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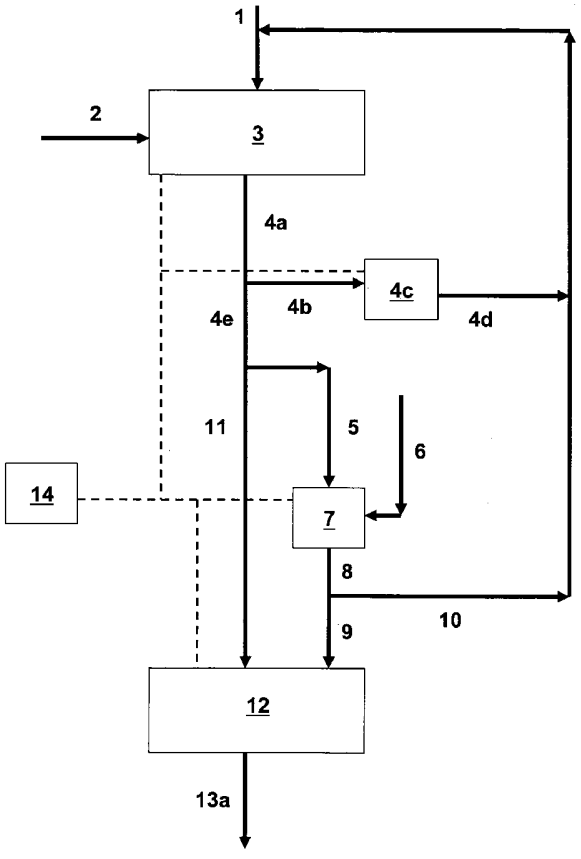
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(54) Title: INTEGRATED SYSTEM FOR REDUCING FUEL CONSUMPTION AND EMISSIONS IN AN INTERNAL COMBUSTION ENGINE



(57) Abstract: An integrated NOx after-treatment system for an internal combustion engine includes (a) a fuel supply subsystem for supplying an inlet fuel stream to the engine fuel intake, (b) an air supply subsystem for supplying an inlet oxygen-containing air stream to the engine air intake, (c) a fuel processor to which a fuel stream having substantially the same composition of the engine inlet fuel stream is directed, the fuel processor converting the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO, (d) an adsorbent bed subsystem that cycles between an adsorbent state in which constituents from the engine exhaust stream are adsorbed and a desorption state in which the constituents are desorbed and converted to at least one of SO_2 and an environmentally-benign component selected from the group consisting of N_2, H_2O and CO_2, and (e) a recirculation stream for directing at least some of the fuel processor output stream to the engine air intake.

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INTEGRATED SYSTEM FOR REDUCING FUEL CONSUMPTION AND EMISSIONS IN AN INTERNAL COMBUSTION ENGINE

Field of the Invention

[0001] The present invention relates to the field of internal combustion engines, including diesel-fueled and gasoline-fueled internal combustion engines.

Background of the Invention

[0002] The present integrated system is capable of reducing fuel consumption and regulated emissions of internal combustion engines. This capability is achieved by integrating a fuel processing device with the engine system and other devices that assist in reducing regulated emissions. The present integrated fuel processing system supplies a hydrogen-containing stream to one or more parts of the engine system resulting in reduced fuel consumption and reduced emissions. The present system is integrated such that components of the engine provide benefits in addition to reducing fuel consumption and reduced regulated emissions.

[0003] Due to the ever-increasing cost of fuel, operators of internal combustion engines are always searching for methods to reduce fuel

costs. Also, engine manufactures are always searching for cost effective methods to reduce emissions so that new engine designs can be certified to emission regulations that are continually being made more stringent.

[0004] To date, reducing fuel consumption has usually meant increasing emissions. Conversely, methods that reduce emissions typically increase fuel consumption. Neither of these outcomes is desirable to engine operators or engine manufacturers. The trade-off between emissions and fuel consumption is therefore a significant problem facing engine operators and manufacturers.

[0005] The present integrated system reduces both fuel consumption and regulated emissions simultaneously, without significant adverse effect on capital costs and with the potential for improved operating costs as a result of better fuel efficiency. Capital cost can be potentially reduced by eliminating certain parts, such as exhaust gas recirculation system components, and/or enabling certain parts, such as diesel particulate filters and engine displacement/total cylinder volume, to be reduced in size.

