United States Patent ***5,636,619***
Poola, et al. **June 10, 1997**

METHOD AND APPARATUS FOR REDUCING COLD-PHASE EMISSIONS BY UTILIZING OXYGEN-ENRICHED INTAKE AIR

Abstract

An oxygen-enriched air intake control system for an internal combustion engine includes air-directing apparatus to control the air flow into the intake of the engine. During normal operation of the engine, ambient air flowing from an air filter of the engine flows through the air-directing apparatus into the intake of the engine. To decrease the amount of carbon monoxide (CO) and hydrocarbon (HC) emissions that tend to be produced by the engine during a short period of time after the engine is started, the air-directing apparatus diverts, for a short period of time following the start-up of the engine, at least a portion of the ambient air from the air filter through a secondary path. The secondary path includes a selectively permeable membrane through which the diverted portion of the ambient air flows. The selectively permeable membrane separates nitrogen and oxygen from the diverted air so that oxygen-enriched air containing about 23-25% oxygen by volume is supplied to the intake of the engine.

Inventors: **Poola; Ramesh B.** (Woodridge, IL); **Sekar; Ramanujam R.** (Naperville, IL); **Stork; Kevin C.** (Chicago, IL)

Assignee: **The University of Chicago** (Chicago, IL)

Appl. No.: **598029**

Filed: **February 7, 1996**

Description

Background of the Invention

1. Field of the Invention

This invention relates to a method and apparatus for reducing carbon monoxide (CO) and hydrocarbon (HC) emissions in the exhaust of an internal combustion engine, and more particularly, to a new and improved method and apparatus for introducing oxygen-enriched air into the intake of an internal combustion engine during at the least the initial start-up and warming-up periods of the engine after the engine is started.

2. Background of the Invention

A significant portion of the total pollutants emitted by light-duty passenger vehicles occurs immediately following the start-up of the engine. During this period, the engine block and exhaust manifold are cold, and the catalytic converter has not yet reached high conversion efficiencies (generally the catalyst is not fully effective at temperatures below about 250ºC for CO and 250ºC to 340ºC for HC emissions conversion). Moreover, it is a common practice to operate spark ignition engines with richer fuel-air mixtures during initial start-up and warming-up periods for proper operating driveability and acceleration. As a result, more unburned and partially burned hydrocarbons and more carbon monoxide are present in the exhaust after the engine is started and within the first 20 seconds of idling. On the other hand, the nitrogen oxide (NOx) emissions in the exhaust tend to be low during this start-up period, but increase significantly when the vehicle is first accelerated. Consequently, the characteristics of the emissions in the exhaust of a spark ignition engine are influenced by both the engine operating conditions and the heating characteristics of the catalytic converter.

To meet the California Air Resources Board (CARB) Transitional Low Emission Vehicle (TLEV), Low Emission Vehicle (LEV). and Ultra Low Emission Vehicle (ULEV) standards, substantial reductions are required for HC and CO emissions from a spark ignition engine during the cold phase of the federal test procedure cycle. Similarly, many light-duty passenger cars are required to reduce these emissions to comply with Tier-II (year 2004) standards. This growing concern over start-up/cold-phase emissions has led to various attempts to develop new emissions treatment techniques that reduce the HC and CO levels in the exhaust emissions.

The attempts to reduce cold-phase (i.e., the first 505 seconds of federal test procedure driving cycle, as specified in the Code of Federal Regulations, Title 40, Part 86, Subpart 8, revised 1993) emissions by after-treatment methods can be grouped into three broad categories: (1) thermal management of the catalytic converter, including low-mass manifolds, double-walled exhaust pipes, electrically heated catalysts, exhaust-gas burners, exhaust-gas igniters, and insulated converters (with vacuum or refractory material); (2) placement of the converter closer to the exhaust manifold; and (3) management of the interaction between the hydrocarbons and the catalyst, using hydrocarbon adsorbent or traps in the exhaust. However, durability, fuel penalty, additional capital costs, unwanted heat in the engine compartment, and the complexity of these systems limit their application in vehicles.

On the other hand, a potentially attractive alternative is to control the emissions at the source itself (i.e., during combustion). One type of in-cylinder emission control is to introduce oxygen-enriched air instead of ambient air to the air intake of the engine. Use of such oxygen-enriched air can potentially reduce CO and HC emissions from a spark ignition engine, even during start-up and warming up periods because oxygen enrichment of the intake air reduces the emissions from the engine rapidly (even when the engine is cold). As a result, it helps to minimize the converter limitations during the cold phase and should improve converter efficiency. This method has the advantage of fewer add-on components, of lesser mechanical complexities, of not altering the fuel economy of the engine, and of an easier to modify system (the air intake system is easier to modify than the exhaust system).

Even though the oxygen enrichment of the intake air in spark ignition engine-powered vehicles results in the lowering of cold-phase HC and CO emissions in the exhaust of the vehicle, it tends to result in an increase in NOx in the exhaust. To some extent, the increase in NOx in the emissions has been offset by newer NOx control technologies that can remove NOx from the emissions. These technologies include lean NOx catalysts and the injection into the exhaust gases of monatomic nitrogen induced by a pulse arc (see, for example, U.S. patent application Ser. No. 08/019,102, filed on Feb. 18, 1993 and assigned to the same assignee of record as the present application). The lack of an economical source of online oxygen equipment has made it difficult to provide a practical application of this concept. Recent developments of relatively compact oxygen-enrichment devices, such as selectively permeable membranes, has made oxygen enrichment potentially practical. Nevertheless, it is necessary to have a simple, compact mechanical system driven by the engine itself that will economically extract oxygen from the air before an oxygen-enriched air intake system can practically be used on a vehicle.

Accordingly, it is an object of the present invention to provide a new and improved method and apparatus for reducing HC and CO emissions in the exhaust of a spark ignition internal combustion engine by introducing oxygen-enriched air into the air intake of a spark ignition engine vehicle during a short period of time following the start-up of the engine.

It is another object of the present invention to provide a new and improved method and apparatus for introducing oxygen-enriched air into the air intake of a spark ignition engine vehicle by diverting the intake air through a selectively permeable membrane for a predetermined time period so that oxygen-enriched air is supplied to the engine intake manifold at least during a short period of time following the start-up of the engine.

It is yet another object of the present invention to provide a new and improved method and apparatus for introducing oxygen-enriched air into the air intake of a spark ignition engine vehicle by diverting the intake air through a selectively permeable membrane for a predetermined time period so that oxygen-enriched air is supplied to an air plenum and from the air plenum into the engine intake manifold at least during a short period of time following the start-up of the engine.

