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(71) Applicant *(for all designated States except US)*: **MASSACHUSETTS INSTITUTE OF TECHNOLOGY** [US/US]; Five Cambridge Center, Cambridge, MA 02142-1493 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **BROMBERG, Leslie** [US/US]; 176 Wilshire Drive, Sharon, MA 02067 (US). **COHN, Daniel, R.** [US/US]; 26 Walnut Hill Road, Chestnut Hill, MA 02467 (US). **HADIDI, Kamal** [US/US]; 38 Madison Street, Apt. 1, Somerville, MA 02143 (US). **HEYWOOD, John, B.** [US/US]; 218 Mill Street, Newton, MA 02460 (US). **RABINOVICH, Alexander** [US/US]; 404 Paradise Road #3L, Swampscott, MA 01907 (US). **WONG, Victor, W.** [US/US]; 53 Chestnut Street, Peabody, MA 01960 (US).

(74) Agent: PASTERNACK, Sam; Choate, Hall & Stewart LLP, Two International Place, Boston, MA 02110 (US).

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(54) Title: OPTIMUM USE OF FUEL REFORMERS FOR REGENERATION OF PARTICULATE FILTERS AND NOx TRAPS

(57) Abstract: Pollution control apparatus. An exhaust aftertreatment unit is fitted to the exhaust of an internal combustion engine and a fuel reformer provides hydrogen rich gas in an optimal way to the aftertreatment unit to regenerate the aftertreatment unit. It is preferred that the hydrogen rich gas be provided only to a portion of the aftertreatment unit at any time to regenerate that portion. Stored hydrogen may be used.

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OPTIMUM USE OF FUEL REFORMERS FOR REGENERATION OF PARTICULATE FILTERS AND NOx TRAPS

Background of the Invention

This invention relates to pollution control apparatus and more particularly to the regeneration of diesel particulate filters and NOx traps using fuel reformers.

Diesel engines have several advantages over other types of internal combustion engines such as durability, high efficiency, and low hydrocarbon and CO emissions. On the other hand, diesel engines have high emissions of NOx and particulates. Concerns about the adverse air quality effects of NOx and particulates have resulted in a United States requirement for large reductions of these pollutants by 2010. Recently there has also been the additional concern about the possibility that soot emission contributes significantly to global warming.

Diesel particulate filter (DPF) technology has been developed to control particulates. Diesel particulate filters trap soot but require periodic regeneration to purge the filters thus to allow them to continue to trap soot without building up an unacceptable back pressure on the engine exhaust. It is deemed unlikely that passive means of regeneration can be robust enough over wide ranges of vehicle operation to be effective. Therefore, active means of regeneration are being considered.

Active regeneration techniques are based on increasing the temperature of the DPF sufficient to burn the soot with free oxygen present in engine exhaust. For example, the increased temperature can be provided by a fuel burner that temporarily increases the temperature of the exhaust impinging on the filter. Different trap systems require different temperatures for effective regenerations; catalysts can be used to reduce the required temperature. For either a catalytic or non-catalytic system to work, however, it is necessary to generate a self-supporting burn in the filter. For a self sustaining burn to occur both increased temperature and sufficient soot loading of the DPF are needed to sustain burning of the soot during the regeneration period. Several means of providing the heat required for regeneration have been considered in the past, including the use of fuel burners, electric heating and engine management.

Fuel burners for regeneration, in addition to increasing exhaust temperature, should have the following capabilities: independent control of the regeneration initiation; ability to control regeneration rates; ability to reduce filter material cost through its ability to control regeneration rate; and ability to control exhaust chemistry through controlling the relative air/fuel ratio. See, Khair, M., A Review of Diesel Particulate Filter Technologies, SAE 2003-01-2303.

It is difficult to meet all of these requirements. Use of hydrogen rich gas from fuel reformers can provide important improvements in capability to meet them. The generation of hydrogen rich gas from fuel reformers has been disclosed in, for example, U.S. Patent No. 6,322,757, *Low Power Compact plasma Fuel Converter*, by D. R. Cohn *et al.* Fuel reformers such as the plasmatron fuel reformer disclosed in this patent have the capability of operating at a wide range of oxygen-to-carbon (O/C) ratios, from stoichiometric partial oxidation (with an oxygen-to-carbon ratio of 1), to full combustion. The use of fuel reformers to regenerate NOx and particulate traps is described in US patents 6,560,958 *Emission Abatement System* by Bromberg *et al*, and US patent 6,718,753 *Emission Abatement System Utilizing Particulate Traps* by Bromberg *et al.*

An object of the present invention is the optimum use of fuel reformers, in particular plasmatron fuel reformers, to regenerate exhaust aftertreatment systems such as diesel particulate filters and NOx traps. As will be seen, the optimum use of fuel reformers can increase the lifetime, reliability and effectiveness of diesel particulate filter technology and reduce the cost of exhaust aftertreatment systems. These improvements may be particularly important in providing practical, cost effective aftertreatment for cars and other light duty vehicles as well as heavy duty vehicles.

Summary of the Invention

The pollution control apparatus according to the invention includes an exhaust aftertreatment unit fitted to the exhaust of an internal combustion engine and a fuel reformer providing hydrogen rich gas to the aftertreatment unit to regenerate the aftertreatment unit. A preferred fuel reformer is a plasmatron reformer. The exhaust aftertreatment unit may be a particulate filter, an NOx trap or the combination of a particulate filter and an NOx trap. In a preferred embodiment the internal combustion engine is a diesel engine.

It is preferred that the fuel reformer be operated at an oxygen-to-carbon atomic ratio between 1 and complete combustion. It is preferred that the flow rate of fuel into the fuel reformer be varied during regeneration. The oxygen-to-carbon ratio of reagents entering the fuel reformer may also vary during regeneration.

In a particularly preferred embodiment, the hydrogen rich gas is provided to only a portion of the aftertreatment unit at any time. In one embodiment movable vanes are provided to localize the hydrogen rich gas to the portion of the aftertreatment unit being regenerated. The vanes may be located upstream or downstream of the aftertreatment unit.

In another embodiment, multiple injection ports are provided for introducing the hydrogen rich gas to localize the hydrogen rich gas to the portion being regenerated. Flow monitoring apparatus may be provided to determine the timing and/or duration of regeneration at a given portion of the aftertreatment unit. Suitable flow monitoring apparatus includes flow meters and pressure transducers. Valves may be provided to control the timing and/or duration of regeneration at a given portion of the aftertreatment unit.

In yet another embodiment the aftertreatment unit comprises a carousel containing a plurality of particulate filter cartridges or NOx trap cartridges. In this embodiment, at least one of the particulate filter cartridges or NOx trap cartridges receives the hydrogen rich gas for regeneration and at the same time at least another cartridge receives the engine exhaust. In a preferred embodiment the hydrogen rich gas mixes with exhaust gas upstream of the particulate filter whereby particulates combust with free oxygen in the exhaust gas. In another embodiment, hydrogen rich gas does not mix with the exhaust gas upstream of a NOx trap whereby a reducing environment required for regeneration is provided with a minimum fuel penalty, while the engine is operating in a lean mode (with excess oxygen).

In yet another embodiment, exhaust gas instead of air is introduced into the fuel reformer to provide a source of oxygen. In another embodiment, a heat exchanger is provided to transfer heat from the exhaust gas to the fuel reformer.

Brief Description of the Drawings

Figs. 1a and 1b are schematic illustrations of embodiments of the invention utilizing exhaust gas as an oxidant for the fuel reformer. Fig. 1a is an embodiment wherein the exhaust gas input to the reformer comes from upstream of the aftertreatment unit. Fig. 1b is an embodiment wherein the exhaust gas input to the reformer comes from downstream from the aftertreatment unit.

Fig. 2 is schematic illustration of an embodiment of the invention that does not use exhaust from the engine as an oxidant for the fuel reformer.

Figs. 3a and 3b are schematic illustrations of embodiments of the invention using multiple hydrogen rich gas injection points. Fig. 3a is an embodiment with coflow, without valving. Fig 3b is an embodiment with backflow and valving.

Figs. 4a and 4b are schematic illustrations of embodiments of the invention using (a) flow meters to control regeneration and (b) with sensors to control end of regeneration.

Fig. 5 is a schematic illustration of an embodiment of the invention including a heat exchanger to preheat air and fuel before entry into a plasmatron fuel reformer.

Fig. 6 is a schematic illustration of an embodiment of the invention having a plasmatron fuel converter placed in a side-stream of exhaust gas.

Fig. 7 is a schematic illustration of an embodiment of the invention in which a plasmatron fuel converter is located in line with the exhaust gas.

Fig. 8a is a schematic illustration of an embodiment of the invention in which exhaust gas mixes with hydrogen rich gas upstream from the aftertreatment unit.

Fig. 8b is a schematic illustration of an embodiment of the invention without mixing of exhaust gas with hydrogen rich gas upstream from the aftertreatment unit.

Fig. 9 is a schematic illustration of an embodiment of the invention in which a plasmatron fuel reformer is located inside an exhaust system.

Fig. 10 is a schematic illustration of an embodiment of the invention with filter cartridges mounted on a carousel.

Figs. 11a and 11b are schematic diagrams of axially partitioned aftertreatment systems.

Description of the Preferred Embodiment

Hydrogen rich gas is an attractive fuel for regenerating a diesel particulate filter because hydrogen rich gas has a wide flammability range and low ignition energy thereby facilitating reliable combustion in the dilute environment of an exhaust gas stream. A fuel reformer such as a plasmatron fuel reformer converts onboard fuel such as diesel fuel into hydrogen rich gas. The output of such a fuel reformer includes hydrogen, carbon monoxide, nitrogen and other light hydrocarbons in addition to water and carbon dioxide at high temperatures. Importantly, the size of the fuel reformer can be minimized by using a system that regenerates only a fraction of the diesel particulate filter at any one time.

The regeneration of the diesel particulate filter can be controlled by changing the O/C ratio of the fuel reformer and the flow rate. It may be advantageous to start regeneration with high hydrogen rich gas temperatures and flow rates, and later reduce the O/C ratio and control the diesel particulate filter regeneration by varying the flow rate of hydrogen rich gas which combusts in the filter.

