An apparatus for removing particulate soot from an exhaust gas of an internal combustion engine includes a particulate filter assembly having a catalyst and a soot filter positioned downstream of the catalyst for trapping soot particles therein. Hydrogen gas is introduced into the exhaust gas at a location upstream of the catalyst. The catalyst catalyzes an exothermic oxidation reaction between the hydrogen gas and oxygen in the exhaust gas. Heat from this exothermic oxidation reaction is transferred to the soot filter thereby igniting the soot particles trapped therein. A method for regenerating a particulate filter assembly is also disclosed.
Fig. 1

10 EMISSION ABATEMENT DEVICE
14 CATALYST
16 FILTER
18 SOURCE OF GAS
12 INTERNAL COMBUSTION ENGINE
H₂ UNTREATED EXHAUST GASES
TREATED EXHAUST GASES
APPARATUS AND METHOD FOR REGENERATING A PARTICULATE FILTER OF AN EXHAUST SYSTEM OF AN INTERNAL COMBUSTION ENGINE

[0001] This application claims priority to U.S. Provisional Patent Application No. 60/575,134 entitled “Apparatus and Method for Regenerating a Particulate Filter of an Exhaust System of an Internal Combustion Engine” filed on Apr. 24, 2002 by Rudolf M. Smaling, the disclosure of which is hereby incorporated by reference.

FIELD OF THE DISCLOSURE

[0002] The present disclosure relates generally to an emission abatement device, and more particularly to a particulate filter assembly for reducing soot emissions.

BACKGROUND

[0003] Untreated internal combustion engine emissions include various effluents such as $NO_x$ (oxides of nitrogen), hydrocarbons, and carbon monoxide, for example. Moreover, the untreated emissions from certain types of internal combustion engines, such as diesel engines, also include particulate carbon-based soot. Federal regulations relating to soot emission standards are becoming more and more rigid thereby furthering the need for devices and/or methods which remove soot from engine emissions. For example, the amount of soot produced and/or released by an engine system can be reduced by fuel injection rate shaping and/or by the use of an emission abatement device such as a filter or trap. Such a filter or trap is periodically regenerated in order to remove the soot therefrom. The filter or trap may be regenerated by use of a burner or electric heater to burn the soot off of the filter.

SUMMARY

[0004] According to the present disclosure, an apparatus is provided for removing particulate soot from an exhaust gas of an internal combustion engine. The apparatus includes a particulate filter assembly having a catalyst and a soot filter positioned downstream of the catalyst for trapping soot particles therein. Hydrogen gas is introduced into the exhaust gas at a location upstream of the catalyst. The catalyst catalyzes an exothermic reaction between the hydrogen gas and a gas containing oxygen. Heat from this exothermic reaction is transferred to the filter thereby igniting the soot particles trapped therein.

[0005] In one exemplary embodiment, the source of hydrogen gas is embodied as a hydrogenerator for generating hydrogen to be introduced into the exhaust gas prior to entering the particulate filter assembly.

[0006] In one implementation of this exemplary embodiment, the hydrogen generator is embodied as a fuel reformer which reforms a hydrocarbon fuel into a hydrogen-rich gas.

[0007] In another implementation of this exemplary embodiment, the fuel reformer is embodied as a plasma torch fuel reformer.

[0008] Further according to the present disclosure, a method for regenerating a soot filter is provided. The method includes generating a reformate gas and introducing the reformate gas into an exhaust gas from an internal combustion engine. The exhaust gas and the reformate gas are advanced into contact with a catalyst which catalyzes an exothermic reaction between the reformate gas and the exhaust gas. Heat generated from the reaction of the reformate gas and exhaust gas with the catalyst ignites the soot present in the soot filter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The detailed description particularly refers to the accompanying figures in which:

[0010] FIG. 1 is a block diagram which demonstrates the concepts of the present disclosure for treating exhaust gases from an internal combustion engine;

[0011] FIG. 2 is a block diagram of a specific exemplary implementation of the concepts of FIG. 1;

[0012] FIG. 3 is a diagrammatic cross sectional view of a particulate filter assembly for use with the concepts disclosed herein;

[0013] FIG. 4 is a block diagram similar to FIG. 2, but showing the particulate filter assembly positioned downstream of a supplemental emission abatement device that partially treats exhaust gases prior to advancement of the gases through the particulate filter assembly; and

[0014] FIG. 5 is a block diagram similar to FIG. 2, but showing a pair of particulate filter assemblies arranged in a parallel arrangement.

DETAILED DESCRIPTION OF THE DRAWINGS

[0015] Referring now to FIG. 1, there is shown an emission abatement device 10 for removing soot particles from the exhaust gases of an internal combustion engine 12. The emission abatement device 10 includes a catalyst 14 and a soot filter 16. The oxidation catalyst 14 is positioned upstream of the soot filter 16. The oxidation catalyst 14 may be spaced apart from the soot filter 16 by a predetermined distance, may be positioned in contact with the soot filter 16, or may even be fabricated as a common structure with the soot filter 16 (e.g., a common structure having a catalyst portion positioned upstream of a filter portion).