Summary of the Invention

In accordance with these and many other objects of the present invention, an oxygen-enriched air intake system for a spark ignition internal combustion engine embodying the present invention includes an air supply control system that enables oxygen-enriched air to be utilized as the intake of the engine after ambient air is processed in a selectively permeable membrane device. The flow of air from the air intake filter of the engine is controlled by an air intake bypass valve that is provided in the intake air flow path downstream of the air filter. During normal operation of the spark ignition engine, ambient or atmospheric air from the air filter flows directly through the closed air intake bypass valve and a closed engine intake bypass valve into an intake manifold of the engine.

To decrease the amount of carbon monoxide (CO) and hydrocarbon (HC) emissions that tend to be produced by the engine during a short period of time after the engine is started, both the air intake and engine intake bypass valves are open so that the intake manifold is supplied with oxygen-enriched air for that short period of time. With the air intake bypass valve open, ambient air from the air filter is diverted to flow through a secondary path that includes a selectively permeable membrane device. The ambient air being diverted through the secondary path is drawn through the permeable membrane device due to the vacuum being produced at the intake manifold of the engine. As the air flows through the permeable membrane device, a predetermined amount of nitrogen is separated from the air so that the air flowing from the membrane device contains about 23-25% oxygen. As a result, oxygen-enriched air is supplied through the open engine intake bypass valve into the engine intake manifold.

After a specified time period (for example, a few minutes) of engine operation following the start-up of the engine, both the air intake bypass valve and the engine intake bypass valve are closed so that air from the air intake filter is not diverted through the secondary air path. As a result, ambient air flows directly from the air filter through the closed air intake and engine intake bypass valves to the engine intake manifold.

The air intake and engine intake bypass valves preferably are set to normally be closed so that ambient air from the air intake filter flows directly to the engine intake manifold. These bypass valves will be activated electronically to close for a desired period of time as the engine is started to divert ambient air from the air intake filter through the permeable membrane device to the engine intake manifold.

In one alternate embodiment of the present invention, a compressor is disposed in the secondary path upstream of the membrane device between the air intake bypass valve and the membrane device. The compressor is used to pressurize the diverted air to several atmospheres on the upstream side of the membrane device while the downstream side of the membrane device is maintained at atmospheric pressure. The resulting differential pressure enables the regulation of the degree of oxygen enrichment by the membrane device. An air plenum can be used in this configuration between the membrane device and the engine intake manifold to regulate the flow of oxygen-enriched air into the intake of the engine and to provide a reservoir for the oxygen-enriched air.

In another alternate embodiment of the present invention, the secondary path through which the ambient air is diverted when the air intake bypass valve is opened includes a blower on the upstream side of the membrane device and a vacuum pump and an air plenum on the downstream side of the membrane device. A differential pressure is produced across the membrane device due to the pressurizing by the blower of the ambient air being diverted through the secondary path to slightly above atmospheric pressure on the upstream side of the permeable membrane device and the vacuum being maintained by the vacuum pump on the other, downstream side of the permeable membrane device. As a result, the diverted air flows through the permeable membrane device and a predetermined amount of nitrogen is separated from the air so that the air flowing through the vacuum pump into the air plenum contains about 23-25% oxygen. The reservoir of oxygen-enriched air within the air plenum will be replenished as the oxygen-enriched air is supplied from the air plenum through the open engine intake bypass valve into the engine intake manifold. Any oxygen-enriched air trapped in the air plenum and in the secondary air flow path when the bypass valves are closed will remain therein for utilization in the next start-up operation of the engine. A pressure relief valve is provided in the air plenum to prevent the oxygen-enriched air from becoming supercharged or over pressurized. In some instances, the blower is not necessary because the vacuum pump provides a sufficient differential pressure across the membrane device to draw the ambient air through the membrane device.

In still a further alternate embodiment of the present invention, the flow of air from the air intake filter of the engine is controlled by an air intake bypass valve that is provided in the intake air flow path downstream of the air filter. During normal operation of the spark ignition engine, ambient or atmospheric air from the air filter flows directly through the closed air intake bypass valve into an air plenum and then into an intake manifold of the engine.

During a short period of time after the engine is started, the air intake bypass valve is partially opened so that a portion (for example, about 20%) of ambient air from the air filter is diverted to flow through a secondary path that includes a blower on the upstream side of a membrane device and a vacuum pump on the downstream side of the membrane device between the membrane device and the air plenum. The ambient air being diverted through the secondary path is drawn through the permeable membrane device due to the differential pressure established across the membrane device by the blower and the vacuum pump. As the air flows through the permeable membrane device, a predetermined amount of nitrogen is separated from the air so that the air flowing from the membrane device contains, for example, about 30% oxygen. This oxygen-enriched air flows into the air plenum where it is mixed with the ambient air flowing into the air plenum from the air intake valve. As a result, oxygen-enriched air containing about 23-25% by volume of oxygen is supplied from the air plenum into the engine intake manifold.

After a specified time period (for example, a few minutes) of engine operation following the start-up of the engine, the air intake bypass valve is closed so that no portion of the ambient air from the air intake filter is any longer diverted through the secondary air path. As a result, ambient air flows directly from the air filter through the closed air intake bypass valve and the air plenum into the engine intake manifold.

The blower or compressor for pressurizing the diverted ambient air and the vacuum pump for drawing the air through the permeable membrane device can be mechanically driven from the engine or electrically driven with power from the engine's electrical system (i.e., the alternator). Oxygen-enriched intake air also can be used continuously to boost the power output of an engine during normal conditions. In such a situation, a suitable NOx aftertreatment device should be used to lower any NOx emissions in the exhaust of the engine.

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 an internal combustion engine with an air intake control system which supplies oxygen-enriched air to the engine and which embodies the present invention;

FIG. 2 is a diagrammatic illustration of an internal combustion engine with an alternate embodiment of air intake control system which supplies oxygen-enriched air to the engine and which embodies the present invention;

FIG. 3 is a diagrammatic illustration of an internal combustion engine with another alternate embodiment of air intake control system which supplies oxygen-enriched air to the engine and which embodies the present invention;

FIG. 4 is a diagrammatic illustration of an internal combustion engine with yet another alternate embodiment of an air intake control system which supplies oxygen-enriched air to the engine and which embodies the present invention;

FIG. 5 is a diagrammatic illustration of an internal combustion engine with still another alternate embodiment of an air intake control system which supplies oxygen-enriched air to the engine and which embodies the present invention;

FIG. 6 is a partially exploded perspective view of an oxygen-enrichment device that can be used in the air intake control systems of FIGS. 1-5; and

FIGS. 7A-7C are illustrations of components from the oxygen-enrichment device of FIG. 6.

