intake air and the fuel tends to reduce the amount of total particulates in the exhaust gases being emitted from the diesel engine **10** through the exhaust manifold **16** in part due to the increase temperature of combustion within the engine **10** and also tends to increase the power being generated by the engine **10** in part due the increase of fuel being combusted, the level of NO_X in those exhaust gases tends to be undesirably increased. However, the level of NO_X can be controlled by having the electronic fuel injection system **14** retard the injection timing of the engine **10**. By retarding the injection timing (i.e., delaying the time in the engine cycle when the fuel is injected into a cylinder), the length or duration of combustion is decreased resulting in less NO_X being formed and emitted from the engine **10**. This retarding of the engine injection timing also tends to maintain the temperature within the cylinder and therefore the cylinder pressure at relatively typical levels. It is this combination of increased concentration level of oxygen in the intake air (optimally, 23%–25% by volume) and the increased quantity of fuel along with the retarding of the injection timing that results in the decrease of both total particulates and NO_X in the exhaust gases being emitted from the exhaust manifold **16** of the diesel engine **10**. Moreover, the power being generated by the engine **10** also is improved due to the increased combustion of fuel in the engine **10**.

As previously indicated, ambient air flowing into the air filter **22** (as represented by arrows **22***a*) flows through an air duct **50** (as indicated by an arrow **50***a*) to the air intake bypass valve **24**. The air intake bypass valve **24** controls the amount of air flowing from the air filter **22** along an air duct **52** (as indicated by an arrow **52***a*) to the blower **28** and/or along an air duct **54** (as indicated by an arrow **54***a*) to the mixing chamber **26**. In effect, the air intake bypass valve **24** will determine the oxygen level in the air mixed in the mixing chamber **26** because it controls the amount of ambient air flowing to the mixing chamber **26** through the duct **54** and the amount of ambient air flowing to the blower **28** and thereby to the air separation membrane **20** which produces oxygen enriched air and from which the oxygen enriched air is supplied through the vacuum pump **30** to the mixing chamber **26**.

In order to provide the oxygen enriched air to the mixing chamber **26**, the air intake bypass valve **24** is activated to permit some of the ambient air from the air filter **22** to flow along the air duct **52** as indicated by the arrow **52***a*. The flow of ambient air along the air duct **52** is caused by the actuation of the blower **28** and the vacuum pump **30** that produces a pressure differential across the air separation membrane **20**. The blower **28** and the vacuum pump **30** can be mechanically driven as diagrammatically shown in FIG. **1** from energy supplied from the rotating shaft **38** of the engine **10** or the compound turbine **44** through turbine shafts **56** and **58** respectively. Alternatively, the blower **28** and the vacuum pump **30** can be driven by electric motors powered by the electrical system of the engine **10**. With the blower **28** and the vacuum pump **30** so actuated and depending on the state of the air intake bypass valve **24**, at least a portion of the air flowing into the air filter **22** will flow through the air duct **52** (as indicated by an arrow **52***a*), through the blower **28**, through an air duct **60** (as indicated by arrows **60***a* and **60***b*) toward an input **62** of the membrane device **20**. The ambient air flowing through the ducts **52** and **60** will flow toward the input **62** of the membrane device **20** due to the differential pressure that is established across the input **62** and an outlet **64** of the membrane device **20** by the blower **28** and the vacuum pump **30** with the pressure being higher at the input **62** as compared to the outlet **64**. This differential in pressure across the membrane device **20** will result in the ambient air flowing into the input **62** and through the membrane device **20** so that oxygen enriched air will permeate from the higher pressure, upstream side of the membrane device **20** at the input **62** to the lower pressure, downstream side of the membrane device **20** at the outlet **64** and thereby to an outlet duct **66** and nitrogen enriched air will likewise flow out of an outlet **68** to atmosphere. Alternatively, the differential pressure across the input **62** and the outlet **64** of the membrane device **20** can be established with a compressor that pressurizes the input **62** of the membrane device **20** while the outlet **64** is maintained at atmospheric pressure.