It may be advantageous with respect to the present invention to operate at oxygen-to-carbon ratios outside the typical ratio from partial oxidation (O/C ~ 1) up to and including stoichiometric combustion. Lower oxygen-to-carbon ratios (O/C < 1) will result in the generation of large amounts of light hydrocarbons (ethane, ethylene, and higher), useful when the engine is operating at relatively low flow rates (in this case, large heating value of reformate at lower temperatures). Further, operating at O/C higher than combustion (lean combustion) would result in lower temperature, oxygen-rich (with free oxygen) product gases that could prevent overheating of the reformer unit or any downstream components including a trap being regenerated.

There are several embodiments that can be used for partial regeneration of the filter. For example, it is possible to use a vane either upstream of the diesel particulate filter or downstream of the filter. Because it is difficult to completely seal a section of a DPF in the environment of a diesel engine exhaust it is preferable to inject the hydrogen rich gas and oxidizer upstream of the diesel particulate filter. However, for some applications the regeneration of an exhaust aftertreatment device can be done by flowing the exhaust from the reformer in a back-flow configuration, as shown in **Fig. 3b**. This is the case when the NO_x trap has a sulfur trap upstream. In a back flow configuration the sulfur regenerated from the trap will not contaminate the NO_x trap.

The oxidant may be free oxygen present in engine exhaust as shown in **Fig. 1a** (instead of using a backflow approach). As shown in **Fig. 1a** exhaust **10** from an engine (not shown) passes through a diesel particulate filter **12** in an exhaust aftertreatment unit **14**. Part of the exhaust **10** is introduced into a plasmatron fuel reformer **16** along with fuel **18**. The plasmatron fuel reformer **16** generates hydrogen rich gas **20** that is directed onto a portion of the diesel particulate filter **12** by a movable vane **22**. As the movable vane **22** moves, the hydrogen rich gas regenerates different portions of the diesel particulate filter **12**. **Fig. 1b** shows the use of clean exhaust **11** (from downstream from the aftertreatment unit) as the oxidizer for the reformer **16.**

If the engine whose exhaust is being treated is operated at stoichiometric or nearly stoichiometric combustion there will not be sufficient free oxygen to serve as an oxidant for the plasmatron fuel reformer **16**. In this case, as shown in **Fig. 2**, air **24** is introduced into the plasmatron fuel reformer **16** to provide the requisite oxidant.

In the regeneration process illustrated in **Figs. 1a, 1b** and **2** the vane **22** is stationary while a given portion of the DPF is being regenerated. The vanes move to regenerate a different section of the filter. It is contemplated that the vanes may rotate in the same direction or oscillate. It is preferable that after regeneration the vane will move away from the diesel particulate filter in order that the exhaust is exposed to the entire cross-sectional area of the filter. In this way it is possible to minimize the size of the diesel particulate filter for those cases when the time between regeneration is longer than a regeneration time. This situation is the case when regenerating diesel particulate filters.

As an alternative, the hydrogen rich gas **20** is preferentially introduced at a location upstream of, but proximate to, the diesel particulate filter **12** in such a way that the hydrogen rich gas goes through a fractional section of the DPF **12**. This preferential introduction can be accomplished with a single point of injection that moves with respect to the diesel particulate filter **12** or it could be performed by using multiple, stationary points of injection. This latter embodiment as shown in **Fig. 3a**. A set of tubes **30** controlled by valves **32** introduce hydrogen rich gas **20** at multiple injection points as shown in the figure.

Both the use of a moving single injection point illustrated in **Figs. 1a, 1b** and **2** or multiple injection points shown in **Fig. 3a** are special cases of non-uniform distribution of fuel in the exhaust upstream from the diesel particulate filter **12**. It is intended that any means of regenerating the diesel particulate filter **12** forms a part of this disclosure as will be appreciated by those of ordinary skill in the art. **Fig. 3b** shows a backflow configuration for the regeneration of the aftertreatment unit. A valve **31** is shut-off during regeneration, while the other valves **33** remain open.

As discussed above, the fuel reformer **16** can operate with fresh air as the oxidant or it can use the free oxygen present in the exhaust (either upstream or downstream from the aftertreatment unit) of engines that operate lean such as diesel engines and lean-operated spark ignition engines. It should also be noted that the diesel particulate filter **12** could be a single block or comprise multiple blocks. A preferred fuel reformer is a plasmatron fuel reformer since such reformers have been shown to effectively, rapidly and robustly convert even hard to reform fuel such as diesel without the production of soot.

With reference now to **Fig. 4a** flow meters **40** monitor flow through the diesel particulate filter **12**. The flow meters **40** may be an anemometer, measuring gas speed. The output of the flow meters **40** goes into a control unit **42** that communicates with the valve **32** to select the location of particulate filter regeneration. Thus, if part of the filter **12** is plugged, flow through that region is decreased. **Fig. 4b** is an embodiment including sensors **41** to control the end point of regeneration. The sensors in Fig. 4b could also be used for controlling regeneration. Temperature sensors could indicate a temperature of the aftertreatment device outside of the preferred operating regime, and appropriate changes can be undertaken by the fuel reformer to adjust the temperature.

As shown in **Fig. 5** heat from an engine **50** may pass through a heat exchanger **52** to preheat the air and fuel before entering the plasmatron fuel reformer **16**. The use of the heat exchanger **52** will decrease the amount of fuel required to raise the temperature of particulates in the emission control device **54**.

It is well known in burner applications that pre-heating the fuel prior to its aerosolization helps decrease its viscosity and therefore facilitates its atomization. It is contemplated that the fuel can be pre-heated prior to its aerosolization by different means such as the use of some of the exhaust heat or heat from the plasmatron reformer itself or any localized source of electric heating.

It has been shown that under some circumstances hydrocarbon fuels react homogeneously without the presence of a flame in a background gas that contains free oxygen. An example is an exhaust from an internal combustion engine that operates with excess air (as is the case in diesel engines, lean SI engines and in gasoline direct injection (GDI) engines). It is advantageous to place the hydrogen rich source as close as possible to the emission control device which could be an NO_x trap, a selective catalytic reduction (SCR) catalyst, a conventional three-way catalyst or a particulate trap, among others. This is the case even if the desired result is purely thermal because of heat losses in the pipe between the hydrogen generation sources and the emission control device.

Lean engine operation (as is the case in diesel engines) results in the presence of free oxygen in the exhaust. This free oxygen can be used as the oxidizer in a fuel reformer such as a plasmatron fuel reformer in particular. The exhaust gas is already hot, facilitating the reforming and decreasing electrical power consumption. In addition, due to the presence of water in the exhaust gas stream, soot from the diesel fuel reformer can be minimized allowing operation at reduced oxygen-to-carbon ratios. Because the main reaction is partial oxidation requiring free oxygen, the concept works only when the engine is operating in an oxygen-rich environment. However, this is the case for either GDI or diesel, and even an engine that usually operates at stoichiometric conditions could for a short time operate with free oxygen during catalyst regeneration.

It is also contemplated to locate the fuel reformer either in a side-stream with exhaust gas flowing through the device during emission control device regeneration (as shown in **Figs. 1, 3** and **4**), or it could be in-line with the exhaust flowing continuously through the fuel reformer. As before, a preferred fuel reformer is a plasmatron fuel reformer. It is possible to operate either with or without additional air.

Fig. 6 shows the plasmatron fuel reformer **16** located in a side stream of the exhaust gas. The figure shows that additional air may be injected into the plasmatron fuel reformer **16** if desired. It is contemplated to operate the system illustrated in **Fig. 6** with a fraction of the exhaust gas flowing continuously through the plasmatron fuel converter or it could be valved.

With reference now to **Fig. 7**, the plasmatron fuel reformer **16** is located in-line with the exhaust gas stream from the engine **50**. The plasmatron fuel converter **16** may operate with either a fraction of the flow, as is the case of the side stream location, or it could operate with the full exhaust. The amount of fuel is determined by the desired result. If only a thermal response is desired, it is possible to decrease the fuel flow rate, with a constant gas flow rate through the plasmatron fuel reformer, thereby operating with free oxygen-to-carbon ratios substantially greater than 1 and even below air/fuel ratios needed for combustion. In this case, the use of the plasmatron fuel converter **16** is to operate as an ignition device, igniting a mixture that otherwise would be difficult to burn. It is likely that some hydrogen will be produced but most of the fuel would be converted to combustion products.

It is also contemplated to operate by injecting amounts of fuel required for production of hydrogen by adjusting the O/C ratio. It is also possible to operate at conditions in which the exhaust produces hydrogen very efficiently by operating in an autothermal mode. The inventors have demonstrated that it is possible to operate the plasmatron reformer in such a manner that the endothermicity of reforming with CO_2 and H_2O in the exhaust balances the exothermicity of the partial oxidation reaction. This mode of operation could be used for either the in-line or side-line placement of the plasmatron fuel converter.

An advantage of partial regeneration of the diesel particulate filter is that the average temperature of the flow is not increased substantially. Otherwise, if a NO_x trap were located downstream from a DPF undergoing uniform regeneration, the temperature of the NO_x trap may exceed design limitations. By regenerating only a section of the DPF at a time, it is possible to keep the average gas temperature downstream from the DPF at lower values. For regeneration of the DPF, oxygen needs to be present for combustion of soot. It is, therefore, envisioned that the exhaust from the fuel reformer be mixed with exhaust gas upstream from a DPF as shown in **Fig. 8a**. In this case, the exhaust gas **10** mixes with the output of the reformate injector **56.**

Alternatively, the reformer can be combined with air at the exhaust of the reformer. This air can be obtained from the main air input into the reformer. This air will partially cool the reformate, and it will provide the oxygen required for the burning of the soot particles and the hydrogen-rich gas from the reformation process. The combustion of the hydrogen rich gas takes place where the reformate/air or reformate/exhaust mixture first encounters hot soot.