Detailed Description of the Preferred Embodiment

Referring now more specifically to FIG. 1, therein is disclosed a diagrammatic representation of an internal combustion engine (10) having an intake line or duct (12) for receiving air that is to be combined with fuel in the engine (10) and an exhaust line or duct (14) through which is expelled exhaust gases produced by the engine (10). The exhaust gases contain a number of different pollutants, including carbon monoxide (CO), hydrocarbon (HC), and oxides of nitrogen

(NOx). To limit the amount of CO and HC that is present in the exhaust gases expelled from the engine (10) through the exhaust line (14), particularly during the short period of time after the engine is started, the engine (10) is provided with an air supply control system that is generally designated by the reference numeral (16) and that embodies the present invention. The air supply control system (16) includes an oxygen-enrichment or membrane device (18) that separates nitrogen from air so that oxygen-enriched air is produced. To decrease the amount of CO and HC emissions in the exhaust line (14) that tend to be produced by the engine (10) during a period of time just after the engine (10) is started, both an air intake bypass valve or air-directing device (20) and an engine intake bypass valve or air-directing device (22) are opened so that ambient air from an air filter or inlet (24) is diverted to flow through a secondary path (26) that includes the membrane device (18). The ambient air is diverted from the air filter (24) through the secondary path (26). The portion of the diverted ambient air that becomes oxygen-enriched in the oxygen-enrichment device (18) is supplied through the open engine intake bypass valve (22) and through the engine intake line (12) into the engine (10).

After a specified time period (for example, 2-3 minutes) of engine operation following the start-up of the engine (10), both the air intake bypass valve (20) and the engine intake bypass valve (22) are closed so that air from the air intake filter (24) is no longer diverted through the secondary air path (26). As a result, ambient air flows directly from the air filter (24) through the closed air intake bypass valve (20) and the engine intake bypass valve (22) to the air intake line (12) of the engine.

As previously indicated, ambient air flows directly from the air filter (24) through an air duct (28) to the air intake bypass valve (20). The air intake bypass valve (20) is normally closed so that the ambient air from the air filter (24) flows past the closed air intake bypass valve (20) and through an air duct (30) (as indicated by arrows 30a and 30b) to the engine intake bypass valve (22). The engine intake bypass valve (22) also remains closed during normal operations of the engine (10). Consequently, ambient air flows through the engine intake bypass valve (22) and the intake line (12) (as indicated by the arrow 12a) into the intake manifold of the engine (10) so that it can be combined with a combustible fuel.

The engine (10) may be any type of internal combustion engine in which air supplied through the intake line (12) is combined with a combustible fuel. As is the case with all such internal combustion engines, exhaust gases are produced that are expelled through the exhaust line (14) (as indicated by an arrow 14a). These exhaust gases typically will include pollutants such as carbon monoxide (CO), hydrocarbon (HC), and oxides of nitrogen (NOx). The carbon monoxide (CO) and hydrocarbon (HC) are particularly prevalent in the emissions being expelled through the exhaust line (14) during the first few minutes of operation of the engine (10) after it is started. This is due in part to the fact that the engine block and exhaust manifold of the engine (10) are cold and the emissions are not efficiently converted by the catalytic converter that can be used with the engine (10) when it has not reached a sufficient elevated temperature. Moreover, it is a common practice to operate spark ignition engines, like the engine (10), with richer fuel-air mixtures during initial start-up and warming-up periods for proper operating driveability and acceleration. However, the rich fuel mixture tends to result in an increase in the carbon monoxide (CO) and hydrocarbon (HC) in the emissions being expelled through the exhaust line (14). To limit the amount of such pollutants in those emissions, oxygen-enriched air is supplied through the air intake line (12) to the engine (10).

The air intake bypass valve (20) and the engine intake bypass valve (22) preferably are set to normally be closed so that ambient air from the air intake filter (24) flows directly to the engine

(10) through the air lines (28, 30 and 12 as indicated by the arrows 30a, 30b and 12a). As the engine (10) is started, both the air intake bypass valve (20) and the engine intake bypass valve (22) will be activated electronically to open for a desired period of time. When the air intake bypass valve (20) is opened, air flowing in the duct (28) will be diverted into the secondary path (26) so as to flow into an air duct or input line (32) (as indicated by an arrow 32a) toward the membrane device (18). The diverted ambient air will flow in the air duct (32) because of the vacuum being produced at the engine intake manifold through an outlet line (34), the open engine bypass valve (22) and the intake line (12) so that the diverted air is drawn through the oxygen enrichment device (18). In this vacuum mode of operation, the vacuum maintained at the outlet line (34) on the downstream side of the membrane device (18) causes the oxygen to permeate from the higher pressure, upstream side of the membrane device (18) at the inlet line (32) to the lower pressure, downstream side of the membrane device (18) at the outlet line (34). This vacuum mode is typically energy efficient primarily because a vacuum is only applied to the downstream side of the membrane device (18) and requires no additional components to affect the flow of the diverted air through the membrane device (18).

The oxygen enrichment device (18) is adapted to separate oxygen and nitrogen present in the air being supplied through the input line (32) so as to produce oxygen-enriched air (permeate) at the outlet line (34) and nitrogen-enriched air (retentate) at another outlet line (36). The oxygen enrichment device (18) 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 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.

One configuration of such an oxygen enrichment device (18) is illustrated in FIGS. 6 and 7A-7C. As shown in FIG. 6, the oxygen enrichment device (18) may be in the form of cylindrical outer housing (38) with opposed end caps (40 and 42) closing the ends of the housing (38) and providing respectively, an input (44) to be connected to the input line (32) and an output (46) to be connected to the output line (34).

As illustrated in FIGS. 6 and 7A, three cartridges (48, 50, and 52) are disposed within the housing (38). Each of the cartridges (48, 50, and 52) contain fiber bundles, such as bundle (54) illustrated in FIG. 7B. The fiber bundles (54) can be formed of hollow polymer fibers in an asymmetric structure (a hollow fiber 56 is illustrated in FIG. 7C).

The capability of the oxygen enrichment device (18) [in terms of throughput capacity and ability to separate the components in the ambient air flowing through the oxygen-enrichment device (18) from the input (44) to the output (46)] is determined in part by the properties of the membrane material coated (inside or outside) on the hollow fibers (56) (permeability and selectivity) and by the operating conditions of temperature, differential pressure across the oxygen enrichment device (18) and the percent recovery. The size of the housing (38) of the oxygen enrichment device (18) depends on the skin thickness of the coating, the arrangement of the fibers (56) for best packing density and geometry, and the mode of operation [vacuum, pressure or a combination of both across the oxygen enrichment device (18)]. Because the air flow control system (16) needs to be mounted in the engine compartment of an automobile, the size of the housing (38) is a significant limiting design criteria for the air flow control system (16) for automotive engine applications. While membrane material can be made of rubbery polymers (silicon rubber) or glassy polymers (ethyl cellulose and polysulfone), perfluorodioxole membrane material of the type disclosed in U.S. Pat. No. 5,051,114 possibly is more suitable for the hollow fibers (56) particularly in automobile applications.