[0016] The oxidation catalyst 14 is configured to catalyze an oxidation reaction between a gaseous component containing oxygen and hydrogen gas. Specifically, when hydrogen gas is advanced into contact with the oxidation catalyst 14 in the presence of a gaseous component containing oxygen, the oxidation catalyst catalyzes an oxidation reaction which converts the hydrogen gas and a portion of the oxygen into, amongst other things, water.

[0017] This oxidation reaction is highly exothermic, and, as a result, produces heat that is transferred to the downstream-positioned soot filter 16. The heat, which may illustratively be in the range of 600-650 degrees Celsius, raises the temperature of the soot particles trapped in the filter 16 to a temperature sufficient to ignite the particles thereby regenerating the filter 16. It should be appreciated that such regeneration of the soot filter 16 may be self-sustaining once initiated by heat from the exothermic reaction catalyzed by the oxidation catalyst 14. Specifically, once the soot filter 16 is heated to a temperature at which the soot particles trapped therein begin to ignite, the ignition of an initial portion of soot particles trapped therein can cause the ignition of the
remaining soot particles much in the same way a cigar slowly burns from one end to the other. In essence, as the soot particles “burn,” an amount of heat is released in the “burn zone.” Locally, the soot layer (in the burn zone) is now much hotter than the immediate surroundings. So, such heat is transferred to the as yet un-ignited soot layer downstream of the burn zone. The energy transferred may be sufficient to initiate oxidation reactions that raise the un-ignited soot to a temperature above its ignition temperature. As a result of this, heat from the oxidation catalyst 14 may only be required to commence the regeneration process of the soot filter 16 (i.e., begin the ignition process of the soot particles trapped therein).

[0018] In an illustrative embodiment, the soot filter 16 may have a catalytic material such as, for example, a precious metal catalytic material, disposed on the surfaces thereof. The amount of catalytic material disposed on the filter 16 may be varied to fit the needs of a given system design. In one illustrative implementation, the soot filter 16 may only use about 3% of the amount of catalytic material (e.g., precious metals) that is present on a typical oxidation catalyst. In such a configuration (i.e., use of a catalyzed filter 16), the ignition temperature of the soot particles trapped in the filter 16 is reduced. Indeed, depending on, amongst other things, the amount of catalytic material disposed on the filter 16 and the amount of accumulated soot particles, the ignition temperature of the soot particles may be lowered to an ignition temperature of between 300-600 degrees Celsius. In other exemplary implementations, the soot ignition temperature may be lowered to a temperature in the range of 300-550 degrees Celsius, more particularly in the range of 300-450 degrees Celsius, and even more particularly in the range of 300-350 degrees Celsius.

[0019] It should be appreciated that in addition to the aforesaid use of the oxidation catalyst 14 to regenerate the soot filter 16, the oxidation catalyst 14 may also function as an oxidation catalyst for removing certain compounds from the exhaust gases of the engine 12. In particular, the oxidation catalyst 14 may be configured to catalyze, in the presence of heat supplied by the exhaust gases (e.g., 250 degrees Celsius), an oxidation reaction which converts, for example, hydrocarbons (HC) and carbon monoxide (CO) into water vapor, carbon dioxide, and other less toxic gases. Hence, the emission abatement device 10 may be used to not only remove soot from the engine’s exhaust gases, but also other compounds as well (e.g., HC, CO).

[0020] As with conventional aftertreatment configurations, such functionality of an oxidation catalyst 14 is generally not achieved until the exhaust gases produced by the engine 12 become hot enough to heat the oxidation catalyst 14 to its light off temperature (e.g., approximately 250 degrees Celsius). Hence, during startup, emissions of such compounds can reach undesirable levels since compounds can pass untreated through the oxidation catalyst 14 prior to the catalyst 14 reaching its light off temperature. However, hydrogen gas may be supplied to the oxidation catalyst 14 during startup to instantaneously, or near instantaneously, light off the oxidation catalyst 14. Specifically, during startup of the engine 12, hydrogen gas may be advanced to the face of the oxidation catalyst 14 thereby quickly lighting off the catalyst 14 in a much shorter period of time than if the catalyst 14 had to be lighted off by heat from the engine’s exhaust gases passing therethrough. Such instantaneous, or near instantaneous, light off of the catalyst 14 prevents the release of untreated compounds during engine startup that the catalyst 14 is otherwise designed to treat.

[0021] As described above, the oxidation catalyst 14 catalyzes an exothermic reaction between a gaseous component containing oxygen and hydrogen. Generally, exhaust gases from the internal combustion engine 12 may function as the source of oxygen. In particular, suitable amounts of oxygen for sustaining such an oxidation reaction exist in the exhaust gases of an internal combustion engine without the introduction of additional oxygen. However, to fit the needs of a given design or implementation, supplemental oxygen may be introduced into the engine’s exhaust gases prior to advancement thereof into the emission abatement device 10. One way to do this is by use of an air inlet (not shown) positioned upstream of the oxidation catalyst 14 for introducing a desired amount of air into the engine’s exhaust gases prior to advancement thereof into contact with the oxidation catalyst 14.