[0006] In the past, NOx emissions have been reduced primarily by increasing and/or cooling the exhaust gas recycle stream (EGR). Another technique employed to reduce NOx (nitrogen oxide) emissions has been to retard fuel injection timing. In this regard, the

timing of fuel injection into the engine's combustion chamber(s) can be advanced in relation to fuel injection timing that is retarded to reduce NOx emissions. Advancing fuel injection timing increases fuel economy and engine exhaust NOx emissions, which are in turn reduced downstream in the after-treatment portion of the present system.

[0007] Although each of the foregoing techniques is capable of reducing NOx emissions, they each also increase the engine's fuel consumption. To date, there have been no established techniques for reducing both NOx emissions and fuel consumption simultaneously.

Summary of the Invention

[0008] The above-described and/or other shortcomings of prior techniques for reducing NOx emissions are overcome by an integrated NOx after-treatment system for an internal combustion engine. The system comprises:

(a) a fuel supply subsystem for supplying an inlet fuel stream to the engine fuel intake;

(b) an air supply subsystem for supplying an inlet oxygen-containing air stream to the engine air intake;

(c) a fuel processor to which a fuel stream having substantially the same composition of the engine inlet fuel stream is directed, the fuel processor converting the

fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO;

(d) a catalyst/adsorbent material bed subsystem that cycles between a trapping state in which constituents from the engine exhaust stream are trapped and a regenerating state in which the constituents are desorbed and converted to at least one of SO_2 and an environmentally-benign component selected from the group consisting of N_2, H_2O and CO_2;

(e) a recirculation stream for directing at least some of the fuel processor output stream to the engine air intake.

[0010] In a preferred system embodiment, conversion of the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO can be promoted by thermal means. In a preferred system embodiment, conversion of the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO can also be promoted by a catalyst material. A preferred catalyst material adsorbs CO, and preferably comprises platinum. The platinum-containing catalyst material can be disposed on a supporting substrate. A preferred supporting substrate is ceramic, preferably selected from the group consisting of zirconia and alumina.

[0011] In a preferred system embodiment, the fuel processor outlet stream molar concentration of each of H_2 and CO is in the range of 5-30 percent.

[0012] In a preferred system embodiment, the fuel processor outlet stream comprising H_2 and CO is passed periodically through the catalyst/adsorbent bed to evolve adsorbed NOx at a temperature lower than the NOx desorption temperature of stream compositions other than that of the fuel processor outlet stream. In a preferred system embodiment, the fuel processor outlet comprising H_2 and CO is passed periodically through the catalyst/adsorbent bed to evolve adsorbed SOx at a temperature lower than the SOx desorption temperature of stream compositions other than that of the fuel processor outlet stream.

[0013] A method for reducing NOx emissions and fuel consumption in an internal combustion engine comprises:

(a) supplying an inlet fuel stream to the engine fuel intake;

(b) supplying an inlet oxygen-containing air stream to the engine air intake;

(c) directing a fuel stream having substantially the same composition of the engine inlet fuel stream to a fuel processor;

(d) converting the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO;

(e) cycling an adsorbent bed between an adsorbent state in which constituents from the engine exhaust stream are adsorbed and a desorption state in which the constituents are desorbed and converted to at least one of SO_2 and an environmentally-benign component selected from the group consisting of N_2, H_2O and CO_2;

(f) directing at least some of the fuel processor output stream to the engine air intake.

[0014] In a preferred method embodiment, fuel injection timing is advanced in relation to fuel injection timing that is retarded to reduce NOx emissions.

[0015] In a preferred method embodiment, conversion of the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO can promoted by thermal means. In a preferred method embodiment, conversion of the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO can also be promoted by a catalyst material. A preferred catalyst material adsorbs CO, and preferably comprises platinum. The platinum-containing catalyst material can be disposed on a supporting substrate. A preferred supporting substrate is ceramic, preferably selected from the group consisting of zirconia and alumina.

[0016] In a preferred method embodiment, the fuel processor outlet stream molar concentration of each of H_2 and CO is in the range of 5-30 percent.