The membrane device **20** is adapted to separate oxygen and nitrogen present in the air being supplied through the input **62** so as to produce oxygen enriched air (permeate) at the outlet **64** and nitrogen enriched air (retentate) at another outlet **68**. 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 air flowing out from the outlet **64** of the membrane device **20** and the particular percentage of nitrogen contained within the air flowing out from the outlet **68** of the membrane device **20** can be adjusted by providing the proper membrane device **20**. In this regard, the membrane surface area and the pressure differential across the membrane device **20** will in part determine the amount of nitrogen separated from the ambient air flowing into the input **62** and thereby the percentage of oxygen within the air flowing out from the outlet **64**. In general, the oxygen enriched air flowing from the outlet **64** of a membrane device, like the membrane device **20**, may contain from about 23% to about 25% oxygen concentration by volume.

Once the oxygen enriched air is produced by the membrane device **20**, it will flow from the outlet **64** through the air duct **66** (as indicated by an arrow **66***a*), through the vacuum pump **30** and through an air duct **70** (as indicated by arrows **70***a* and **70***b*) to the mixing chamber **26**. The level of oxygen in the oxygen enriched air being supplied from the mixing chamber **26** via an air duct **72** (as indicated by arrows **72***a* and **72***b*) to the compressor **32** is in part dependent on the concentration of oxygen in the oxygen enriched air flowing from the outlet **64** of the air separation membrane **20** and in part dependent on the amount of ambient air that is supplied directly to the mixing chamber **26** through the air intake bypass valve **24** and the air duct **54** and through that valve **24** to the air separation membrane **20**. As previously indicated, the mixing chamber **26** is not necessarily required because both oxygen enriched air and ambient air can be supplied to the intake manifold **12** of the engine **10** resulting in the proper concentration of oxygen enriched air being supplied to the engine **10**. No matter how the oxygen enriched air is supplied to the engine **10**, typically for engines **10** of the type with which the emission control system **18** is used the oxygen concentration by volume in the oxygen enriched air being supplied to the engine **10** will be increased to 23% to 25% by volume (this is compared to the concentration of oxygen in ambient air which is approximately 21% by volume).

The oxygen enriched air flowing in the air duct **72** is compressed (i.e., elevated in pressure) by the compressor portion **32** of the turbocharger **34**. The turbine portion **40** of the turbocharger **34** is driven by the energy from the exhaust gases being emitted from the exhaust manifold **16** through an air duct **74** (as indicated by an arrow **74***a*) and an air duct **76** (as indicated by an arrow **76***a*). The energy from such exhaust gases that are at elevated temperatures is used to drive the turbine portion **40** of the turbocharger **34** such that a shaft **82** is rotated thereby driving the compressor portion **32**. The compressor portion **32** compresses the intake air flowing through the air duct **72** such that the intake air flowing out from the compressor portion **32** through an air duct **78** (as indicated by an arrow **78***a*) to the inter-cooler **36** is at an appropriate elevated pressure when it flows out from the inter-cooler **36** via an air duct **80** (as indicated by an arrow **80***a*) and supplied to the intake manifold **12**. The inter-cooler **36** is designed to act as a heat exchanger to cool the intake air flowing into the intake manifold **12**. By cooling the intake air, NO_X formed in the engine **10** tends to be decreased.

In view of the fact that the intake air has a higher concentration of oxygen than ambient air, the amount of fuel being supplied to the engine **10** by the fuel injection system **14** also should be increased. This increase in fuel quantity can be at a minimum proportional to the increase in the oxygen content of the intake air. For example, the fuel quantity can be increased by the ratio of the increase of the weight of oxygen in the intake air over the weight of oxygen in ambient air divided by the weight of oxygen in ambient air. If the quantity (weight) of fuel being supplied to the engine **10** when ambient air is used is "F1", the weight of oxygen in ambient air is "AA" and the weight of oxygen in the intake air is "AO", then the quantity (weight) "F2" of the fuel that should be supplied to the engine **10** by the fuel injection system **14** when oxygen enriched air is used could be determined by the following formula:

$$F2=F1\times(AO/AA).$$

While increasing the concentration level of oxygen in the intake air being supplied to the engine **10** through the intake manifold **12** with a commensurate increase in the fuel being supplied to the engine **10** through the fuel injection system **14** tends to diminish the amount of total particulates in the exhaust gases flowing from the exhaust manifold **16** of the engine **10** and also tends to increase the power being generated by the engine **10** in part due the increase of fuel being combusted, the NO_X in such exhaust gases tend to be at an undesirable elevated amount. This is due in part to the fact that the increase temperatures of combustion within the cylinders of the engine **10** tend to form more oxides of nitrogen in those exhaust gases. However, the amount of such NO_X in those exhaust gases can be reduced by retarding the injection timing of the engine **10** in addition to increasing the concentration level of oxygen in the intake air and increasing the fuel quantity being supplied to the engine **10**. The injection timing can be controlled by the electronic fuel injection system **14**. The retarding of the injection timing effectively delays the time when fuel is injected in a cylinder of the engine **10**. This delay lessens the combustion time and thereby decreases the amount of oxides of nitrogen that is formed during combustion. While the extent to which the injection timing is decreased depends on the concentration levels of oxygen in the intake air and the characteristics of the engine **10**, a retarding of injection timing in the range of 4 to 10 degrees of crank angle would tend to be sufficient to aid in diminishing the amount of NO_X present in the exhaust gases being emitted from the exhaust manifold **16** of the engine **10**.

In this regard, the graphs of FIGS. **2**, **3** and **4** demonstrate how the increase in oxygen concentration in the intake air, the increase in fuel quantity and the retarding of injection timing can reduce both the total particulates and NO_X simultaneously within the exhaust gases being emitted from the exhaust manifold **16** of the engine **10** and also increase the power being generated by the engine **10**. These graphs are based on information from a typical two cylinder research (large bore, medium speed, two-stroke) diesel engine running at a full load.

Referring first to FIG. **2**, that graph compares the amount of total particulates (shown on a relative scale or a normalized index above or below a base or index level) that is present in the exhaust gases of a diesel engine depending on the concentration level of oxygen (shown as a percentage of volume of the intake air) when a typical amount of fuel (base fueling rate) is supplied to the engine (diamond shaped points), when an increased amount of fuel (higher fueling rate) is supplied to the engine (square shaped points) and when both an increased amount of fuel is supplied and the injection timing is retarded (in the case of this graph, the injection timing was retarded approximately 7 degrees of crank shaft angle)(triangular shaped points). As can be discerned from the graph of FIG. **2**, the amount of total particulates decrease in all cases when the concentration level of oxygen in the intake air is increased above the concentration level of oxygen in ambient air.

The graph of FIG. **3** similarly compares what is happening with respect to oxides of nitrogen (NO_X) (shown on a relative scale or normalized index above or below a base or index level) in the exhaust gases of a diesel engine depending on the concentration level of oxygen (shown as a percentage of volume of the intake air) when a typical amount of fuel (base fueling rate) is supplied to the engine (square shaped points), when an increased amount of fuel (higher fueling rate) is supplied to the engine (diamond shaped points) and when both an increased amount of fuel is supplied and the injection timing is retarded (in the case of this graph, the injection timing was retarded approximately 7 degrees of crank shaft angle)(triangular shaped points). As can be discerned from this graph, the amount of NO_X in the exhaust gases tends to increase in all cases when the concentration level of oxygen in the intake air is increased. On the other hand, the graph of FIG. **3** does indicate that the amount of NO_X in such exhaust gases are maintained at an acceptable level below a base level even when the oxygen level in the intake air is increased to around 23% of the volume of the intake air, the base fuel rate is increased and the injection timing of the engine is retarded. At that same level of oxygen concentration, the graph of

FIG. 2 shows that the total particulates in the exhaust gases are at a relatively low level, well below a base or acceptable level, when the oxygen concentration of the intake air is at that same approximate 23% by volume, the base fuel rate is increased and the injection timing of the engine is retarded. Accordingly, the graphs of FIGS. **2** and **3** confirm that the levels of both total particulates and NO_X in the exhaust gases of a diesel engine can be reduced to acceptable levels when the oxygen concentration of the intake air is increased modestly above the concentration of oxygen in ambient air (for example, increased to approximately 23% oxygen by volume), the amount of fuel being supplied to the engine is increased (for example, proportional to the increase in the amount of oxygen in the intake air) and the injection timing of the engine is retarded (for example, retarded by 7 degrees crank shaft angle).