[0022] As shown in FIG. 1, hydrogen gas is supplied from a source of hydrogen gas 18. The source of hydrogen gas 18 may be embodied as a number of different types of devices. For example, the source of hydrogen gas may be embodied as tank of hydrogen gas (i.e., “bottled” hydrogen gas). Alternatively, the source of hydrogen gas 18 may be embodied as a hydrogen generator that generates hydrogen from other compounds. One example of a hydrogen generator is a device that produces hydrogen gas via electrolysis. Other examples of a hydrogen generator include fuel reformers that reform (i.e., convert) hydrocarbon fuels into a reformat gas that includes, amongst other things, hydrogen gas. Examples of such fuel reformers include, amongst other types, catalytic fuel reformers and thermal fuel reformers.

[0023] One additional type of fuel reformer, which is particularly useful as the source of hydrogen gas 18, is a plasma-fuel reformer, or “plasmatron”. A plasmatron uses plasma to convert hydrocarbon fuel into a reformat gas which is rich in, amongst other things, hydrogen gas and carbon monoxide. Systems including plasmatrons are disclosed in U.S. Pat. No. 5,425,332 issued to Rabinovich et al.; U.S. Pat. No. 5,437,250 issued to Rabinovich et al.; U.S. Pat. No. 5,409,784 issued to Bromberg et al.; and U.S. Pat. No. 5,887,554 issued to Cohn et al., the disclosures of each of which is hereby incorporated by reference. Additional examples of systems including plasmatrons are disclosed in pending U.S. patent application Ser. No. 10/158,615 entitled “Low Current Plasmatron Fuel Converter Having Enlarged Volume Discharges” which was filed on May 30, 2002 by A. Rabinovich, N. Alexeev, L. Bromberg, D. Cohn, and A. Samokhin, along with pending U.S. patent application Ser. No. 10/102,774 entitled “Plasmatron Fuel Converter Having Decoupled Air Flow Control” which was filed on Apr. 11, 2003 by A. Rabinovich, N. Alexeev, L. Bromberg, D. Cohn, and A. Samokhin, the disclosures of both of which are hereby incorporated by reference.

[0024] In such an exemplary implementation, a plasmatron may be operated to reform the same hydrocarbon fuel being combusted by the engine 12 (such as gasoline or diesel fuel, for example). Alternatively, a plasmatron may be operated to reform a type of hydrocarbon fuel that is distinct from the engine’s fuel. In either case, a plasmatron may be
operated to produce only the amount of hydrogen-rich reformate gas that is needed by the emission abatement device thereby eliminating the need to store additional quantities of hydrogen gas. As such, a plasmatron may be operated to produce hydrogen-rich reformate gas “on demand”.

[0025] More specific exemplary embodiments of the concepts of the present disclosure will now be described in regard to FIGS. 2-5. The exemplary embodiments herein-after described in regard to FIGS. 2-5 relate to the use of a specific fuel reformer, a plasmatron, along with a specific type of internal combustion engine, a diesel engine. It should be appreciated that while the specific exemplary embodiments described in regard FIGS. 2-5 have significant advantages, such embodiments are merely descriptive in nature, and should not be construed as limiting to the claims in any way absent specific language in the claims to the contrary.

[0026] Referring now to FIG. 2, there is shown an emission abatement system for use in conjunction with a diesel engine 50. The system includes an emission abatement device 52 and a plasmatron 54. The plasmatron 54 converts hydrocarbon fuel 60 into a reformate gas 58 that is rich in amongst other things, hydrogen and carbon monoxide. The hydrocarbon fuel 60 is supplied by a fuel tank 62 to both the engine 50 and the plasmatron 54. As shown in FIGS. 2 and 3, air 64 is also input into the plasmatron 54. A fuel input mechanism, such as a fuel injector, injects hydrocarbon fuel 60 and air 64 into a plasma arc created by the plasmatron 54. The fuel injector may be any type of fuel injection mechanism that produces a desired mixture of fuel 60 and air 64 and thereafter injects such a mixture into the plasma-generating portion of the plasmatron 54. In certain configurations, it may be desirable to atomize the fuel-air mixture prior to, or during, injection of the mixture into the plasma-generating portion of the plasmatron 54. Such fuel injector assemblies (i.e., injectors which atomize the fuel mixture) are commercially available. Moreover, additional amounts of air 64 may also be input into the plasmatron 54 by use of, for example, an air inlet valve (not shown) to allow for the creation of a desired air-to-fuel ratio within the plasmatron 54.

[0027] As shown in FIG. 2, the hydrocarbon fuel 60 supplied to the plasmatron 54 is generally the same hydrocarbon fuel being combusted by the diesel engine 50 (i.e., diesel fuel). Alternatively, the hydrocarbon fuel 60 supplied to the plasmatron 54 may be a type of hydrocarbon fuel that is distinct from the engine’s fuel.

[0028] The hydrogen-rich reformate gas 58 generated by the plasmatron 54 is supplied to the emission abatement device 52 to regenerate the device 52. Specifically, as shown in FIG. 3, the emission abatement device 52 may be configured as a particulate filter assembly 72 having a catalyst 74 and a soot particulate filter 76 positioned downstream from catalyst 74. The catalyst 74 may be spaced apart from the soot filter 16 by a predetermined distance (as shown in FIG. 3), may be positioned in contact with the soot particulate filter 76, or may even be fabricated as a common structure with the soot particulate filter 76 (e.g., a common structure having a catalyst portion positioned upstream of a filter portion).