[0017] In a preferred method embodiment, the fuel processor outlet stream comprising H_2 and CO is passed periodically through the catalyst/adsorbent bed to evolve adsorbed NOx at a temperature lower than the NOx desorption temperature of stream compositions other than that of the fuel processor outlet stream. In a preferred method embodiment, the fuel processor outlet comprising H_2 and CO is passed periodically through the catalyst/adsorbent bed to evolve adsorbed SOx at a temperature lower than the SOx desorption temperature of stream compositions other than that of the fuel processor outlet stream.

[0018] A fuel and an engine exhaust stream are employed in the present system and method to produce a stream containing hydrogen and carbon monoxide. This stream is produced substantially continually in a fuel processing device and supplied to a catalyst and adsorbent bed, which has trapped oxides of nitrogen (NOx) adsorbed to the adsorbent and/or the adsorbent/catalyst. The stream promotes NOx desorption and reacts with the NOx and regenerates the NOx adsorption material so that it can be made available to another cycle of trapping NOx from the engine's exhaust stream. The catalyst and adsorbent bed can be contained within a number of beds, including a

rotating bed, that is controlled in a manner that decreases or minimizes the reducing agent required to achieve a desired reduction in NOx emissions, and/or decreases or minimizes the size and cost of the equipment involved, and/or provides some trade-off between the amount of reducing agent required and the size/cost of the equipment. The adsorbent material can also be contained in a plurality of beds that are made to undergo a cycle of adsorption and regeneration. The cycle length and frequency is controlled or set so as to decrease or minimize the quantity of reducing agent required or desirable to achieve a desired reduction in NOx emissions.

[0019] A single material could potentially act as both a catalyst and an adsorbent. Such a material would include platinum, which in hydrocarbon catalytic reactors (reformers) can act as a catalyst for the decomposition of the hydrocarbon feed material to hydrogen, carbon dioxide and carbon monoxide, and also acts as an adsorbent of carbon monoxide, which preferentially adsorbs on catalytic materials containing platinum. Other such adsorbent/catalyst materials are carbon nanohorns, which adsorb ethanol and, in the presence of oxygen, catalyze the oxidation reaction between ethanol and oxygen (see Nisha et al., "Adsorption and catalytic properties of single-walled carbon nanohorns", Chemical Physics Letters 328 (2000), pp. 381-386).

Brief Description of the Drawing(s)

[0020] Figure 1 is a schematic process flow diagram illustrating a preferred embodiment of the present system for reducing emissions and fuel consumption in an internal combustion engine system.

[0021] Figure 2 is a top schematic view of the rotary adsorbent bed of the system for reducing emissions and fuel consumption illustrated in Figure 1.

[0022] Figure 3 is a cross-sectional schematic view of the rotary adsorbent bed of the system for reducing emissions and fuel consumption illustrated.

[0023] Figure 4 illustrates an alternative catalyst and adsorbent bed configuration where two or more beds are cycled between an adsorption and a regeneration step.

Detailed Description of Preferred Embodiment(s)

[0024] In Figure 1, intake air stream 1 is supplied to an internal combustion engine 3. The air intake system typically includes filters and flow control devices such as a throttle valve or a compressor of some type. If a compressor such as a turbo-compressor or a super charger is employed an intercooler can be included as part of the air intake stream. Sensors such as temperature and flow measuring devices are typically included to assist in optimizing the engine's

operation. Most engines will also supply exhaust gas to the intake air as part of an exhaust gas recycle (EGR) system employed to reduce emissions from the engine.

[0025] Fuel stream 2 is supplied to the internal combustion engine 3. Typically the supply of fuel stream 2 is via fuel injectors that could have various fuel spray patterns and injection schemes controlled by the engine's control unit 14. The spray patterns and injection schemes are employed to improve or optimize the fuel consumption and exhaust emission operating parameters. Fuel supply equipment is continuously being improved and thus the fuel supply equipment employed in the embodiment should be those that are deemed to be available and well- or best-suited for the desired end use.

[0026] Internal combustion engine 3 could be a diesel, gasoline, natural gas, liquid propane gas (LPG) or similarly fueled engine of either compression ignition of spark ignition type. The engine mostly likely will have an EGR system but this is not required for the present embodiment. Also, the engine can optionally have various after-treatment devices (not shown in figure 1) located in the exhaust system. Such after-treatment devices would typically be oxidation catalysts and particulate filters that assist the total engine system to meet various emission regulations.