As is the case with the diesel particulate filter, non-uniform regeneration of a NO_x trap has the advantage of minimizing the fuel penalty for a system with a single leg in which regeneration takes place in-line. By concentrating the plasmatron reformate into a section of a NO_x trap by the methods illustrated in **Figs. 1-4**, it is possible to decrease the flow of exhaust through this section of the trap that is being regenerated. Since the amount of free oxygen that needs to be eliminated prior to reduction of the NO_x is decreased (by either mechanical means, as shown in **Figs. 1, 2 and 4**, or by gas dynamic means shown in **Fig. 3**), the fuel penalty can be substantially decreased. This technique is equivalent to that of multiple legs for regeneration without the complexity of having multiple legs, and in some cases, such as shown in **Figs. 1, 2, 3a and 4,** could be done without valving. It is advantageous to design fuel reformer injection in such a manner that the reformate does not mix with the exhaust gas thereby minimizing the hydrogen requirement. **Fig. 8b** shows the reformate injector **56** not mixing with the exhaust gases **10**.

For this application, the use of a fuel reformer with varying composition and flow rates will also be advantageous. The use of a fuel reformer operating at varying values of O/C is advantageous in that the temperature of the reformate can be traded off against the hydrogen content. At an O/C close to partial oxidation the temperature is lower and the hydrogen concentration is higher while at higher O/C, the temperature is higher but the hydrogen concentration is lower. It has been demonstrated that the regeneration temperature substantially affects the amount of hydrogen that is required for regeneration with higher temperatures (up to a point) requiring reduced hydrogen. In addition, it may be advantageous for the fuel reformer to operate at high O/C ratios closer to complete combustion during the initial phases of NO_x trap regeneration to allow for catalyst warm-up followed by cooler operation with lower O/C ratios for NO_x reduction. Thus, a fuel reformer capable of operating dynamically over a wide range of O/C ratios is advantageous for the regeneration of NO_x traps (either uniformly or non-uniformly).

Fig. 9 is a schematic diagram of an exhaust aftertreatment system in which the plasmatron fuel reformer **16** is located inside an exhaust system and is used to regenerate the exhaust control device 54. In this case, the moving vane **22** is downstream from the diesel particulate filter **12**.

A particularly preferred embodiment of the invention is shown in **Fig. 10**. In this embodiment, the plasmatron fuel reformer **16** is static and connected to a carousel **60** that has two or more emission control devices **54** arranged as cartridges within the carousel **60**. The emission control device **54** may be a diesel particulate filter or a NO_x trap. The carousel **60** rotates about an axis **62** presenting one filter cartridge **54** in front of engine exhaust **10** and another cartridge to be regenerated in front of the plasma fuel reformer **16**. Thus, while one filter cartridge is being used, another one will be regenerated at the same time by the plasma fuel reformer **16**. In the case of a diesel particulate filter, a pressure sensor (not shown) in the exhaust channel and/or a flow monitor in the exhaust of the cartridge **54** that is being used for filtration will determine when the carousel **60** will need to rotate so as to put a regenerated cartridge in front of the exhaust **10** and the used cartridge in front of the plasma fuel reformer **16** to be regenerated. The approach of a carousel with multiple cartridges will significantly reduce the size of the plasmatron fuel reformer needed in this application. The carousel **60** can be rotated by several means including pneumatic and electric actuators. The carousel **60** can also be rotated by an over pressure due to filter clogging.

In the case of a NOx trap, a NOx sensor or other sensors to determine the end of the regeneration process are used instead. NOx sensors are relatively expensive. An alternative to the use of a NOx sensor is to use a hydrogen, or CO, sensor downstream from the NOx aftertreatment device. When the NOx trap has been regenerated, there is a substantial breakthrough of reformate with hydrogen and CO. The process of regeneration of the trap can be performed until there is breakthrough of the reductant. By using a control algorithm to monitor the engine NOx emission rate and integrate it, and using multiple regeneration cycles, it should be possible to predict when the element of the NOx control device becomes saturated. This could be done by performing sequential regeneration of an NOx control element, while monitoring the amount of reformate for regeneration. Saturation of the trap occurs when the amount of reductant for regeneration becomes independent of the amount of NOx through the trap, some of it trapped (measured by integrating the expected NOx emissions, determined either by engine calibration or by using an expert system that can learn from its performance).

In addition to non-uniform regeneration by regenerating filter sections that are side-to-side (in a parallel configuration) as illustrated in the earlier figures, it is contemplated herein to non-uniformly regenerate filters that are placed downstream from one another (in a series configuration). In this case the aftertreatment unit is partitioned axially along the flow path. This scheme is particularly attractive when regeneration is exothermic. By mixing hydrogen rich gas with products of aftertreatment unit regeneration, which are usually hotter, regeneration of downstream aftertreatment units becomes easier. This method of regeneration takes advantage of reactions taking place in upstream sections.

Embodiments illustrating this concept are shown in **Figs. 11a** and **11b**. As shown in **Fig. 11a**, filter sections **70**, **72**, **76** and **78** get progressively larger downstream. By mixing hydrogen rich gas from the fuel reformer **16** with the products of filter regeneration at the various sections, the size of the reformer **16** can be made smaller because less hydrogen rich gas is required. In the case of diesel particulate regeneration, only the very first upstream unit **70** needs to be started using hydrogen rich gas from the fuel reformer **16**. The mixture ratio of hydrogen rich gas and products of filter regeneration can be controlled by a number of means, including flow diverters or modulators **79**, to control the temperature of and flow through the downstream filter sections. For example, the downstream filter section **72** can be brought to a higher temperature for initiating regeneration by closing the flow modulators 79, allowing predominantly or all of the hotter products of filter regeneration to enter a downstream filter section **72**. Once a higher temperature is reached to initiate a self-sustaining exothermic particulate incineration, additional flow can be supplied to the filter section **72** to maintain or control the regeneration by subsequently opening the flow modulators **79**. Silicon carbide matrix or other fibrous filters, in particular, are very suitable for use with the arrangement shown in **Fig. 11a**. Wire mesh filters are also suitable for this arrangement.

For a diesel particulate filter, different size particulates can be trapped in different stages. For example, the first stage **70** might trap large size particles while the second unit **72** traps smaller size particles and so forth. The filter material, pore sizes, or fiber densities of a trap medium and its construction can be optimized separately. Different size particulates may require different temperatures for regeneration. The arrangement of **Fig. 11a** allows for the flexibility needed to optimize regeneration. Alternatively, as shown in **Fig. 11b**, further flexibility is obtained by regenerating the sections **80, 82, 84** and **86** independently of upstream sections. In this embodiment, all of the flow passes through all of the filter elements **80-86**.

The regeneration temperature in the embodiments of **Figs. 11a** and **11b** can be progressively reduced through the use of different kinds of filters. Thus, the first aftertreatment unit, such as **70** or **80**, may have high temperature capability, with appropriate materials and composition, while the second and other aftertreatment filter units have reduced temperature capabilities. It is contemplated, for example, to use non-catalytic DPF filters with large pore sizes and high temperature capabilities for regeneration of the first unit **70** or **80** while downstream stages are catalytic units and trap smaller particulates.

As should be clear at this point, using hydrogen rich gas injected upstream from the DPF can substantially improve the performance of a fuel reformer/combustor DPF system. It is possible during regeneration to ignite and combust the hydrogen rich gas fuel by hot soot particles in the DPF. This is the case because hydrogen has a very low ignition energy and hot soot particles can ignite it. In addition, the reformate is usually at high temperature > 700 C. The ignition and combustion properties of hydrogen are very different from other fuels that have substantially larger ignition energy requirements and that have ignition properties not too different from that of the soot particulates (which have substantial amounts of hydrocarbons). In fact, hot spots in the case of combustion engines due to soot deposits of the cylinder are sufficient to prematurely ignite hydrogen fuel used in these engines.

The hydrogen rich gas will be combusted where it first encounters hot soot particulates in the upstream regions of the filter. As the filter regenerates and the soot in these regions is combusted the combustion zone moves downstream in the filter to those regions that still have soot. This behavior may actually result in decreased fuel consumption for diesel particulate filter regeneration. The decreased fuel consumption is due to the more localized combustion (with a smaller amount of fuel) being able to locally raise the temperature of the region to the temperatures required for non-self-sustained ignition of the particulates.

Catalytic diesel particulate filters may also be used. The combustion of the hydrogen fuel occurs inside the diesel particulate filter itself, aided by the soot and the catalyst present in the DPF. The presence of the catalyst can also help the combustion of the soot particulates, therefore offering both simplicity and optimization.

An advantage of the approach according to the invention is that the diesel particulate filter does not have to be loaded with a catalyst. Further, the particulate loading for regeneration is relatively low (lower particulate loading is required for hydrogen assisted regeneration rather than self-sustained soot ignition). In the embodiments of the invention disclosed herein, hydrogen rich gas can be used for enhancing the burning of the particulates without self-ignition of the particulates. In order for the particulates to self-ignite, relatively high temperatures and high particulate loading are required. Such high temperatures, however, have consequences on the design and durability of the diesel particulate filter both because of thermal stress as well as temperature cycling. In the case of a heavily loaded filter the self-sustaining temperature might exceed the allowable temperature of the DPF. It is therefore possible to combust particulates at lower temperatures by using hydrogen rich gas ignited by the relatively hot particulates at temperatures and particulate loading levels that are not sufficient for self-ignition. The hot particulates themselves are good sources of ignition of the hydrogen rich gas because such gas has a high temperature for self-ignition but a low energy requirement for ignition. The method according to the invention may result in improved control of the regeneration process since it is possible to turn down or even shut down the hydrogen generation. Since the soot burn is not self sustaining, it can be stopped.

A different embodiment encompassed by the invention ignites the hydrogen rich gas by using a glow plug, a spark or plasmatron-type discharge. Since the ignition of the fuel is in the exhaust flow there is a large amount of diluents so that it would difficult to ignite diesel fuel in such exhaust. When the hydrogen rich gas is generated upstream, either a glow discharge or a spark may be used to ignite the mixture because of the excellent combustion characteristics of hydrogen (which requires little energy for ignition).