The particular percentage of oxygen contained within the air flowing out from the oxygen enrichment device (18) through the air duct (34) into the intake line (12) of the engine (10) can be adjusted by providing the proper oxygen enrichment device (18). In this regard, the membrane surface area and the pressure differential across the membrane device (18) will in part determine the amount of nitrogen separated from the ambient air and thereby the percentage of oxygen within the air flowing into the engine (10). While the particular percentage of oxygen within the air flowing into the engine (10) can be varied depending on the performance requirements of the engine (10), typically the air should have about 21%-25% oxygen by volume and preferably, about 23%-25% oxygen by volume. With such a percentage of oxygen, the oxygen-enriched air that is supplied to the air intake line (12) of the engine (10) during the first few minutes after the engine (10) is started will tend to minimize the amount of HC and CO in the exhaust emissions flowing out from the engine (10) in the exhaust line (14) during this start-up period of time.

The vacuum mode of air control system (16) disclosed in FIG. 1 has the economic advantage of not requiring auxiliary components that might otherwise require additional power and space to draw the air through the membrane device (18). However, the air control system (16) of FIG. 1 does not ensure constant oxygen-enriched air flowing to the air intake line (12) of the engine (10) in part because the differential pressure across the membrane device (18) that affects the oxygen concentration in the permeate flowing from the membrane device (18) varies with the vacuum developed in the intake manifold of the engine (10). In some applications, the vacuum developed at the intake manifold of the engine (10) is not sufficient to ensure a desired concentration of oxygen-enriched air at the intake of the engine (10) irrespective of the engine intake manifold vacuum conditions. Air supply control systems (70 and 72) operating in a vacuum mode that do provide such a desired concentration of oxygen-enriched air are disclosed in FIGS. 2-3 and embody the present invention.

The air supply control system (70) is illustrated diagrammatically in FIG. 2 and includes some of the same components as the air supply control system (16). The components of the air supply control system (70) that are essentially the same as corresponding components in the air supply control system (16) are referenced by the same reference numerals. The air supply control system (70) is used with the internal combustion engine (10) that has the intake line or duct (12) for receiving air (as indicated by the arrow 12a) that is combined with fuel in the engine (10) and the exhaust line or duct (14) through which is expelled (as indicated by the arrow 14a) exhaust gases produced by the engine (10). During normal operation of the engine (10), both the air intake bypass valve (20) and the engine intake bypass valve (22) are closed so that ambient air from the air intake filter (24) flows directly from the air filter (24) through the closed air intake bypass valve (20), through the air duct (30) (as indicated by the arrows 30a and 30b), and through the closed engine intake bypass valve (22) to the air intake line (12) of the engine (10).

To decrease the amount of carbon monoxide (CO) and hydrocarbon (HC) emissions in the exhaust line (14) that tend to be produced by the engine (10) during a period of time just after the engine (10) is started, both the air intake bypass valve (20) and the engine intake bypass valve (22) are opened so that ambient air from the air filter (24) is diverted to flow to an air plenum (74) through a secondary path (76) that includes a blower (78), the membrane device (18) and a vacuum pump (80). For the first few seconds at the beginning of operation of the engine (10) after it is started, the engine (10) draws through the open engine intake bypass valve (22) oxygen-enriched air that has been stored in the air plenum (74) from a previous operation of the engine (10). The ambient air is diverted through the secondary path (76). The portion of the diverted ambient air that becomes oxygen-enriched in the oxygen enrichment device (18) is supplied to the air plenum (74). This air contains about 23-25% oxygen. As a result, the reservoir of oxygen-enriched air within the air plenum (74) will be replenished as the oxygen-enriched air flows from the air plenum (74) through the open engine intake bypass valve (22) and through the engine intake line (12) into the engine (10).

The air intake bypass valve (20) and the engine intake bypass valve (22) preferably are set to normally be closed so that ambient air from the air intake filter (24) flows directly to the engine (10) through the air lines (28, 30 and 12 as indicated by the arrows 30a, 30b and 12a). As the engine (10) is started, both the air intake bypass valve (20) and the engine intake bypass valve (22) will be activated electronically to open for a desired period of time. When the air intake bypass valve (20) is opened, air flowing in the duct (28) will be diverted into the secondary path (76) so as to flow into an air duct (82 as indicated by an arrow 82a) toward the blower (78). The blower (78) and the vacuum pump (80) can be mechanically driven from the engine (10) or electrically driven with power from the electrical system (i.e., the alternator) of the engine (10). In either case, the blower (78) and the vacuum pump (80) establishes a pressure differential across the membrane device (18) so the diverted ambient air flowing in the air duct (82) is drawn to the oxygen-enrichment device (18) through an input line (84 as indicated by an arrow 84a).

The membrane device (18) can be of the type disclosed in FIGS. 6 of the drawings in which case the input line (84) is connected to the input (44) and the output (46) is connected to an output line (86). The oxygen-enriched air (permeate) flows from the output (46) of the oxygen enrichment device (18) through the output line (86 as indicated by an arrow 86a), the vacuum pump (80), and an air duct 88 (as indicated by an arrow 88a) into the air plenum (74). The air plenum (74) provides a reservoir chamber for the oxygen-enriched air flowing from the oxygen enrichment device (18). As long as the air intake bypass valve (20) and the engine intake bypass valve (22) remain open, the air being diverted through the secondary path (76) will be oxygen-enriched, accumulate in the air plenum (74), and flow out of the air plenum (74) along an air duct (90 as indicated by arrows 90a and 90b), through the open engine intake bypass valve (22), and through the air intake line (12) into the engine (10). As a result, the air plenum (74) regulates the oxygen-enriched (permeate) air supply into the engine (10). To ensure that the air within the air plenum (74) does not become over pressurized or supercharged, a pressure relief valve (92) is used with the air plenum (74).

For the first few seconds at the beginning of operation of the engine (10), oxygen-enriched air will be supplied to the engine (10) from the air that has been stored in the plenum (74) from the previous operations of the engine (10). Thereafter, oxygen-enriched air will be continuously supplied to the air plenum (74) and thereby to the engine (10) as is described hereinabove. After a desired amount of time [for example, a few minutes of operation of the engine (10)] after it is started, both the air intake bypass valve (20) and the engine intake bypass valve (22) will revert to their normally closed condition so that ambient air is no longer diverted to the secondary path (76) and the ambient air will flow directly from the air filter (24) to the engine intake line (12). The air trapped in the air plenum (74) as well as in the secondary path (76) will remain there for utilization during the next immediate operation of the engine (10).