[0029] The catalyst 74 may be embodied as any type of catalyst that is configured to catalyze the herein described reactions. In one exemplary embodiment, the catalyst 74 is embodied as substrate having a precious metal or other type of catalytic material disposed thereon. Such a substrate may be constructed of ceramic, metal, or other suitable material. The catalytic material may be, for example, embodied as platinum, rhodium, palladium, including combinations thereof, along with any other similar catalytic materials.

[0030] The soot particulate filter 76, on the other hand, traps soot or other particulates present in the untreated exhaust gases 66 from the diesel engine 50. The soot particulate filter 76 may be embodied as any known exhaust particulate filter such as a “deep bed” or “wall flow” filter. Deep bed filters may be embodied as metallic mesh filters, metallic or ceramic foam filters, ceramic fiber mesh filters, and the like. Wall flow filters, on the other hand, may be embodied as a cordierite or silicon carbide ceramic filter with alternating channels plugged at the front and rear of the filter thereby forcing the gas advancing therethrough into one channel, through the walls, and out another channel.

[0031] Similarly to as described above in regard to the soot filter 16, the soot particulate filter 76 may also be impregnated with a catalytic material such as, for example, a precious metal catalytic material. In such a configuration, the soot temperature of the soot trapped in the filter 76 may be significantly lowered thereby lowering the amount of heat that is required from the exothermic reactions at the face of the catalyst 74. The amount of catalytic material disposed on the soot particulate filter 76 may be varied to fit the needs of a given system design. For example, in one illustrative implementation, the soot particulate filter 76 may only use about 3% of the amount of catalytic material (e.g., precious metals) that is present on a typical oxidation catalyst. In such a configuration (i.e., use of a catalyzed filter 76), the ignition temperature of the soot particles trapped in the filter 76 is reduced. Indeed, depending on, amongst other things, the amount of catalytic material disposed on the filter 76 and the amount of accumulated soot particles, the ignition temperature of the soot particles may be lowered to an ignition temperature of between 300-600 degrees Celsius. In other exemplary implementations, the ignition temperature may be lowered to a temperature in the range of 300-550 degrees Celsius, more particularly in the range of 300-450 degrees Celsius, and even more particularly in the range of 300-350 degrees Celsius.

[0032] Reformate gas 58 from the plasmatron 54 is advanced into contact with the catalyst 74 to catalyze an oxidation reaction between the oxygen in the exhaust gas 66 of the engine 50 and the reformate gas 58. Specifically, when the reformate gas 58 is advanced into contact with the catalyst 74 in the presence of exhaust gas 66, the catalyst 74 catalyzes an oxidation reaction which converts the hydrogen gas present in the reformate gas 58 and the oxygen present in the exhaust gases 66 into carbon dioxide. Both of these oxidation reactions are highly exothermic, and, as a result, produce heat that is transferred to the downstream-positioned soot particulate filter 76. The heat, which may illustratively be in the range of 600-650 degrees Celsius, ignites soot particles trapped in the particulate filter 76 thereby regenerating the filter 76.
It should be appreciated that in the case of lowering the ignition temperature of the soot particles by use of a catalyzed soot filter 76, the amount of heat required from the exothermic reactions catalyzed by the catalyst 74 is reduced. In particular, if the ignition temperature of the soot particles trapped in the filter 76 is reduced by use of a catalytic filter design, the amount of heat required from the upstream oxidation reactions at the catalyst 74 is likewise reduced. As such, the design of the catalyst 74 may be varied (e.g., use of different, perhaps less expensive, catalyst materials) to produce only the amount of heat needed to ignite the soot particles trapped in the catalyzed filter 76. Alternatively, the amount or type of reformate gas may also be varied to produce only the amount of heat needed to ignite the soot particles trapped in the catalyzed filter 76.

It should be appreciated that such regeneration of the soot filter 76 may be self-sustaining once initiated by heat from the exothermic reaction catalyzed by the catalyst 74. Specifically, once the soot particulate filter 76 is heated to a temperature at which the soot particles trapped therein begin to ignite, the ignition of an initial portion of soot particles trapped therein can sustain the ignition of the remaining soot particles much in the same way a cigar slowly burns from one end to the other. In particular, if described herein in regard to the soot filter of FIG. 1, as the soot particles trapped in the filter 76 "burn," an amount of heat is released in the "burn zone." Locally, the soot layer (in the burn zone) is now much hotter than the immediate surroundings. As such, heat is transferred to the as yet un-ignited soot layer downstream of the burn zone. The energy transferred may be sufficient to initiate oxidation reactions that raise the un-ignited soot to a temperature above its ignition temperature. As a result of this, heat from the catalyst 74 may only be required to commence the regeneration process of the soot particulate filter 76 (i.e., begin the ignition process of the soot particles trapped therein). Hence, during regeneration of the filter 76, the plasmatron 74 may be operated to supply a predetermined amount of reformate gas 58 to the catalyst 74 to ignite an initial portion of the soot particulate trapped in the soot particulate filter 76, and thereafter cease generation of the reformate gas 58 once the regeneration process within the soot particulate filter 76 becomes self-sustaining.