In addition, if all that is desired is the thermal content of the fuel it would be possible to ignite, followed by full combustion, the fuel/exhaust by having a non-uniform distribution of fuel/exhaust gas. Richer mixtures could then be obtained which would be easier to ignite and combust followed by mixing between the hot combustion products and the rest of the exhaust gas upstream from the diesel particulate filter. Alternatively, the hot product gas resulting from the non-uniform mixing followed by combustion could be used to regenerate the diesel particulate filter in the non-uniform manner described above.

It may be advantageous during regeneration to divert some of the exhaust gases from the emission control device. In this case, the amount of hydrogen rich gas from the fuel reformer, and plasmatron reformer energy consumption in particular, could be significantly decreased. A disadvantage of this approach is the need of a high temperature valve for the purpose of diverting the hot exhaust gases flowing from the emission control device to a bypass. The diverted exhaust gas goes through a heat exchanger either separate from, or combined with, the plasmatron fuel converter. The heat exchanger warms the reagents introduced into the plasmatron fuel converter and cools down the exhaust gases thereby allowing for a low temperature valve for exhaust gas flow control. The setting of the low temperature control valve can be adjusted either to prevent most of the exhaust (with some free oxygen) from going to the emission control device, or it could allow for some exhaust gas (with some free oxygen) to go to the device. This allows some control of the chemistry in the emission control device from mostly reducing (with low amounts of free oxygen) to mostly oxidizing (with lots of free oxygen from the exhaust). Operation of a low temperature valve should be synchronized with on-off switching of the plasmatron fuel converter. When the plasmatron is operating, the valve is open and when the plasmatron is off, the valve is shut off.

When operating with a pair of emission control devices in parallel (in a tandem configuration), it would be possible to use the same scheme to regenerate one emission control device while diverting the exhaust gases to the other emission control device. In this case, there are two plasmatron reformers, each upstream from each emission control device. The plasmatron fuel converter associated with one of the emission control devices can be turned on to shut down much or all of the exhaust flow through the emission control device under regeneration.

It is also contemplated to operate the fuel reformer in a manner in which the reformate/products of combustion, flow rate and composition vary with time during the regeneration process. For a constant composition, it would be possible to modulate the flow rate by turning the device on and off at a rate fast compared with the length of the regeneration process (that is, several times during the regeneration process). In this manner, the temperature of the exhaust can be modulated. This technique is useful for controlling the temperature of the DPF and also for controlling the temperature downstream from the DPF (if there are other exhaust aftertreatment devices downstream from the DPF such as a NOx trap). Further, by modulating the flow it is possible to effectively gain dynamic range but with a device that operates at a single flow rate. Such operation simplifies the fuel reformer as it can be optimized for a single flow rate (with a single air/fuel flow that simplifies the air/fuel control system) but providing dynamic range.

A second option for pulsed operation involves changing the composition of the gas from the fuel reformer. At the start of the regeneration process the fuel reformer may operate at higher values of O/C resulting in a state closer to combustion and to lower hydrogen concentration as a result of higher temperatures. After the DPF is substantially heated (to temperatures greater than 400°C) the air/fuel flow rate may be adjusted to produce increased hydrogen content at lower temperatures.

It is to be noted that stored hydrogen can be used in any of the embodiments disclosed herein in place of, or in addition to, hydrogen rich gas from an on-board reformer. The use of stored hydrogen thus forms a part of the present invention.

It is recognized that modifications and variations of the invention disclosed herein will occur to those of ordinary skill in the art and it is intended that all such modifications and variations be included within the scope of the appended claims.

What is claimed is:

1. Pollution control apparatus comprising:
an exhaust aftertreatment unit fitted to the exhaust of an internal combustion engine;
a fuel reformer providing hydrogen rich gas to the aftertreatment unit to regenerate the aftertreatment unit;
and wherein the fuel flow rate and/or the oxygen-to-carbon ratio of reagents entering the reformer varies during regeneration.

2. The pollution control apparatus of claim 1 wherein the fuel reformer is a plasmatron fuel reformer.

3. The pollution control apparatus of claim 1 wherein the aftertreatment unit is a particulate filter.

4. The pollution control apparatus of claim 1 wherein the aftertreatment unit is a NOx trap.

5. The pollution control apparatus of claim 1 wherein the aftertreatment unit comprises a particulate filter and an NOx trap.

6. The pollution control apparatus of claim 1 wherein the internal combustion engine is a diesel engine.

7. The pollution control apparatus of claim 1 wherein the fuel reformer operates at a higher oxygen-to-carbon ratio for particulate filter regeneration than for NOx trap regeneration.

8. The pollution control apparatus of claim 1 wherein the fuel reformer operates at one O/C ratio during start of regeneration and subsequently changes the O/C ratio and/or the fuel flow rate.

9. The pollution control apparatus of claim 8 wherein the fuel reformer operates at a high O/C ratio during start of regeneration and subsequently lowers the O/C ratio.

10. The pollution control apparatus of claim 1 wherein exhaust gas is introduced into the fuel reformer to provide a source of oxygen.

11. The pollution control apparatus of claim 1 wherein the fuel reformer is operated at an oxygen-to-carbon ratio between 0.5 and 1, or higher than for full combustion (lean combustion).

12. Pollution control apparatus comprising:
an exhaust aftertreatment unit fitted to the exhaust of an internal

combustion engine;

a fuel reformer providing hydrogen rich gas to the aftertreatment unit to regenerate the aftertreatment unit;

wherein hydrogen rich gas is provided only to a portion of the aftertreatment unit at any time.

13. The pollution control apparatus of claim 12 further including movable vanes to localize the hydrogen rich gas to the portion of the aftertreatment unit.

14. The pollution control apparatus of claim 13 wherein the vanes are located upstream of the aftertreatment unit.

15. The pollution control apparatus of claim 1 wherein the vanes are located downstream of the aftertreatment unit.

16. The pollution control apparatus of claim 12 further including multiple injection ports for introducing the hydrogen rich gas so that the hydrogen rich gas be localized to the portion being regenerated.

17. The pollution control apparatus of claim 12 further including monitoring apparatus to determine timing and/or duration of regeneration at a given portion of the aftertreatment unit.

18. The pollution control apparatus of claim 17 wherein the monitoring apparatus comprises at least one flow meter.

19. The pollution control apparatus of claim 17 wherein the monitoring apparatus comprises at least one pressure transducer.

20. The pollution control apparatus of claim 17 wherein a sensor to monitor the composition of the gas exiting the aftertreatment device is used to optimize the performance of the aftertreatment device.

21. The pollution control apparatus of claim 20 wherein the sensor measures NO_x.

22. The pollution control apparatus of claim 20 wherein the sensor measures H_2.

23. The pollution control apparatus of claim 20 wherein the sensor measures CO.

24. The pollution control apparatus of claim 12 further including valves to control timing and/or duration of regeneration at a given portion of the aftertreatment unit.

25. The pollution control apparatus of claim 12 wherein the aftertreatment unit comprises a carousel containing a plurality of particulate filter cartridges.

26. The pollution control apparatus of claim 12 wherein the aftertreatment unit comprises a carousel containing a plurality of NO_X trap cartridges.

27. The pollution control apparatus of claim 25 wherein at least one of the particulate filter cartridges receives the hydrogen rich gas for regeneration and at the same time at least another cartridge receives the engine exhaust.

28. The pollution control apparatus of claim 26 wherein at least one of the NO_X trap cartridges receives the hydrogen rich gas for regeneration and at the same time at least another cartridge receives the engine exhaust.

29. The pollution control apparatus of claim 3 wherein the hydrogen rich gas mixes with exhaust gas upstream of the particulate filter whereby particulates combust with free oxygen in the exhaust gas.

30. The pollution control apparatus of claim 4 wherein hydrogen rich gas does not mix with the exhaust gas upstream of the NO_X trap whereby a reducing environment required for regeneration is provided with a minimum of fuel penalty.

31. The pollution control apparatus of claim 12 wherein exhaust gas is introduced into the fuel reformer to provide a source of oxygen.

32. The pollution control apparatus of claim 12 further including a heat exchanger to transfer heat from the exhaust gas to the reformates entering the fuel reformer.

33. The pollution control apparatus of claim 1 wherein the aftertreatment unit is partitioned axially into different partitions.

34. The pollution control apparatus of claim 33 wherein the hydrogen rich gas mixes with products of regeneration from one filter section before entering another section.

35. The pollution control apparatus of claim 34 wherein downstream partitions are generated separately from upstream partitions.

36. The pollution control apparatus of claim 33 wherein materials and construction of different partitions are different from each other.

37. The pollution control apparatus of claim 33 wherein the aftertreatment unit is a diesel particulate filter and the material and composition of the different partitions are such that large particles are trapped in upstream partitions while smaller particles are trapped in downstream partitions.

38. The pollution control apparatus of claim 36 wherein regeneration of a given partition is optimized for the particulate size trapped in said partition.

39. Pollution control apparatus comprising:
an exhaust aftertreatment unit fitted to the exhaust of an internal combustion engine;
a source of hydrogen gas providing the hydrogen gas to the aftertreatment unit to regenerate the aftertreatment unit, wherein the fuel flow rate and/or the oxygen-to-carbon ration of reagents entering the reformer varies during regeneration.

40. The pollution control apparatus of claim 39 wherein the hydrogen gas is stored on a vehicle.

41. Pollution control apparatus comprising:
an exhaust aftertreatment unit fitted to the exhaust of an internal combustion engine;
a source for providing hydrogen gas to the aftertreatment unit to regenerate the aftertreatment unit;
wherein the hydrogen gas is provided only to a portion of the aftertreatment unit at any time.