FIG. 3 illustrates another air supply control system (72) for supplying oxygen-enriched air to the engine (10) utilizing a vacuum mode of operation. The air supply control system (72) illustrated diagrammatically in FIG. 3 includes essentially the same components as the air supply control system (70) of FIG. 2. Consequently, the components of the air supply control system (72) which are essentially the same as corresponding components in the air supply control system (70) are referenced by the same reference numerals. Basically the air supply control systems (70 and 72) operate in essentially the same way with the only significant difference being the elimination of the blower on the upstream side of the membrane device (18). The ambient air that is diverted into a secondary path (94) when the air intake bypass valve (20) is opened flows through an air inlet duct (96 as indicated by an arrow 96a) directly into the membrane device (18) and more specifically the inlet (44) on the membrane device (18) illustrated in FIG. 6. As was the case with the air supply control system (70), vacuum is applied on the downstream, permeate side of the membrane device (18) through the outlet duct (86) by the vacuum pump (80). Without a blower on the upstream side of the membrane device (18), the differential pressure across the membrane device (18) from the inlet (44) to the outlet (46) is decreased as compared to the differential pressure established across the membrane device (18) in the air supply control system (70) disclosed in FIG. 2. This decrease in pressure differential can limit the amount of oxygen-enriched air produced in the membrane device (18) and possibly affect the purging of the retentate out from the outlet (36) of the membrane device (18). While this pressure differential across the membrane device (18) might limit the effectiveness of the air supply control system (72) as compared to the air supply control system (70), the air supply control system (72) operates in the same way as does the air supply control system (70) with the added advantage of decreasing equipment cost and the power requirements by the elimination of the blower.

The air supply control systems (16, 70 and 72) illustrated in FIGS. 1-3 operate in a vacuum mode wherein the differential pressure across the membrane device (18) is established principally by a vacuum applied to the permeate or downstream side of the membrane device (18) at, for example, the outlet (46) of the membrane device (18) in FIG. 6. This vacuum mode is particularly suited to light-duty applications. In certain applications, a higher flow rate of air is required. In such instances, an air supply control system (100) illustrated in FIG. 4 can be used and is operated in a pressurized mode.

The air supply control system (100) illustrated diagrammatically in FIG. 4 is another embodiment of the present invention and includes essentially the same components as the air supply control system (16) of FIG. 1. Consequently, the components of the air supply control system (100) that are essentially the same as corresponding components in the air supply control system (16) are referenced by the same reference numerals. Basically air supply control system (100) operates in the same fashion as the air supply control system (16) with the only significant difference being the addition of a compressor (102) on the upstream side of the membrane device (18). The ambient air that is diverted into a secondary path (104) when the air intake bypass valve (20) is opened flows through an air duct 106 (as indicated by an arrow 106a) and is pressurized by the compressor (102) to typically several atmospheres (absolute). The pressurized diverted ambient air flows through an inlet duct (108 as indicated by an arrow 108a) into the inlet (44) on the membrane device (18) illustrated in FIG. 6. As was the case with the air supply control system (16), oxygen-enriched air from the downstream, permeate side of the membrane device (18) flows through the outlet duct (34 as indicated by the arrow 34a) into the intake manifold of the engine (10) through the open engine air bypass valve (22) and the intake duct (12). Higher forces driving the air through the membrane device (18) can be obtained by using the air supply control system (100) because a higher differential pressure can be established by the compressor (102) across the membrane device (18). This higher differential pressure results in the need for a lesser membrane area in the membrane device (18). On the other hand, the air supply control system (100) requires more energy to operate in view of the large volumes of air that have to be compressed to elevated pressures. While the air supply control system (100) illustrated in FIG. 4 does not include an air plenum to provide a reservoir for the oxygen-enriched air, an air plenum like the air plenum (74) used in the air control system (72) can be used between the membrane device (18) and the engine intake bypass valve (22) if the oxygen-enriched air flowing into the engine (10) needs to be further regulated.

Another air supply control system (110) embodying the present invention is disclosed in FIG. 5. This air supply control system (110) operates in a mixed mode (partially pressure and partially vacuum) and embodies the present invention. The air supply control system (110) includes essentially the same components as the air supply control system (70) of FIG. 2. Consequently, the components of the air supply control system (110) that are essentially the same as corresponding components in the air supply control system (70) are referenced by the same reference numerals. Basically the only difference between the air supply control systems (70 and 110) is the elimination of the engine intake bypass valve (22) used in the air supply control system (70). Instead of such a valve, ambient air flowing through an air intake bypass valve (112) and oxygen-enriched air flowing from the membrane device (18) are mixed in an air plenum (114) so that air with the desired oxygen concentration can be supplied to the air intake line (12) of the engine (10).

The air supply control system (110) is used with the internal combustion engine (10) that has the intake line or duct (12) for receiving air (as indicated by the arrow 12a) that is combined with fuel in the engine (10) and the exhaust line or duct (14) through which is expelled (as indicated by the arrow 14a) exhaust gases produced by the engine (10). During normal operation of the engine (10), the air intake bypass valve (112) is closed so that ambient air from the air intake filter (24) flows directly from the air filter (24) through the closed air intake bypass valve (112), through the air duct (30 as indicated by the arrows 30a and 30b), and through an air plenum (114) to the air intake line (12) of the engine (10).

To decrease the amount of carbon monoxide (CO) and hydrocarbon (HC) emissions in the exhaust line (14) that tend to be produced by the engine (10) during a period just after the engine (10) is started, the air intake bypass valve (112) is opened, resulting in a portion of the ambient air from the air filter (24) being diverted to flow to through a secondary path (116). For example, about 20% of the air flowing in the air duct (28) from the air filter (24) is directed into the secondary path (116) with the remaining 80% of the air flowing from the air filter (24) continuing to flow through the air duct (30) to the air plenum (114). The secondary air path (116) includes the blower (78), the membrane device (18) and the vacuum pump (80). When the engine (10) is initially started, the engine (10) draws air from the air plenum (114) that is flowing through the air intake bypass valve (112) and through the air duct (30). After a few seconds, the portion of the ambient air that has been diverted through the secondary path (116) and therefore through the oxygen enrichment device (18) is supplied to the air plenum (114). This air contains about 30% oxygen by volume. When this oxygen-enriched air is combined in the air plenum (114) with the ambient air flowing into the air plenum (114) from the air duct (30), the air within the air plenum (114) will be oxygen-enriched with about 23%-25% oxygen by volume. This oxygen-enriched air then flows through the engine intake line (12) into the engine (10).