It should be appreciated that in addition to the aforementioned use of the catalyst 74 to regenerate the soot particulate filter 76, the catalyst 74 may also function as an oxidation catalyst for removing certain compounds from the exhaust gases 66 of the diesel engine 50. In particular, the catalyst 74 may be configured to catalyze, in the presence of heat supplied by the exhaust gases (e.g., approximately 250 degrees Celsius), an oxidation reaction which converts, for example, hydrocarbons (HC) and carbon monoxide (CO) into water vapor, carbon dioxide, and other less toxic gases.

As with conventional aftertreatment configurations, such functionality of an oxidation catalyst is generally not achieved until the exhaust gases produced by the engine 50 become hot enough to heat the catalyst to its light off temperature (e.g., approximately 250 degrees Celsius). Hence, during engine startup, emissions of such compounds can reach undesirable levels since such compounds can pass untreated through the catalyst prior to the catalyst reaching its light off temperature. However, the plasmatron 54 may be operated during engine startup to instantaneously, or near instantaneously, light off the catalyst 74. Specifically, during startup of the engine 50, the plasmatron 54 may be operated to provide reformate gas 58 to the catalyst 74 thereby quickly lighting off the catalyst 74 in much shorter period of time than if the catalyst 74 had to be lighted off by heat from the exhaust gases 66 passing therethrough. Such instantaneous, or near instantaneous, light off of the catalyst prevents the release of untreated compounds during engine startup that the catalyst is otherwise designed to treat.

Referring now to FIG. 3, the particulate filter assembly 72 is shown in greater detail. The catalyst 74 and the filter 76 of the particulate filter assembly 72 are housed in an interior chamber 96 of a housing 78. The housing 78 has a first end 80 coupled to an exhaust pipe 82, and a second end 84 coupled to either another exhaust pipe 86 that is open to the atmosphere or coupled to an additional exhaust system component (not shown) positioned downstream of the particulate filter assembly 72. The first end 80 of the housing 78 defines an exhaust gas inlet 90, whereas the second end 84 of the housing 78 defines an exhaust gas outlet 92. Hence, exhaust gases 66 from the diesel engine 50 enter the housing 78 through the exhaust gas inlet 90, are advanced through the catalyst 74 and the soot particulate filter 76, and then are exhausted from the housing 78 via the exhaust gas outlet 92.

The particulate filter assembly 72 has an inlet 88 for receiving reformate gas 58 from the plasmatron 14. The inlet may be configured as an orifice that is defined in the walls of the housing 78, or, alternatively, may include a tube, coupling assembly, or other structure which extends through the wall of the housing 78. In addition, if the reformate gas 58 is introduced upstream of the first end 80 of the housing 78, the exhaust gas inlet 90 of the housing 78 functions as the reformate gas inlet of the particulate filter assembly 72.

The plasmatron 54 is fluidly coupled to the reformate gas inlet associated with the particulate filter assembly 72. In particular, a first end of a fluid line 94 is coupled to the outlet of the plasmatron 54, whereas a second end of the fluid line 94 extends through, or is coupled to, the gas inlet 88 such that reformate gas 58 may be introduced into the chamber 96 of the housing 78. In such a manner, reformate gas 58 from the plasmatron 54 may be introduced into the exhaust gases of the engine 50 prior to advancement thereof into contact with the catalyst 74.

A control valve 98 is utilized to control the flow of reformate gas 58 from the plasmatron 54 to the particulate filter assembly 72. The control valve 98 is under the control of a controller 100. The controller 100 also controls the operation of the plasmatron 54. Specifically, the controller 100 is coupled to the plasmatron 54 via a signal line 102 to selectively actuate and deactivate the plasmatron 54 thereby selectively controlling the production of reformate gas 58.

It should be appreciated that in certain design configurations, the controller 100 may control the flow of reformate gas 58 to the particulate filter assembly 72 without the use of the control valve 98. Specifically, one particularly useful feature of the plasmatron 54 is its relatively rapid response to requests for changes in the production of reformate gas. Indeed, unlike other types of fuel reformers (e.g., catalytic fuel reformers or thermal fuel reformers), the amount of reformate gas produced by the plasmatron 54 may be quickly increased or decreased to fit the needs of a given situation. As such, in lieu of the control valve 98, the
algorithms executed by the controller 100 may provide for relatively fast actuation and deactuation of the plasmatron 54 thereby eliminating the need for the control valve 98.

[0042] As shown in FIG. 3, the controller 100 is also electrically coupled to a pair of pressure sensors 104 via a signal line 106. The pressure sensors 106 may be utilized to sense the pressure difference across the particulate filter assembly 72 in order to determine when the filter assembly 72 requires regeneration. Specifically, when the pressure drop across the particulate filter assembly 72 increases to a predetermined value, the controller 100 commences the filter regeneration process. It should be appreciated that while shown in FIG. 3 as utilizing two pressure sensors, a single pressure sensor on either side of filter assembly 72 may be utilized, if desired. In such a configuration, the controller 100 would monitor when the pressure sensed by the single pressure sensor exceeded a predetermined upper threshold or was below a predetermined lower threshold, as opposed to monitoring the pressure drop across the filter assembly 72.