FIG.1a

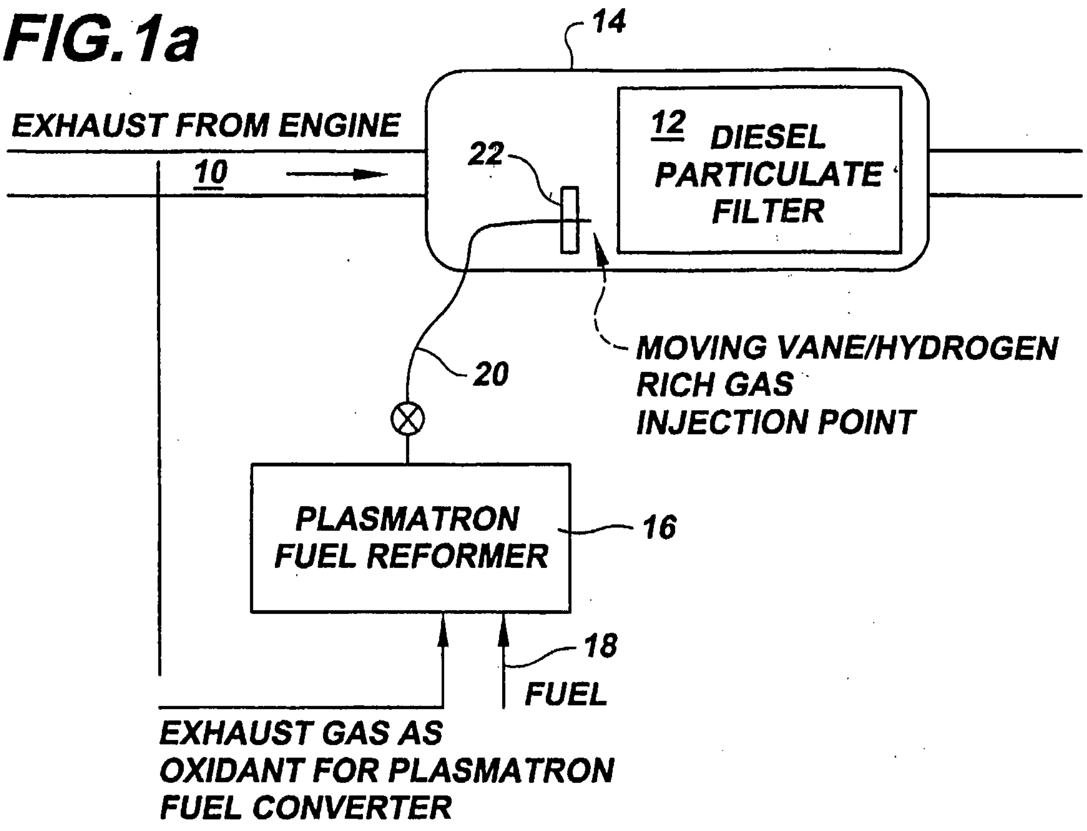

14
EXHAUST FROM ENGINE
10
22
12 DIESEL PARTICULATE FILTER
MOVING VANE/HYDROGEN RICH GAS INJECTION POINT
20
PLASMATRON FUEL REFORMER
16
18
FUEL
EXHAUST GAS AS OXIDANT FOR PLASMATRON FUEL CONVERTER

FIG.1b

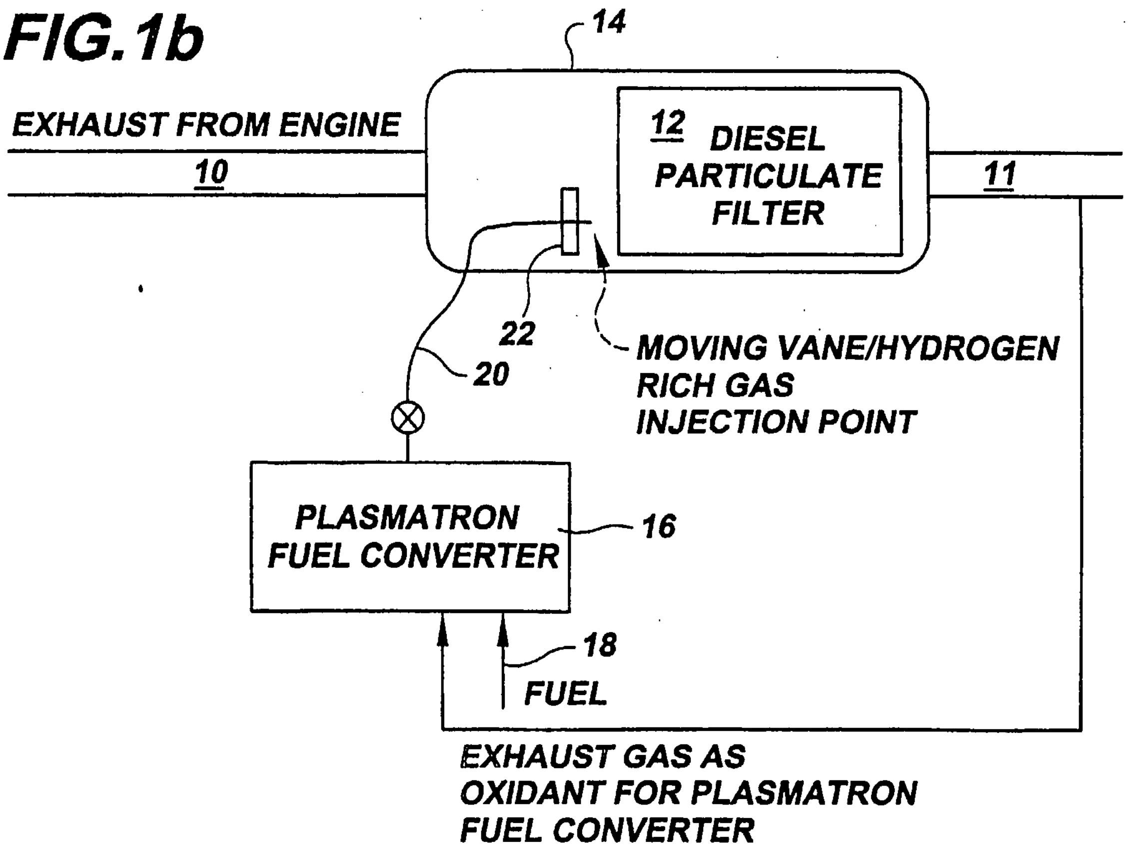

14
EXHAUST FROM ENGINE
10
12 DIESEL PARTICULATE FILTER
11
22
20
MOVING VANE/HYDROGEN RICH GAS INJECTION POINT
PLASMATRON FUEL CONVERTER
16
18
FUEL
EXHAUST GAS AS OXIDANT FOR PLASMATRON FUEL CONVERTER

FIG.2

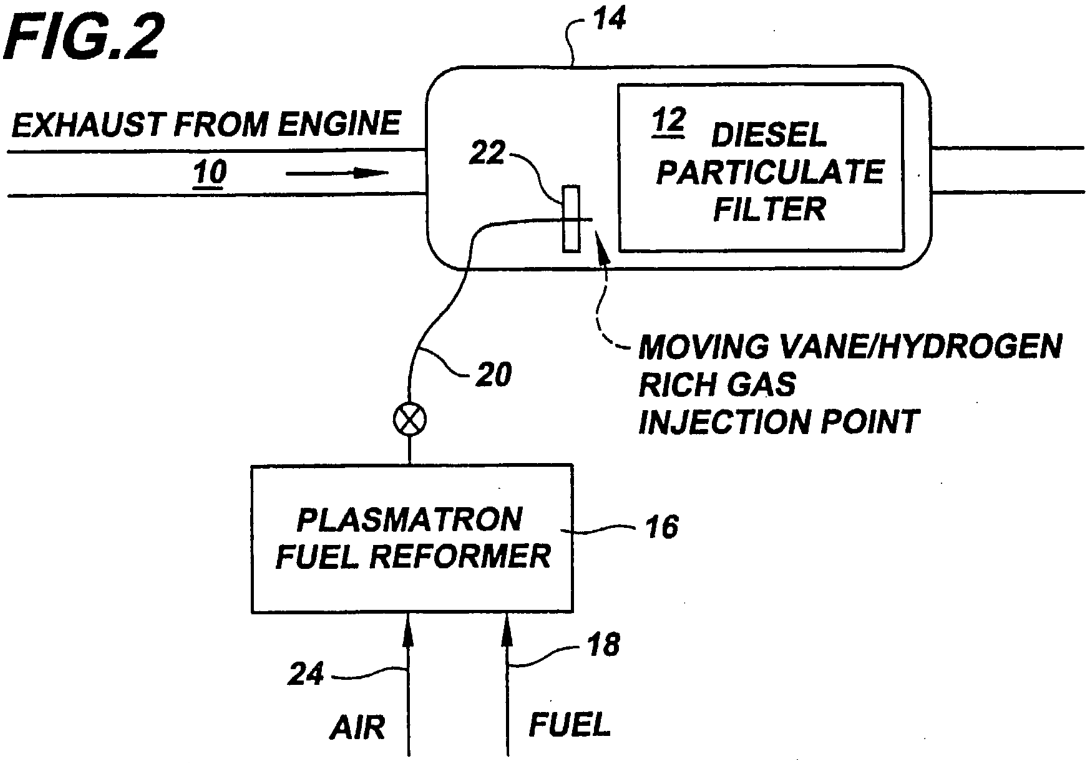

14
EXHAUST FROM ENGINE
10
12 DIESEL PARTICULATE FILTER
22
20
MOVING VANE/HYDROGEN RICH GAS INJECTION POINT
PLASMATRON FUEL REFORMER
16
18
24
AIR
FUEL