The graph of FIG. **4** compares what is happening with respect to the brake power being generated by a typical diesel engine (shown on a relative scale or normalized index above or below a base or index level) depending on the concentration level of oxygen (shown as a percentage of volume of the intake air) when a typical amount of fuel (base fueling rate) is supplied to the engine (square shaped points), when an increased amount of fuel (higher fueling rate) is supplied to the engine (diamond shaped points) and when both an increased amount of fuel is supplied and the injection timing is retarded (in the case of this graph, the injection timing was retarded approximately 7 degrees of crank shaft angle)(triangular shaped points). As can be discerned from this graph, the power output from the engine tends to increase as the amount of fuel being combusted within the engine increases. In the case where the oxygen level in the intake air is increased to around 23%–25% of the volume of the intake air, the base fuel rate is increased and the injection timing of the engine is retarded, the output power is increased above the base level or the level of output power of a normally running engine. Consequently, the graphs of FIGS. **2**, **3** and **4** indicate that the output of the engine can be increased while the total particulates and the NO_X in the exhaust gases are maintained at a relatively low level, well below a base or acceptable level, when the oxygen concentration of the intake air is increased modestly above the concentration of oxygen in ambient air (for example, increased to approximately 23% oxygen by volume), the amount of fuel being supplied to the engine is increased (for example, proportional to the increase in the amount of oxygen in the intake air) and the injection timing of the engine is retarded (for example, retarded by 7 degrees crank shaft angle).

While the use of the emission control system **18** aids in reducing both the total particulates and the NO_X present in the exhaust gases being expelled from the exhaust manifold **16** of the engine **10**, a certain amount of additional energy over the energy normally needed to operate the engine **10** is needed in order for the oxygen to be produced by the membrane device **20**. As previously discussed, the blower **28** and the vacuum pump **30** create a sufficient differential pressure across the separation membrane device **20** so that the resulting oxygen enriched air can be supplied to the mixing chamber **26** and then to the intake manifold **12** of the engine **10**. At least some of this additional energy can be provided by the compound turbine **44**. As also previously discussed, the exhaust gases being expelled from the exhaust manifold **16** flow along the air duct **74** (as indicated by the arrow **74***a*) and the air duct **76** (as indicated by the arrow **76***a*) through the turbine portion **40** of the turbocharger **34**. These exhaust gases are at elevated temperatures (in fact, the temperatures tend to be higher than normal due to the increase of oxygen in the intake air) so that energy can be imparted to the turbine portion **40** of the turbocharger **34** from this exhaust gas. The exhaust gases flow out from the turbine portion **40** through an air duct **84** (as indicated by arrows **84***a* and **84***b*) and through another air duct **86** (as indicated by arrows **86***a* and **86***b*) to the turbine portion **42** of the compound turbine **44**. The amount of and the temperature of the exhaust gases flowing to the compound turbine **44** can be controlled to some extent by the wastegate control valve **48**. When that wastegate control valve **48** is opened to at least some extent, a portion of the exhaust gases flowing in the air duct **74** directly from the exhaust manifold **16** will be diverted along an air duct **88** (as indicated by an arrow **88***a*) and then to the air duct **86** so that the diverted exhaust gases will flow as indicated by the arrows **86***a* and **86***b* along the air duct **86** to the turbine portion **42** of the compound turbine **44**.

The energy contained in the exhaust gases being expelled from the exhaust manifold **16**, particularly in view of the elevated temperatures of those gases caused by the increased levels of oxygen in the intake air of the engine **10**, can be used in driving the turbine **42** of the compound turbine **44**. In this regard, the exhaust gases flow through the turbine portion **42** and then is exhausted to atmosphere as indicated by an arrow **90**. While the disclosed embodiment of the emission control system **18** shown in FIG. **1** indicates that a compound turbine **44** can be used to add to the energy of the crankshaft **38**, other devices can be used such as a positive screw expander, turbochargers, and other bottoming cycles that can convert the energy in the exhaust gases into mechanical energy. The amount of energy generated by the compound turbine **44** is partly dependent on the amount of the exhaust gases that are supplied directly from the exhaust manifold **16** under the control of the wastegate control valve **48** as opposed to the exhaust gases that first flow through the turbine **40**.

In the case of the compound turbine **44**, the amount of energy produced by the turbine **42** and imparted to a shaft **92** and thereby through the output **46** to the crankshaft **38** is represented in FIG. **1** as W_{pt}. The amount of energy being imparted to the crankshaft by both the engine and the compound turbine **44** is represented in FIG. **1** as W_e. On the other hand, the amount of energy being taken from the crankshaft **38** at an output **94** to drive the vacuum pump **30** through the shaft **56** is represented in FIG. **1** as W_v and to drive the blower **28** through the shaft **58** as W_b. Ideally, W_{pt} should be equal to or greater than the sum of W_v and W_b so that the total amount of energy W_e will not be decreased due to the emission control system **18**. Even if the amount of energy W_e imparted to the crankshaft **38** is decreased slightly, that decrease in energy is offset by the advantage of decreasing the amount of total particulates and NO_X in the exhaust gases being expelled to the atmosphere from the engine **10**.