The air intake bypass valve (112) preferably is set to normally be closed so that ambient air from the air intake filter (24) flows directly to the engine (10) through the air lines (28 and 30 as indicated by the arrows 30a, 30b), the air plenum (114) and the air line (12 as indicated by the arrow 12a). As the engine (10) is started, the air intake bypass valve (112) will be activated electronically to open for a desired period of time. When the air intake bypass valve (112) is opened, not all of the air flowing in the duct (28) is diverted into the secondary path (116). Instead, only about 20% of the air flowing in the air duct (28) will be diverted so as to flow into the air duct (82 as indicated by an arrow 82a) toward the blower (78). The blower (78) and the vacuum pump (80) can be mechanically driven from the engine (10) or electrically driven with power from the electrical system (i.e., the alternator) of the engine (10). In either case, the blower (78) and the vacuum pump (80) establishes a pressure differential across the membrane device (18) so the diverted ambient air flowing in the air duct (82) is drawn to the oxygen enrichment device (18) through the input line (84 as indicated by an arrow 84a).

The membrane device (18) can be of the type disclosed in FIGS. 6 in which case the input line (84) is connected to the input (44) and the output (46) is connected to an output line (86). The oxygen-enriched air (permeate) flows from the output (46) of the oxygen enrichment device (18) through the output line (86) (as indicated by an arrow 86a), the vacuum pump (80), and the air duct (88 as indicated by an arrow 88a) into the air plenum (114). The air plenum (114) provides a reservoir chamber for the oxygen-enriched air flowing from the oxygen-enrichment device (18) and provides a mixing chamber for mixing of the oxygen-enriched air form the secondary path (116) and the ambient air from the air duct (30). As long as the air intake bypass valve (112) remains open, the air being diverted through the secondary path (116) will be oxygen-enriched, flow into the air plenum (114) where it is mixed with ambient air and flow out of the air plenum (114) through the air intake line (12) into the engine (10).

For the first few seconds at the beginning of operation of the engine (10), ambient air will be supplied to the engine (10) from the air that is flowing into the air plenum (114). Thereafter, oxygen-enriched air will be continuously supplied to the air plenum (114) and mixed with ambient air so that the mixed air (i.e., oxygen-enriched air) will be supplied to the engine (10) as is described hereinabove. After a desired amount of time [for example, a few minutes of operation of the engine (10)] after it is started, the air intake bypass valve (112) will revert to its normally closed condition so that no portion of the ambient air is any longer diverted to the secondary path (116) and the engine (10) will be supplied ambient air.

Use of the air supply control system (110) in FIG. 5 in a mixed mode of operation enables a higher differential pressure to be maintained across the membrane device (18). As a result, higher oxygen-enrichment levels can be obtained so that a lower volume of air needs to be treated by the membrane device (18). Nevertheless, the system (110) ensures that the engine (10) will be supplied with air even if any of the components in the secondary path (116), including in particular the membrane device (18), fails to deliver oxygen-enriched air because ambient air is being supplied at all times to the air plenum (114). Even though higher differential pressures must be established across the membrane device (18) in the control (110). the power requirements are comparable to a vacuum mode of operation [for example, the control system (70)] because a lower level of air flow is needed across the membrane device (18).

Obviously, many modifications and variations of the present invention are possible in light of the above teachings. In this regard, the air intake valve (20) and the engine intake bypass valve (22) can be otherwise selectively opened other than for the short period of time after the engine (10) is initially started to boost the power output of the engine (10) by having oxygen-enriched air supplied to the engine intake line (12). In such a situation, a suitable NOx aftertreatment device should be used to lower any NOx emissions in the exhaust line (14) of the engine (10). 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.

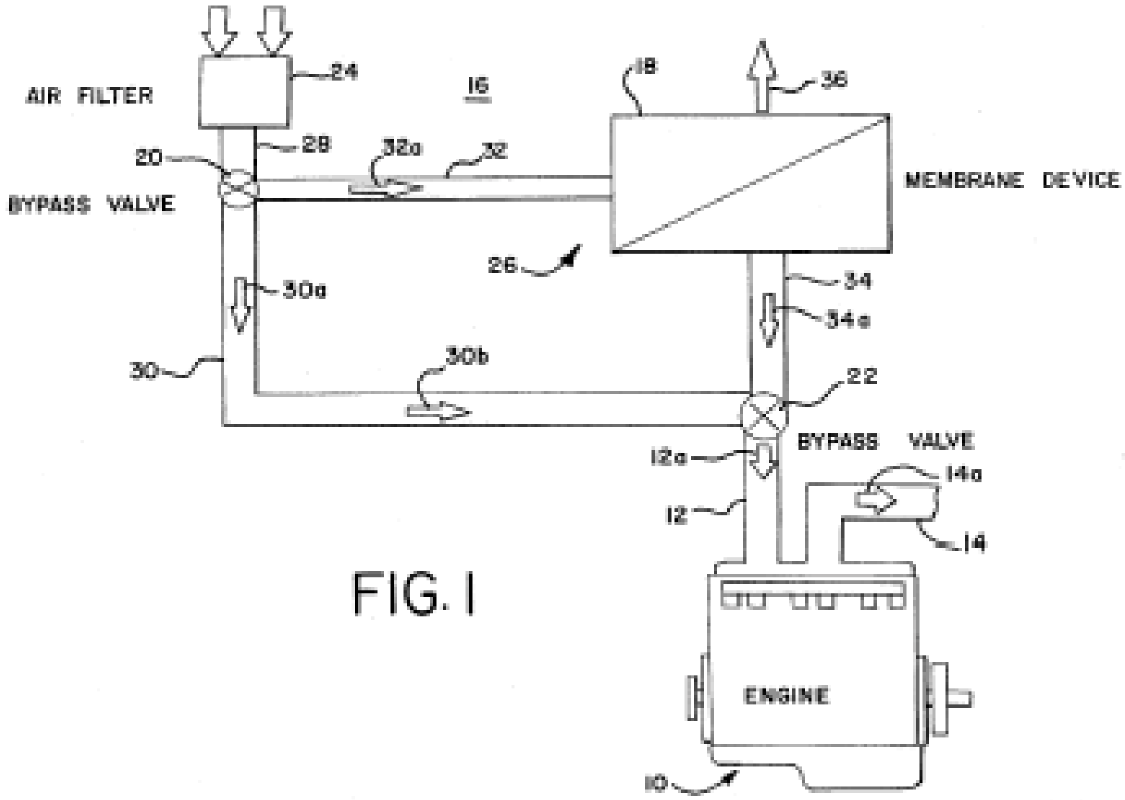
AIR FILTER
24
16
18
36
28
20
32a
32
BYPASS VALVE
MEMBRANE DEVICE
26
30a
34
34a
30
30b
22
BYPASS VALVE
12a
14a
12
14
ENGINE
10