FIG.3a

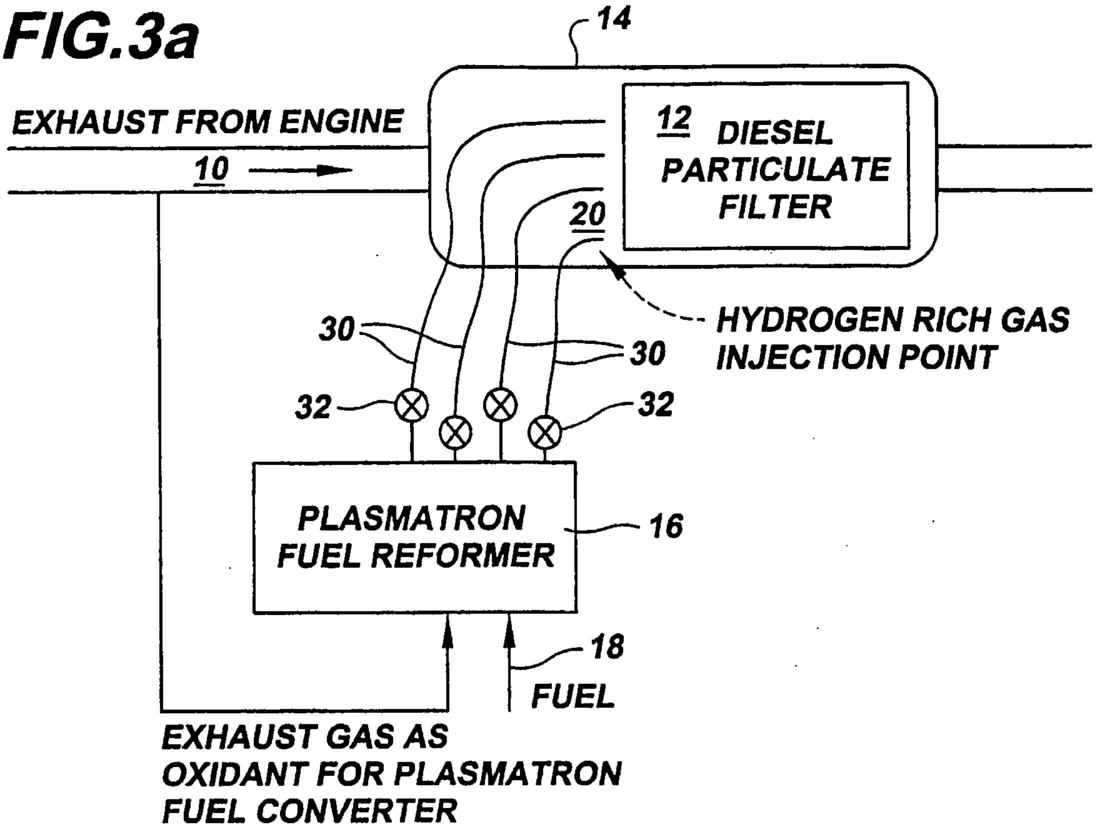

14
EXHAUST FROM ENGINE
10
12 DIESEL PARTICULATE FILTER
20
HYDROGEN RICH GAS INJECTION POINT
30
30
32
32
PLASMATRON FUEL REFORMER
16
18
FUEL
EXHAUST GAS AS OXIDANT FOR PLASMATRON FUEL CONVERTER

FIG.3b

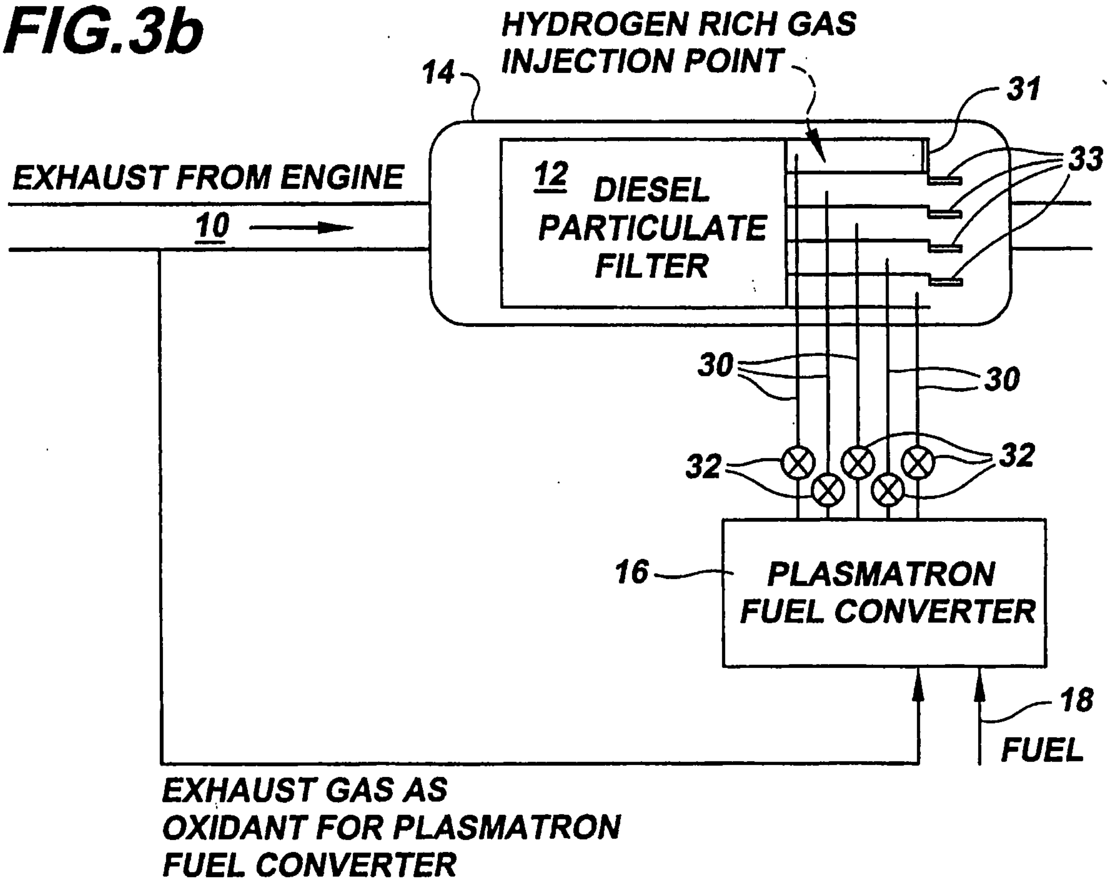

HYDROGEN RICH GAS INJECTION POINT
14
31
33
EXHAUST FROM ENGINE
10
12 DIESEL PARTICULATE FILTER
30
30
32
32
16
PLASMATRON FUEL CONVERTER
18
FUEL
EXHAUST GAS AS OXIDANT FOR PLASMATRON FUEL CONVERTER

FIG.4a

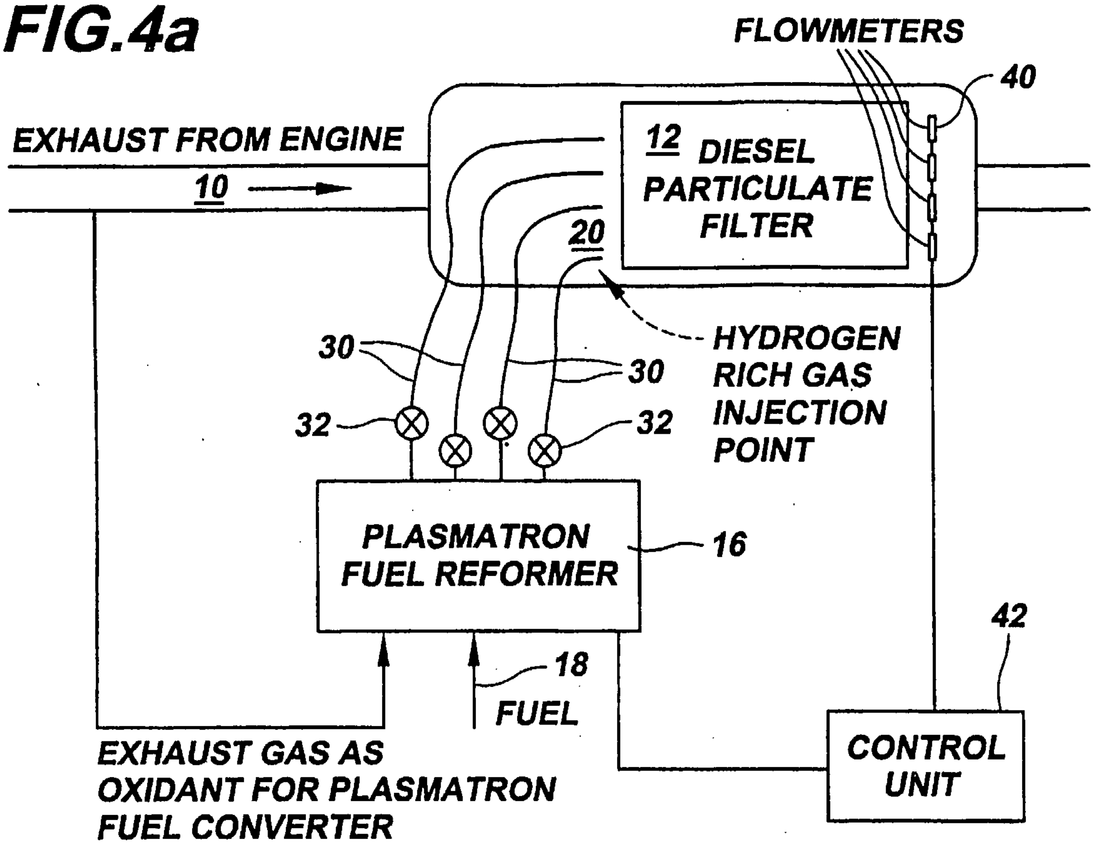

FLOWMETERS
40
EXHAUST FROM ENGINE
10
12 DIESEL PARTICULATE FILTER
20
HYDROGEN RICH GAS INJECTION POINT
30
30
32
32
PLASMATRON FUEL REFORMER
16
18
FUEL
42
CONTROL UNIT
EXHAUST GAS AS OXIDANT FOR PLASMATRON FUEL CONVERTER