[0043] As shown in FIGS. 2 and 3, reformat gas 58 from the plasmatron 14 is introduced into the exhaust gases 66 from the diesel engine 50 at a location upstream of the catalyst 74. In this way, the gaseous compound containing hydrogen and carbon monoxide (e.g., reformat gas from the plasmatron 14) is introduced into the gaseous compound containing oxygen (e.g., exhaust gas) prior to advancement thereof into contact with the catalyst 74. As such, when the gases contact the catalytic substrate, an exothermic reaction hot enough to light off the soot particulate filter 76 is initiated.

[0044] In operation, exhaust gases 66 from the diesel engine 50 are advanced through the particulate filter assembly 72. As described above, during such advancement of exhaust gases 66 through the particulate filter assembly 72, the catalyst 74 catalyzes a reaction which removes the hydrocarbons and carbon monoxide from the exhaust gases 66 by converting such hydrocarbons and carbon monoxide into water vapor, carbon dioxide, and other less toxic gases. During startup of the engine 50, the controller 100 may actuate the plasmatron 54 (and open the flow valve 98, if such a valve is used) to generate and deliver reformate gas 58 to the catalyst 74 so as to light off the catalyst 74 contemporaneously with startup of the engine 50 thereby preventing the escape of certain untreated emissions through the catalyst 74 prior to light off of the catalyst 74 by the heat from the exhaust gases 66. However, once the catalyst 74 has achieved its light off temperature (e.g., 250 degrees Celsius), the controller 100 deactivates the plasmatron 54 (and closes the flow valve 98, if such a valve is used) such that no additional reformate gas 58 is produced and delivered to the catalyst 74.

[0045] During advancement of the exhaust gases 66 from the engine 50 through the particulate filter assembly 72, soot particles present in the exhaust gases 66 are trapped by the soot particulate filter 76. The controller 100 maintains the plasmatron 54 in its deactivated mode of operation (i.e., such that no reformate gas 58 is produced) until the controller 100 determines that the particulate filter assembly 72 needs to be regenerated. Specifically, the controller 100 monitors the output signals from the pressure sensors 104 on the signal line 106 to determine if the buildup of soot in the soot particulate filter 76 has reached a predetermined level. Once the controller 100 determines that the soot particulate filter 76 is in need of regeneration, the controller actuates the plasmatron 54 (and opens the flow valve 98, if such a valve is used) so as to generate and deliver reformate gas 58 into contact with the catalyst 74 to catalyze oxidation reactions between the oxygen in the exhaust gas 66 and the hydrogen and carbon monoxide in the reformate gas 58. These highly exothermic oxidation reactions produce heat that is transferred to the downstream-positioned soot particulate filter 76. This heat, which may be illustrative in the range of 600-650 degrees Celsius (or less in the case of use of a catalyzed soot particulate filter 76), ignites soot particles trapped in the particulate filter 76 thereby regenerating the filter 76.

[0046] As described herein, regeneration of the soot filter 76 may be self-sustaining once initiated by heat from the exothermic reaction catalyzed by the catalyst 74. Hence, once the soot particulate filter 76 is heated to its a temperature at which the soot particles trapped therein begin to ignite, and the soot ignition process is self-sustained in the filter 76, the controller 100 deactivates the plasmatron 54 (and closes the flow valve 98, if such a valve is used) such that no additional reformate gas 58 is produced and delivered to the catalyst 74. The controller 100 then monitors the output from the pressure sensors 104 to determine when the particulate filter assembly 72 is again in need of regeneration.

[0047] As described herein, the catalyst 74 of particulate filter assembly 72 may be configured to burn (i.e., convert) hydrocarbons and carbon monoxide and thus operates as a catalytic converter to remove such effluents from exhaust gases 66 (in addition to functioning as a trap to trap soot particles in filter 76). However, it should be appreciated that particulate filter assembly 72 may be used in, for example, a series arrangement with another emission abatement device 108, as shown in FIG. 4. In such a manner, exhaust gases 66 from the engine 50 may be passed through the emission abatement device 108 to remove, for example, hydrocarbons (HC), oxides of nitrogen (NOₓ), oxides of sulfur (SOₓ), and/or carbon monoxide (CO) from the exhaust gases 66. To do so, the emission abatement device 108 may be embodied as a catalytic converter or a trap or other similar device which removes desired compounds from the engine’s exhaust gases 66.

[0048] Soot particles in the partially treated exhaust gases 110 which exit the emission abatement device 108 are then trapped by the filter 76 of the particulate filter assembly 72 as described above. When the filter 76 needs to be regenerated, the plasmatron 54 may be actuated to produce reformate gas 58 in the manner described above.