FIG. 1

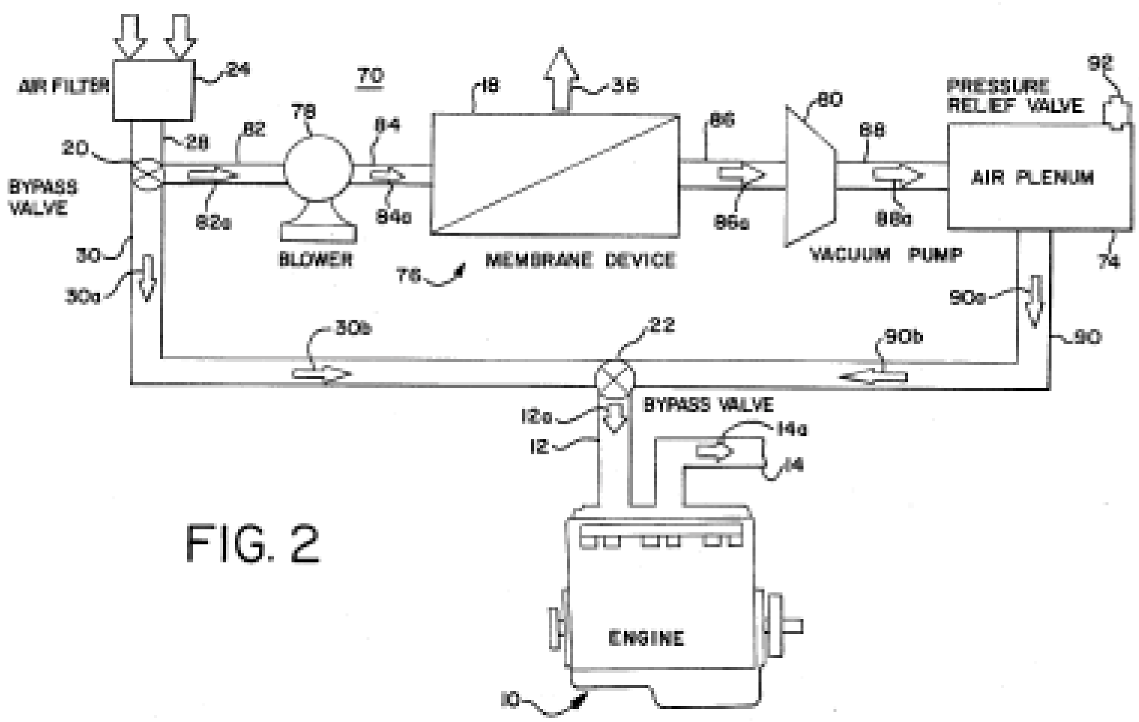
AIR FILTER
24
70
18
36
78
84
80
86
88
PRESSURE RELIEF VALVE
92
20
28
82
BYPASS VALVE
AIR PLENUM
82a
84a
86a
88a
30
BLOWER
76
MEMBRANE DEVICE
VACUUM PUMP
74
30a
90a
30b
22
90b
90
BYPASS VALVE
12a
14a
12
14
ENGINE
10

FIG. 2

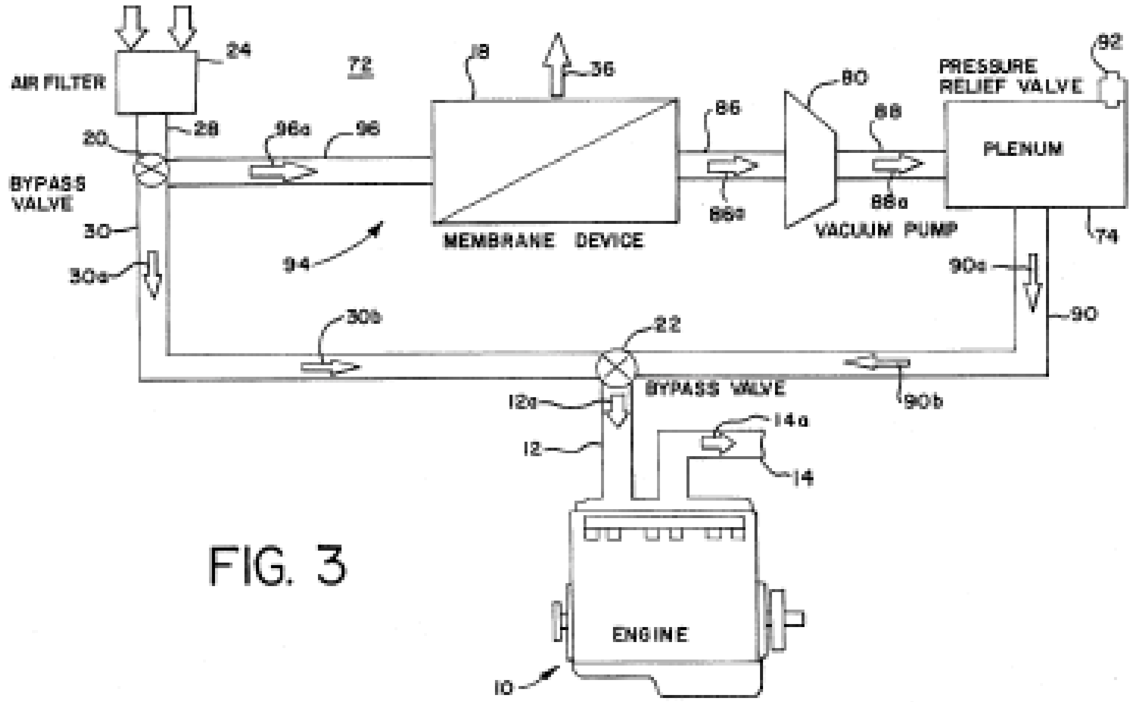
AIR FILTER
24
72
18
36
80
92
PRESSURE RELIEF VALVE
20
28
96a
96
86
88
PLENUM
BYPASS VALVE
86a
88a
30
MEMBRANE DEVICE
VACUUM PUMP
74
94
30a
90a
90
30b
22
BYPASS VALVE
90b
12a
14a
12
14
ENGINE
10