FIG.4b

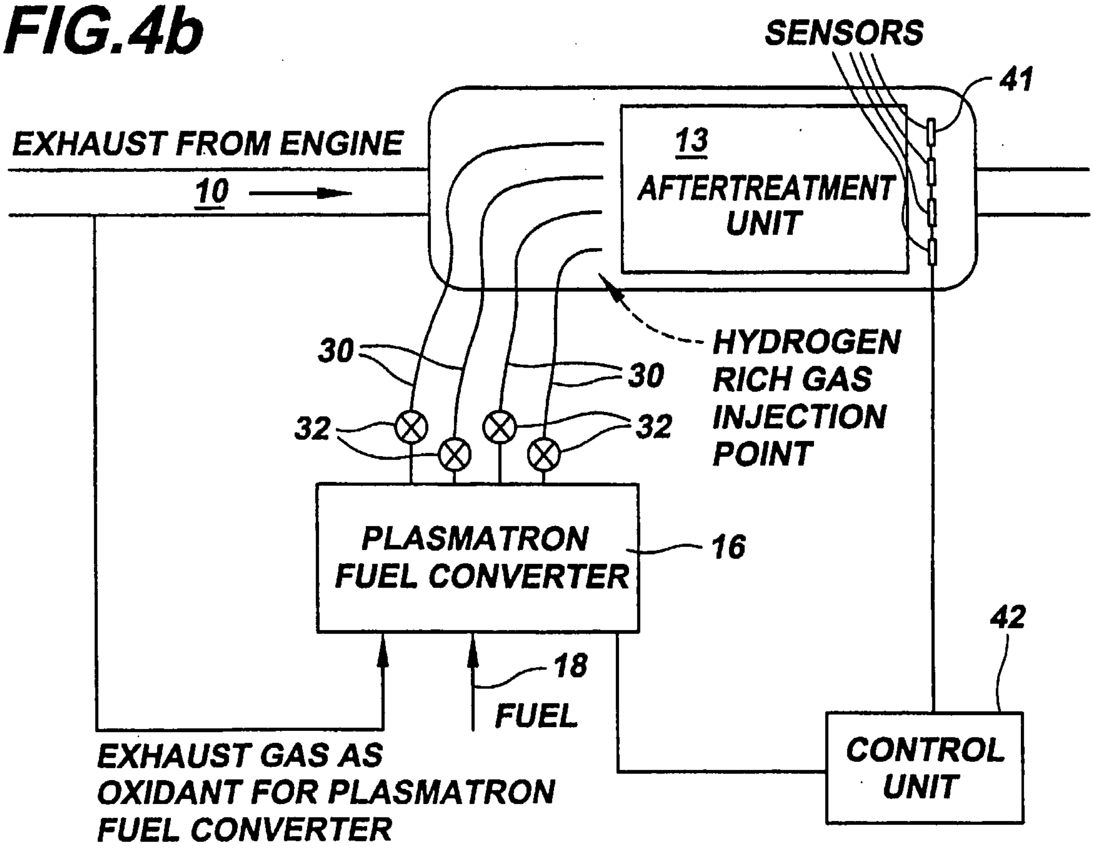

SENSORS
41
EXHAUST FROM ENGINE
10
13
AFTERTREATMENT UNIT
HYDROGEN RICH GAS INJECTION POINT
30
30
32
32
PLASMATRON FUEL CONVERTER
16
18
FUEL
42
CONTROL UNIT
EXHAUST GAS AS OXIDANT FOR PLASMATRON FUEL CONVERTER

FIG.5

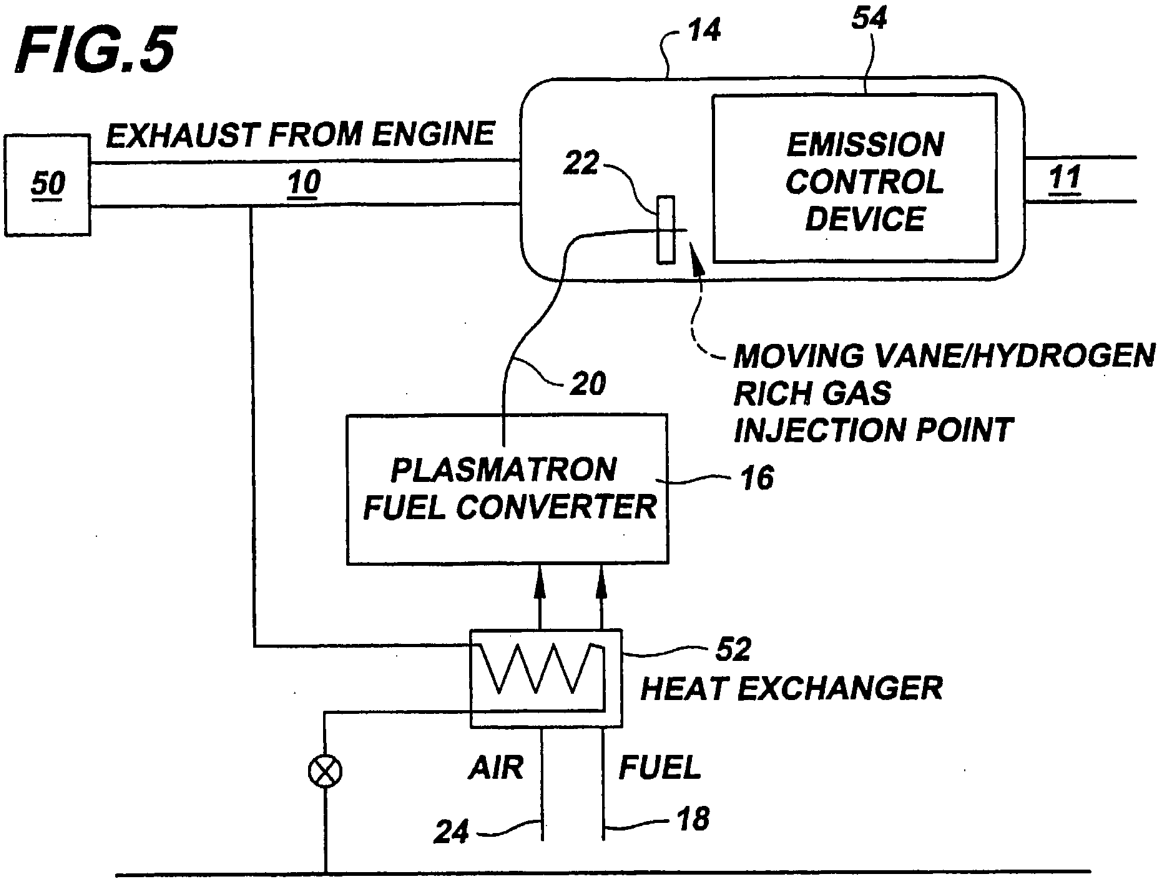

14
54
EXHAUST FROM ENGINE
50
10
22
EMISSION CONTROL DEVICE
11
20
MOVING VANE/HYDROGEN RICH GAS INJECTION POINT
PLASMATRON FUEL CONVERTER
16
52
HEAT EXCHANGER
AIR
FUEL
24
18

FIG.6

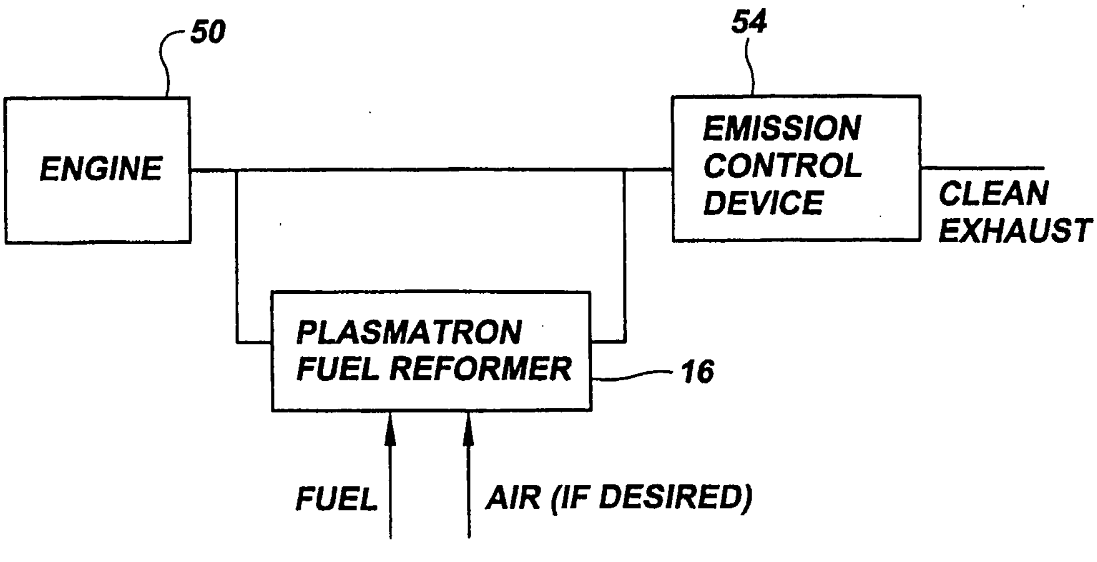

50
54
ENGINE
EMISSION CONTROL DEVICE
CLEAN EXHAUST
PLASMATRON FUEL REFORMER
16
FUEL
AIR (IF DESIRED)