[0027] The engine exhaust stream 4a exits engine 3 and an exhaust gas recycle stream 4b is drawn from stream 4a as controlled by the engine control unit 14 via the EGR valve 4c. A stream 5 that is a portion of the engine's full exhaust stream is also taken from the full exhaust stream. This can be taken at various locations in streams 4, 4b, 4d and 4e. Stream 5 is directed to a fuel processing device 7. The quantity of exhaust supplied via stream 5 can optionally be controlled with a valve or other similar flow control device. Preferably, there should be no active control device and a wide range of flows that result from the passive nature of the device are acceptable for the fuel processor's requirements. An example of such a passive device is an orifice that relies on the concept of sonic flow to limit the flow or flow range through the orifice. The fuel processor is designed to operate as desired within the range resulting from the passive nature. A fuel stream 6 is also supplied at a rate controlled by the engine control unit, 14. The fuel stream 6 is preferably composed of the same type of fuel as in stream 2 and, preferably, is supplied from the same storage device (not shown in Figure 1). It is possible that the fuel type in stream 6 is different than the fuel type of stream 2.

[0028] The fuel processing device 7 employs the oxygen and the water in the engine's exhaust stream to convert the fuel stream 6 into components such as hydrogen and carbon monoxide. The presence of carbon dioxide in the engine exhaust stream also has beneficial effects on the reactions that produce the desired hydrogen and carbon

monoxide components employed in the downstream after-treatment portion of the present system. The exact composition will depend on a number of parameters such as the amount of exhaust stream supplied and the exhaust stream's composition. The composition is a result of the internal design of the fuel processor. Preferably, there is no catalyst employed to promote the desired reactions. Important design considerations are reactant mixing rates, temperature profiles, catalysts employed (if any) and their position in the fuel processing device as well as other considerations. The design of the fuel processor and its operating parameters will be different for each different application. The fuel processor 7 is preferably mechanically integrated with the exhaust stream 11 to assist with desired temperature profiles in the device and reduce equipment costs. This is envisioned to have the reactor tube be positioned within the full exhaust stream tubing but this is not required.

[0029] Not requiring the use of reactants other than the fuel stream and engine exhaust stream greatly simplifies the system and thus reduces costs and increases system reliability.

[0030] The fuel processor's product stream 8 can optionally be supplied, in part or in whole, to the engine's air intake stream 1. If a portion of stream 8 is to be supplied to the engine's intake it can be done directly or via the EGR stream 4d, as shown in Figure 1. In some engine designs the supply of H_2 and CO to the air intake stream

affects the combustion properties in a beneficial way that can be employed to reduce emissions and fuel consumption. For example in a gasoline engine the addition of H_2 and CO or such compounds will extend the lean burn limit of the combustion mixture. This allows more air to be supplied for combustion and thus reduces emissions and increases efficiency. Such performance improvements have also been reported in diesel compression ignition engines. Another benefit is that if H_2 and CO or such compounds are supplied to the engine intake air from the fuel processor the engine's power output is increased.

[0031] Another very beneficial reason for supplying some or all of stream 8 to the engines air intake is that it allows the fuel processor 7 to operate in a completely or rather steady state manner rather than continually going through various transients. Operation at steady state will place less stress on the device and thus extend its lifetime.

[0032] All or a portion of the fuel processor's product stream 9 is supplied to a NOx trapping device 12 that can trap NOx from the exhaust stream 11 when it is passed through the bed material made up of catalyst and/or adsorbent type materials. When the material in the bed is properly exposed to the stream from the fuel processor 9, the NOx desorbs and reacts to form harmless emissions such as N_2 and H_2O. The fuel processor product stream 9 is also employed to

remove sulfur oxide (SOx) compositions that may have adsorbed onto the adsorbent material in the same way that NOx may have adsorbed.

[0033] All or a portion of stream 8 or other syngas stream can also be directed to a diesel particulate filter to assist in regeneration of that device. (Syngas, also referred to as synthesis gas, is a generic term that refers to a fluid stream that contains hydrogen and carbon monoxide, such as that formed, for example, in industrial processes utilizing coal-derived mixtures of carbon monoxide and hydrogen.) This regeneration assistance could be either passive or active or a combination depending on equipment design and the application's duty cycle.