[0049] It should be appreciated that when the particulate filter assembly 72 is used in conjunction with an additional emission abatement device 108, the catalyst 74 may still be configured to remove certain compounds from the engine’s exhaust gases 66. In particular, the emission abatement device 108 may be used to remove a first number of compounds from the engine’s exhaust gases 66, whereas the catalyst 74 is configured to remove a second number of compounds from the exhaust gases 66. Alternatively, the catalyst 74 may be configured to perform only the function of catalyzing the reactions necessary to regenerate the soot.
filter 76 with all other emission abatement functions being performed by the emission abatement device 108 or other devices.

[0050] It should be appreciated that reformate gas from the plasmatron 54 may also be used to light off the catalysts (not shown) associated with the emission abatement device 108 during startup in a similar manner to as described herein in regard to the catalyst 74. In such a case, the plasmatron 54 would be fluidly coupled to an inlet (not shown) associated with emission abatement device 108 via a fluid line (not shown) to provide for the advancement of reformate gas 58 from the plasmatron 54 to the device 108.

[0051] As shown in FIG. 5, it is also within the scope of this disclosure for a pair of particulate filter assemblies 72 to be used in a parallel arrangement. A diverter valve 112, which is under the control of the controller 100, selectively diverts the flow of exhaust gases 66 between the two particulate filter assemblies 72. For example, exhaust gases 66 from the engine 50 may be routed through one of the particulate filter assemblies 72 while the other assembly 72 is maintained “offline.” The offline particulate filter assembly 72 may then be regenerated by use of the plasmatron 54 as described above. Once the soot filter 76 of the offline particulate filter assembly 72 has been regenerated, the position of the diverter valve 112 may be switched such that exhaust gases 66 from the engine 50 are routed through the newly regenerated particulate filter assembly 72, while the other particulate filter assembly 72 is offline for soot filter regeneration.

[0052] While the disclosure is susceptible to various modifications and alternative forms, specific exemplary embodiments thereof have been shown by way of example in the drawings and has herein be described in detail. It should be understood, however, that there is no intent to limit the disclosure to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the disclosure.

[0053] There are a plurality of advantages of the present disclosure arising from the various features of the apparatus and methods described herein. It will be noted that alternative embodiments of the apparatus and methods of the present disclosure may not include all of the features described yet still benefit from at least some of the advantages of such features. Those of ordinary skill in the art may readily devise their own implementations of an apparatus and method that incorporate one or more of the features of the present disclosure and fall within the spirit and scope of the present disclosure.

1. An apparatus for removing particulate soot from an exhaust gas of an internal combustion engine, comprising:
   a source of hydrogen gas,
   a catalyst configured to catalyze an exothermic oxidation reaction between the hydrogen gas and a gaseous component comprising oxygen, and
   a soot filter positioned proximate to the catalyst, wherein heat generated by the exothermic oxidation reaction is transferred to the soot filter.

2. The apparatus of claim 1, further comprising a housing, wherein the catalyst and the soot filter are housed in the housing.

3. The apparatus of claim 1, wherein the heat generated by the exothermic reaction obtains a temperature of between approximately 600 degrees Celsius and approximately 650 degrees Celsius.

4. The apparatus of claim 1, wherein the catalyst is disposed on a ceramic or metallic substrate.

5. The apparatus of claim 1, wherein the source of hydrogen gas comprises a fuel reformer.

6. The apparatus of claim 5, wherein the fuel reformer comprises a plasma fuel reformer.

7. The apparatus of claim 1, wherein the soot filter has a catalytic material disposed thereon.

8. The apparatus of claim 7, wherein the heat generated by the exothermic reaction obtains a temperature of between approximately 300 degrees Celsius and approximately 600 degrees Celsius.

9. The apparatus of claim 7, wherein the heat generated by the exothermic reaction obtains a temperature of between approximately 300 degrees Celsius and approximately 350 degrees Celsius.

10. An apparatus for removing particulate from an exhaust gas of an internal combustion engine, comprising:
    a hydrogen generator configured to produce hydrogen gas, and
    a particulate filter assembly having a catalyst and a soot filter, the particulate filter assembly configured to receive (i) hydrogen gas from the hydrogen generator, and (ii) the exhaust gas from the internal combustion engine.

11. The filter apparatus of claim 10, wherein the soot filter is positioned downstream of the catalyst.

12. An apparatus for removing particulate soot from an exhaust gas, comprising:
    a housing having a chamber and a hydrogen gas inlet,
    a catalyst positioned in the chamber at a position downstream of the hydrogen gas inlet, the catalyst being configured to catalyze an exothermic oxidation reaction between hydrogen gas and a gaseous component comprising oxygen, and
    a filter positioned in the chamber at a position downstream of the catalyst, the filter being configured to trap soot from the exhaust gas.

13. The apparatus of claim 12, further comprising a source of hydrogen gas fluidly coupled to the hydrogen gas inlet.

14. The apparatus of claim 13, wherein the source of hydrogen gas comprises a fuel reformer.

15. The apparatus of claim 14, wherein the fuel reformer comprises a plasma fuel reformer.

16. The apparatus of claim 12, wherein:
    the chamber further has an exhaust gas inlet and an exhaust gas outlet,
    the catalyst being positioned between the filter and the exhaust gas inlet, and
    the filter being positioned between the catalyst and the exhaust gas outlet.