FIG.7

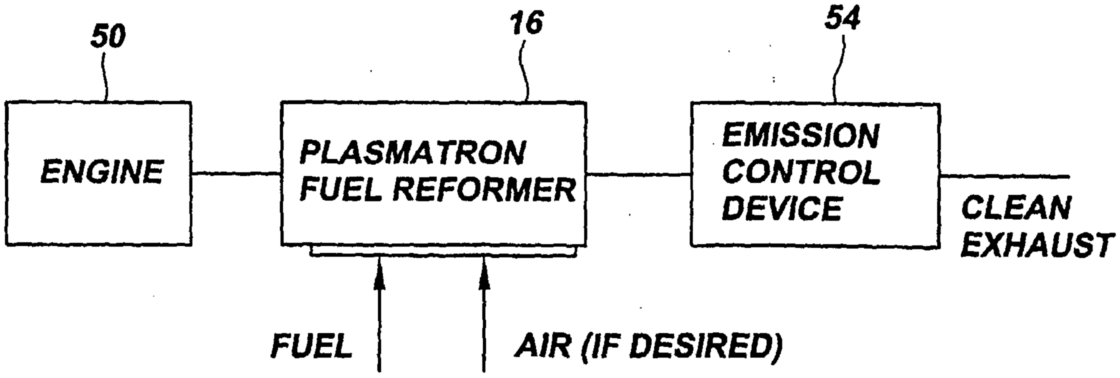
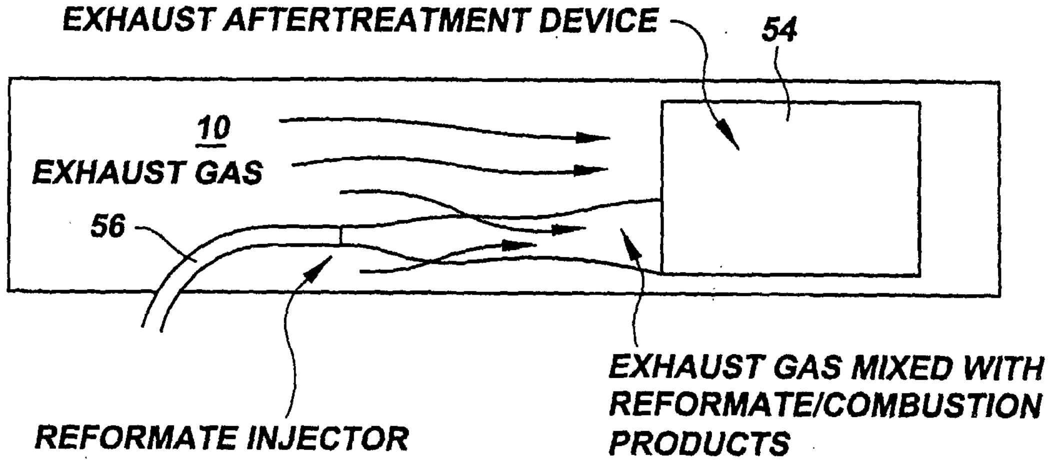
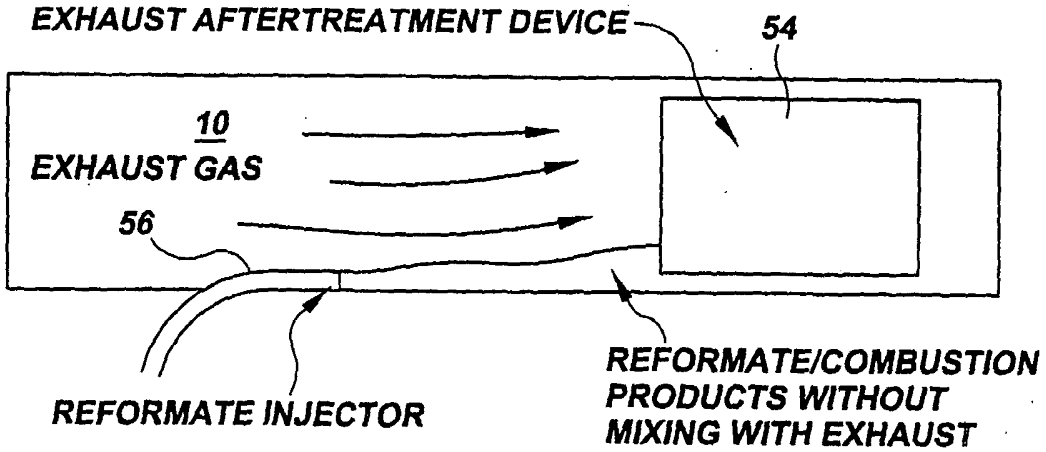


FIG.8a



REFORMATE INJECTION WITH MIXING WITH EXHAUST UPSTREAM FROM CATALYST

FIG.8b



REFORMATE INJECTION WITHOUT MIXING WITH EXHAUST UPSTREAM FROM CATALYST

FIG.9

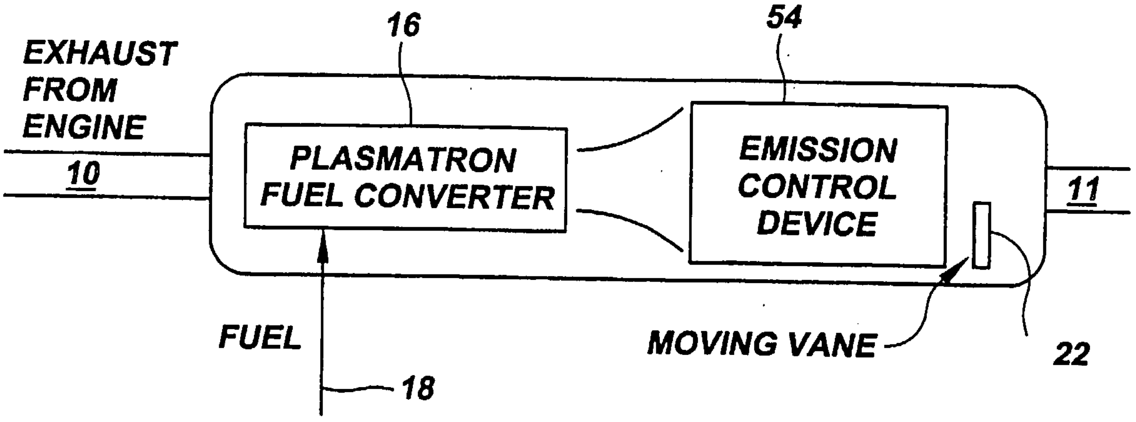

16
54
EXHAUST FROM ENGINE
10
PLASMATRON FUEL CONVERTER
EMISSION CONTROL DEVICE
11
FUEL
18
MOVING VANE
22

FIG.10

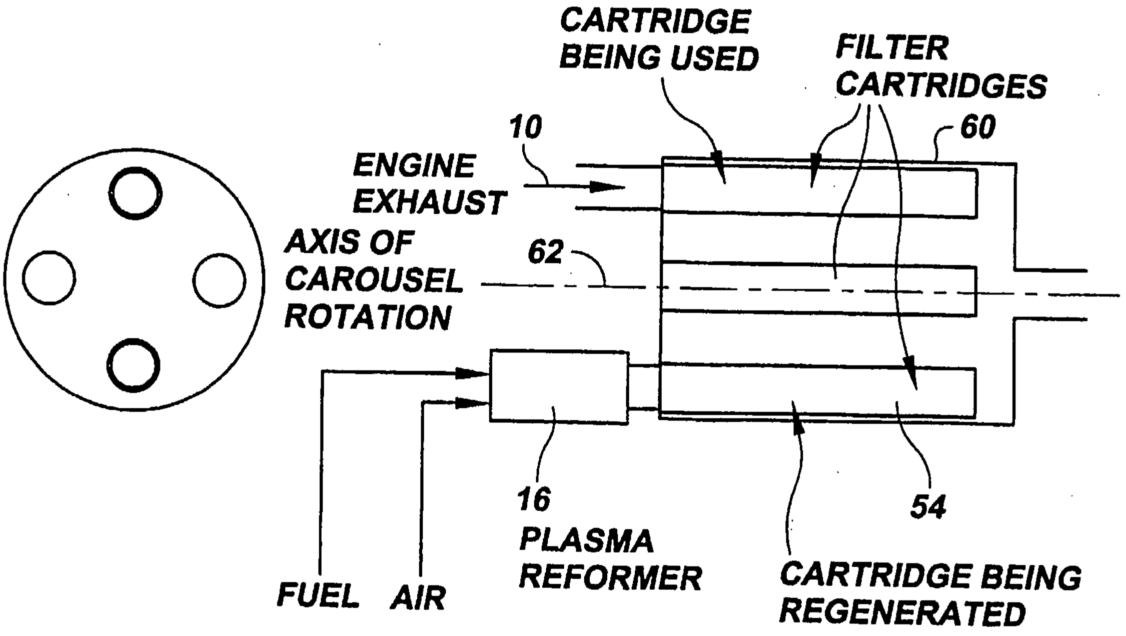

CARTRIDGE BEING USED
FILTER CARTRIDGES
10
60
ENGINE EXHAUST
AXIS OF CAROUSEL ROTATION
62
16
PLASMA REFORMER
54
FUEL
AIR
CARTRIDGE BEING REGENERATED

FIG.11a

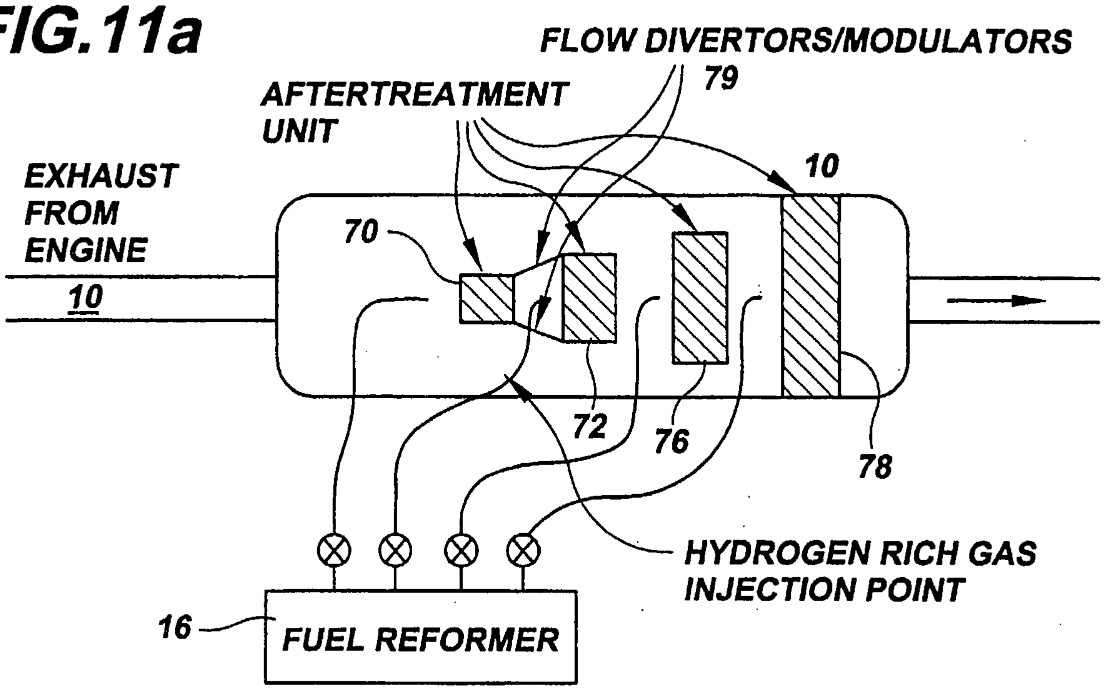


FIG.11b