[0034] Other practitioners of the technology involved here employ agents such as diesel fuel to remove NOx and SOx adsorbed to the bed. The use of H_2 and/or CO allows the removal of these materials in a more effective manner and at lower temperatures that allow a simpler, less expensive system with a longer life time.

[0035] Figure 2 shows some details of the adsorbent bed 12. The core 21 of bed 12 is a structure that is covered with materials that promote the ability to trap NOx and to convert NOx species into species such as N_2, H_2O and CO_2. The adsorption material typically includes platinum, barium oxide and rhodium. Other suitable adsorbent materials can be employed as well. The exact materials

employed and their quantities depend on the specific characteristics of the application and the desired results.

[0036] The core's structure 21 onto which the active materials are placed can be made from various materials such as cordierite, metal meshes, wire meshes and/or fiberglass.

[0037] The materials can be deposited in a non-uniform way so as to more optimally meet the desired requirements of low product cost and minimal reducing agent requirements.

[0038] With the use of appropriate mechanical design, stream 11 is directed through a trapping segment 22 of the bed while the reducing agent stream 9 is directed through the regenerating segment 23 of the bed. The relative sizes of the two segments depend on the specific characteristics of the application and the desired results. The bed can be rotated in either a clockwise or counter clockwise direction so that all parts of the bed are alternately exposed to the exhaust stream 11 and the fuel processor's product stream 9. The speed at which the bed rotates can be controlled if desired. Adjusting the rotational speed of the bed can reduce or minimize the bed size and reduce or minimize the amount of stream 9 that is required. It may be desirable to rotate the bed at a rate between 2 and 120 revolutions per minute (1 cycle every 0.5 sec to 30 seconds). Due to the very fast adsorption, desorption and reaction rates a fast cycle rate would reduce or minimize the size of the bed.

[0039] The bed can also be rotated at such a rate as to keep the NOx loading at a level that is a good trade-off between the efficiency of the adsorption steps and the efficiency of the desorption/reduction steps that result in low NOx emissions.

[0040] In Figure 3, the exhaust stream 11 and the stream 9 are supplied to a valve that is able to direct the flow of both stream 9 and stream 11 to the desired beds. It is possible to have any number of beds more than 1 where stream 9 is only directed to a small number, including only one, bed at a time. The most practical embodiment would include 2 to 5 beds with stream 9 being directed to one at a time while the other beds are receiving stream 11.

[0041] In Figure 4, valve 31a is used to direct the flows of stream 9 and 11 alternatively to beds 32 and 33. Valve 31a is repositioned at such a rate as to minimize the size of the two beds 32 and 33 and still allow desired regeneration of the beds. As with the rotary bed the valve can be cycled at a rate that keeps the NOx loading on the bed fairly constant. Valve 31a can also be cycled at a rate that helps to shrink the total size and mass of the system. Valve 31b is cycled simultaneously as valve 31a is cycled. Stream 13b from the bed that is being regenerated can then be directed to the air intake stream to avoid the wasting of fuel energy. Stream 13a is analogous to stream 10 of Figure 1, but has the advantage of having the recirculated stream pass over/through the catalyst and adsorbent beds to achieve a

clean-up effect on the beds. As mentioned previously it also can increase engine power output due to increased fueling or provide beneficial combustion conditions.

[0042] Some groups have proposed the use of a single-leg configuration where the full engine exhaust stream is passing through the adsorbent bed during the regeneration step. This configuration requires large amounts of oxygen to be consumed by combusting with fuel every time the adsorbent bed is to be regenerated. The benefits of the configurations shown in Figures 2-4 is that the amount of oxygen necessary to be consumed so that regeneration can take place is significantly reduced and thus the fuel penalty associated with regeneration is significantly reduced.

[0043] The exhaust stream with reduced regulated emissions is then sent to the atmosphere via stream 13a. Exhaust stream 13a can optionally be passed through other after-treatment devices before being exhausted to the atmosphere.

[0044] The engine's fuel consumption can also be reduced by advancing the fuel injection timing and using the above-described after-treatment portion of the present system to reduce to acceptable levels engine exhaust stream NOx levels that result from the advanced fuel injection timing. Fuel injection timing advance has the additional benefit of reducing the diesel particulate matter in the exhaust and thus reducing the size and cost of equipment required to

remove diesel particulate matter.