17. A method of regenerating a particulate filter comprising the steps of:
advancing hydrogen gas into contact with a catalyst, generating heat from an exothermic oxidation reaction between the hydrogen gas and a gaseous component containing oxygen in the presence of the catalyst, and igniting particulate trapped in the particulate filter with the heat.

18. The method of claim 17, further comprising the step of reforming a hydrocarbon fuel to produce the hydrogen gas.

19. The method of claim 17, wherein the igniting step comprises heating the particulate trapped in the particulate filter to a temperature of between approximately 600 degrees Celsius and approximately 650 degrees Celsius.

20. The method of claim 17, wherein:
the particulate filter has a catalytic material disposed thereon, and
the igniting step comprises heating particulate trapped in the particulate filter to a temperature of between approximately 300 degrees Celsius and approximately 600 degrees Celsius.

21. The method of claim 17, wherein:
the particulate filter has a catalytic material disposed thereon, and
the igniting step comprises heating the particulate trapped in the particulate filter to a temperature of between approximately 300 degrees Celsius and approximately 350 degrees Celsius.

22. A method of regenerating a soot filter comprising the steps of:
introducing hydrogen gas into an exhaust gas of an internal combustion engine,
advancing the hydrogen gas and the exhaust gas into contact with a catalyst,
generating heat from a reaction between the hydrogen gas and the exhaust gas in the presence of the catalyst, and
igniting soot trapped in the soot filter with the heat.

23. The method of claim 22, further comprising the step of reforming a hydrocarbon fuel to produce the hydrogen gas.

24. The method of claim 22, wherein the igniting step comprises heating the soot trapped in the soot filter to a temperature of between approximately 600 degrees Celsius and approximately 650 degrees Celsius.

25. The method of claim 22, wherein:
the soot filter has a catalytic material disposed thereon, and
the igniting step comprises heating the soot trapped in the soot filter to a temperature of between approximately 300 degrees Celsius and approximately 600 degrees Celsius.

26. The method of claim 22, wherein:
the soot filter has a catalytic material disposed thereon, and
the igniting step comprises heating the soot trapped in the soot filter to a temperature of between approximately 300 degrees Celsius and approximately 350 degrees Celsius.

27. A method of regenerating a particulate carbon-based soot filter of a diesel engine, the method comprising the steps of:
operating a fuel reformer to produce a reformate gas,
introducing the reformate gas into an exhaust gas from the diesel engine,
advancing the reformate gas and the exhaust gas through an oxidation catalyst to generate an exothermic reaction, and
heating the soot filter with heat from the exothermic reaction to a sufficient temperature to ignite soot particulates trapped in the soot filter.

28. The method of claim 27, wherein the operating step comprises operating a plasma rich fuel reformer.

29. The method of claim 27, wherein the operating step comprises operating the fuel reformer to produce a hydrogen-rich reformate gas.

30. An apparatus for removing particulate soot from an exhaust gas of an internal combustion engine, comprising:
a source of an oxidizable gas,
a catalyst configured to catalyze an exothermic oxidation reaction between the oxidizable gas and a gaseous component comprising oxygen, and
a soot filter positioned proximate to the catalyst, wherein heat generated by the exothermic oxidation reaction is transferred to the soot filter.

31. The apparatus of claim 30, further comprising a housing, wherein the catalyst and the soot filter are housed in the housing.

32. The apparatus of claim 30, wherein the heat generated by the exothermic reaction obtains a temperature of between approximately 600 degrees Celsius and approximately 650 degrees Celsius.

33. The apparatus of claim 30, wherein the catalyst is disposed on a ceramic or metallic substrate.

34. The apparatus of claim 30, wherein the source of oxidizable gas comprises a fuel reformer.

35. The apparatus of claim 34, wherein the fuel reformer comprises a plasma fuel reformer.

36. The apparatus of claim 30, wherein the fuel reformer comprises a catalytic material disposed thereon.

37. The apparatus of claim 36, wherein the heat generated by the exothermic reaction obtains a temperature of between approximately 300 degrees Celsius and approximately 600 degrees Celsius.

38. The apparatus of claim 36, wherein the heat generated by the exothermic reaction obtains a temperature of between approximately 300 degrees Celsius and approximately 350 degrees Celsius.

39. The apparatus of claim 30, wherein the oxidizable gas comprises hydrogen.

40. The apparatus of claim 30, wherein the oxidizable gas comprises carbon monoxide.

41. An emission abatement assembly, comprising:
a fuel reformer configured to reform hydrocarbon fuel into a reformate gas,
a catalyst configured to catalyze an exothermic oxidation reaction between the reformate gas and a gaseous component comprising oxygen, and
a soot filter positioned downstream of the catalyst, wherein heat generated by the exothermic oxidation reaction is transferred to the soot filter.

42. The assembly of claim 41, further comprising a housing having a reformate gas inlet, wherein:
the fuel reformer is fluidly coupled to the reformate gas inlet, and
the catalyst and the soot filter are housed in the housing.

43. The assembly of claim 41, wherein the catalyst is disposed on a ceramic or metallic substrate.
44. The assembly of claim 41, wherein the soot filter has a catalytic material disposed thereon.
45. The assembly of claim 41, wherein the fuel reformer comprises a plasma fuel reformer.

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