FIG. 3

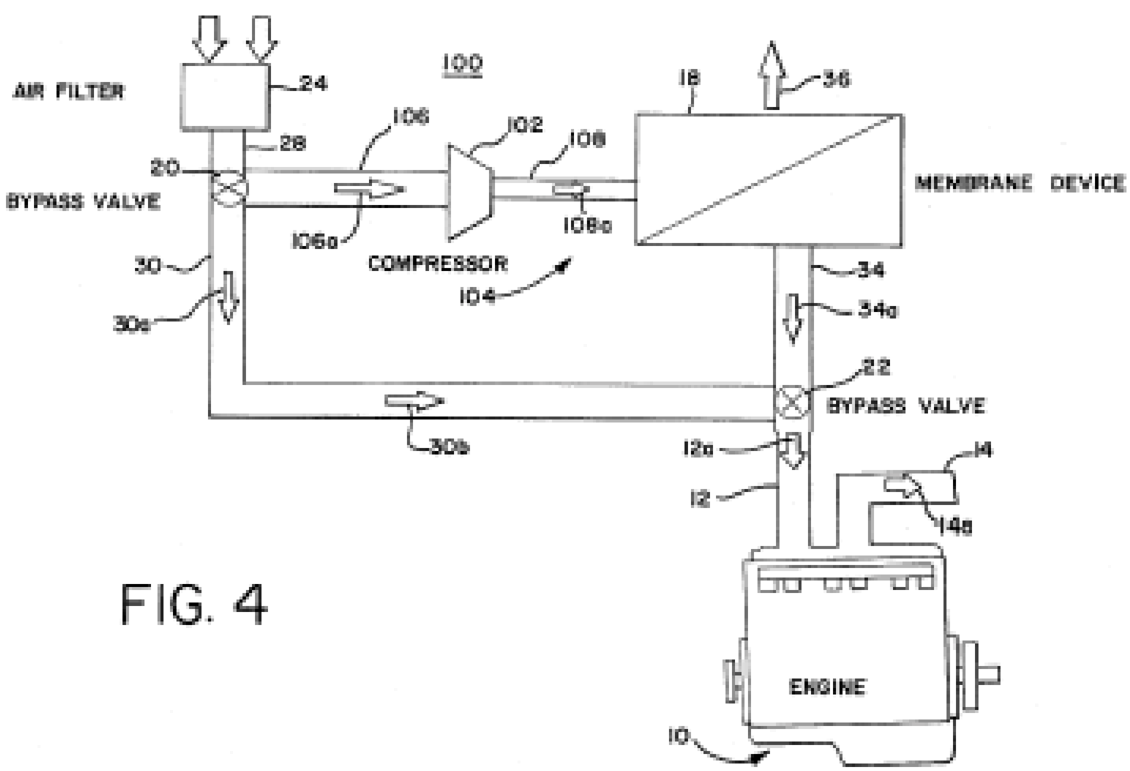
AIR FILTER
24
100
18
36
106
102
108
28
20
BYPASS VALVE
MEMBRANE DEVICE
106a
108a
COMPRESSOR
30
34
104
30a
34a
22
BYPASS VALVE
30b
12a
14
12
14a
ENGINE
10

FIG. 4

FIG. 5

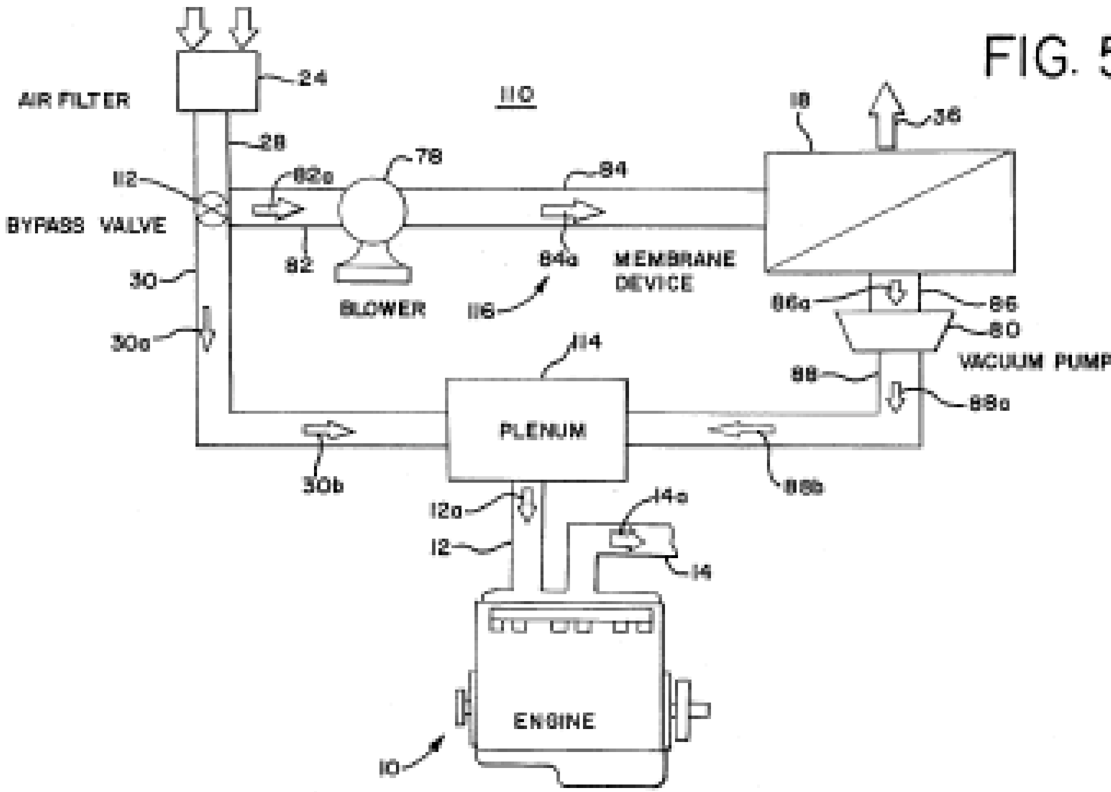
AIR FILTER
24
110
18
36
28
78
112
82a
84
BYPASS VALVE
82
84a
MEMBRANE
DEVICE
30
BLOWER
116
86a
86
80
30a
114
VACUUM PUMP
88
88a
PLENUM
30b
88b
12a
14a
12
14
ENGINE
10

FIG. 6

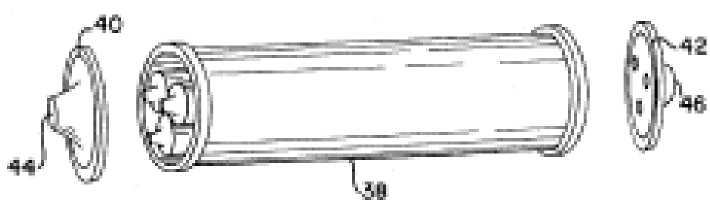
40
42
46
44
38

FIG. 7A

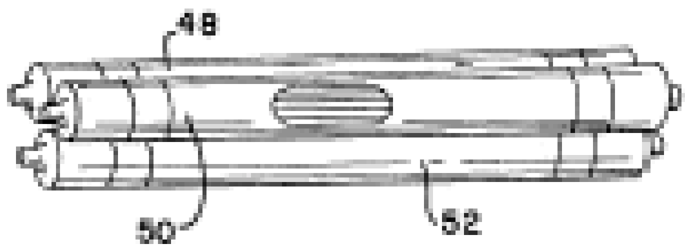

FIG. 7B

FIG. 7C