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.

What is claimed and desired to be secured by Letters Patent of the United States is:

1. An emission control system for a combustion engine to limit pollutants in exhaust gases emitted from an exhaust of said engine, said emission control system comprising:

a source of oxygen enriched air in fluid communication with an air intake of said engine, said oxygen enriched air being supplied to said air intake contains approximately 23%–25% oxygen concentration by volume; and

a fuel and timing control system, said fuel and timing control system controlling the amount of fuel being supplied to said engine such that the amount of fuel is increased at a minimum in proportion to the amount of oxygen in said oxygen enriched air and the injection timing of said engine is retarded approximately 4–10 degrees of crank shaft angle.

2. An emission control system as set forth in claim **1** wherein said source of oxygen enriched air is a selectively permeable membrane for producing oxygen enriched air that is supplied to said air intake.

3. An emission control system as set forth in claim **2** wherein said membrane produces oxygen enriched air containing about 23%–25% oxygen concentration by volume.

4. An emission control system as set forth in claim **2** including an exhaust driven device for supplying energy from said exhaust gases so as to enable said membrane to produce said oxygen enriched air.

5. An emission control system as set forth in claim **2** including a pressure differential means associated with said membrane to establish a differential pressure across said membrane so that ambient air flows through said membrane and one of the products of said membrane is oxygen enriched air.

6. An emission control system as set forth in claim **5** wherein said pressure differential means includes a blower for producing an elevated pressure at an input of said membrane and a vacuum pump associated with an output of said membrane from which said oxygen enriched air flows.

7. An emission control system as set forth in claim **6** wherein said blower and said vacuum pump are mechanically driven at least in part by a driving means driven by energy from said exhaust gases being emitted from said exhaust of said engine.

8. An emission control system as set forth in claim **1** including a mixing chamber in fluid communication with said air intake, said mixing chamber receiving ambient air and said oxygen enriched air from said source of oxygen enriched air and supplying a mixture thereof to said air intake.

9. An emission control system as set forth in claim **8** wherein said mixture of oxygen enriched air and ambient air contains about 23%–25% oxygen concentration by volume.

10. An emission control system as set forth in claim **1** wherein said fuel and timing control system retards said injection timing of said engine approximately 7 degrees of crank shaft angle.

11. A method of reducing the amount of oxides of nitrogen and particulates in gases being emitted from an exhaust of an internal combustion engine, said method comprising:

supplying oxygen enriched air contains approximately 23%–25% oxygen concentration by volume to an air intake of said engine;

supplying an increased amount of fuel to said engine in proportion to the amount of oxygen in said oxygen enriched air; and

retarding the injection timing of said engine approximately 4–10 degrees of crank shaft angle.

12. A method as set forth in claim **11** wherein said oxygen enriched air is supplied by a selectively permeable membrane.

13. A method as set forth in claim **12** wherein a blower and a vacuum pump maintain a differential pressure across said permeable membrane.

14. A method as set forth in claim **11** wherein said fuel being supplied to said engine is at a minimum in proportion to the weight of oxygen in said oxygen enriched air as compared to the weight of oxygen in ambient air.

15. A method of reducing the amount of oxides of nitrogen and particulates in gases being emitted from an exhaust of a diesel engine and increasing the amount of output power from said engine, said method comprising:

producing oxygen enriched air by processing ambient air through a selectively permeable membrane;

mixing said oxygen enriched air from said membrane with ambient air so as to have a resulting oxygen enriched air with approximately 23%–25% oxygen concentration by volume;

supplying said resulting oxygen enriched air into an air intake of said engine;

supplying an increased amount of fuel to said engine at a minimum in proportion to the amount of oxygen in said oxygen enriched air; and

retarding the injection timing of said engine approximately 4–10 degrees of crank shaft angle.

16. A method as set forth in claim **15** wherein said fuel being supplied to said engine is at a minimum in proportion to the weight of oxygen in said resulting oxygen enriched air as compared to the weight of oxygen in ambient air.

17. A method as set forth in claim **15** wherein a differential pressure is maintained across said permeable membrane so that said oxygen enriched air will be produced.

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