What is claimed is:

1. An integrated NOx after-treatment system for an internal combustion engine, the system comprising:

(a) a fuel supply subsystem for supplying an inlet fuel stream to the engine fuel intake;

(b) an air supply subsystem for supplying an inlet oxygen-containing air stream to the engine air intake;

(c) a fuel processor to which a fuel stream having substantially the same composition of the engine inlet fuel stream is directed, the fuel processor converting the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO;

(d) a catalyst/adsorbent material bed subsystem that cycles between a trapping state in which constituents from the engine exhaust stream are trapped and a regenerating state in which the constituents are desorbed and converted to at least one of SO_2 and an environmentally-benign component selected from the group consisting of N_2, H_2O and CO_2;

(e) a recirculation stream for directing at least some of the fuel processor output stream to the engine air intake.

2. The system of claim 1 wherein conversion of the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO is promoted by thermal means.

3. The system of claim 1 wherein conversion of the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO is promoted by a catalyst material.

4. The system of claim 3 wherein the catalyst material adsorbs CO.

5. The system of claim 4 wherein the catalyst material comprises platinum.

6. The system of claim 5 wherein the platinum-containing catalyst material is disposed on a supporting substrate.

7. The system of claim 6 wherein the supporting substrate is a ceramic substrate.

8. The system of claim 7 wherein the ceramic support is selected from the group consisting of zirconia and alumina.

9. The system of claim 1 wherein the fuel processor outlet stream molar concentration of each of H_2 and CO is in the range of 5-30 percent.

10. The system of claim 1 wherein the fuel processor outlet stream comprising H_2 and CO is passed periodically through the catalyst/adsorbent bed to evolve adsorbed NOx at a temperature lower than the NOx desorption temperature of stream compositions other than that of the fuel processor outlet stream.

11. The system of claim 1 wherein the fuel processor outlet comprising H_2 and CO is passed periodically through the catalyst/adsorbent bed to evolve adsorbed SOx at a temperature lower than the SOx desorption temperature of stream compositions other than that of the fuel processor outlet stream.

12. A method for reducing NOx emissions and fuel consumption in an internal combustion engine, the method comprising:

(a) supplying an inlet fuel stream to the engine fuel intake;

(b) supplying an inlet oxygen-containing air stream to the engine air intake;

(c) directing a fuel stream having substantially the same composition of the engine inlet fuel stream to a fuel processor;

(d) converting the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO;

(e) cycling an adsorbent bed between an adsorbent state in which constituents from the engine exhaust stream are

adsorbed and a desorption state in which the constituents are desorbed and converted to at least one of SO_2 and an environmentally-benign component selected from the group consisting of N_2, H_2O and CO_2;

(f) directing at least some of the fuel processor output stream to the engine air intake.

13. The method of claim 12 wherein fuel injection timing is advanced in relation to fuel injection timing that is retarded to reduce NOx emissions.

14. The method of claim 12 wherein conversion of the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO is promoted by thermal means.

15. The method of claim 12 wherein conversion of the fuel stream directed to the fuel processor to an outlet stream comprising H_2 and CO is promoted by a catalyst material.

16. The method of claim 15 wherein the catalyst material adsorbs CO.

17. The method of claim 16 wherein the catalyst material comprises platinum.

18. The method of claim 17 wherein the platinum-containing catalyst material is disposed on a supporting substrate.

19. The method of claim 18 wherein the supporting substrate is a ceramic substrate.

20. The method of claim 19 wherein the ceramic support is selected from the group consisting of zirconia and alumina.

21. The method of claim 12 wherein the fuel processor outlet stream molar concentration of each of H_2 and CO is in the range of 5-30 percent.

22. The method of claim 12 wherein the fuel processor outlet stream comprising H_2 and CO is passed periodically through the catalyst/adsorbent bed to evolve adsorbed NOx at a temperature lower than the NOx desorption temperature of stream compositions other than that of the fuel processor outlet stream.

23. The method of claim 12 wherein the fuel processor outlet comprising H_2 and CO is passed periodically through the catalyst/adsorbent bed to evolve adsorbed SOx at a temperature lower than the SOx desorption temperature of stream compositions other than that of the fuel processor outlet stream.

Figure 1

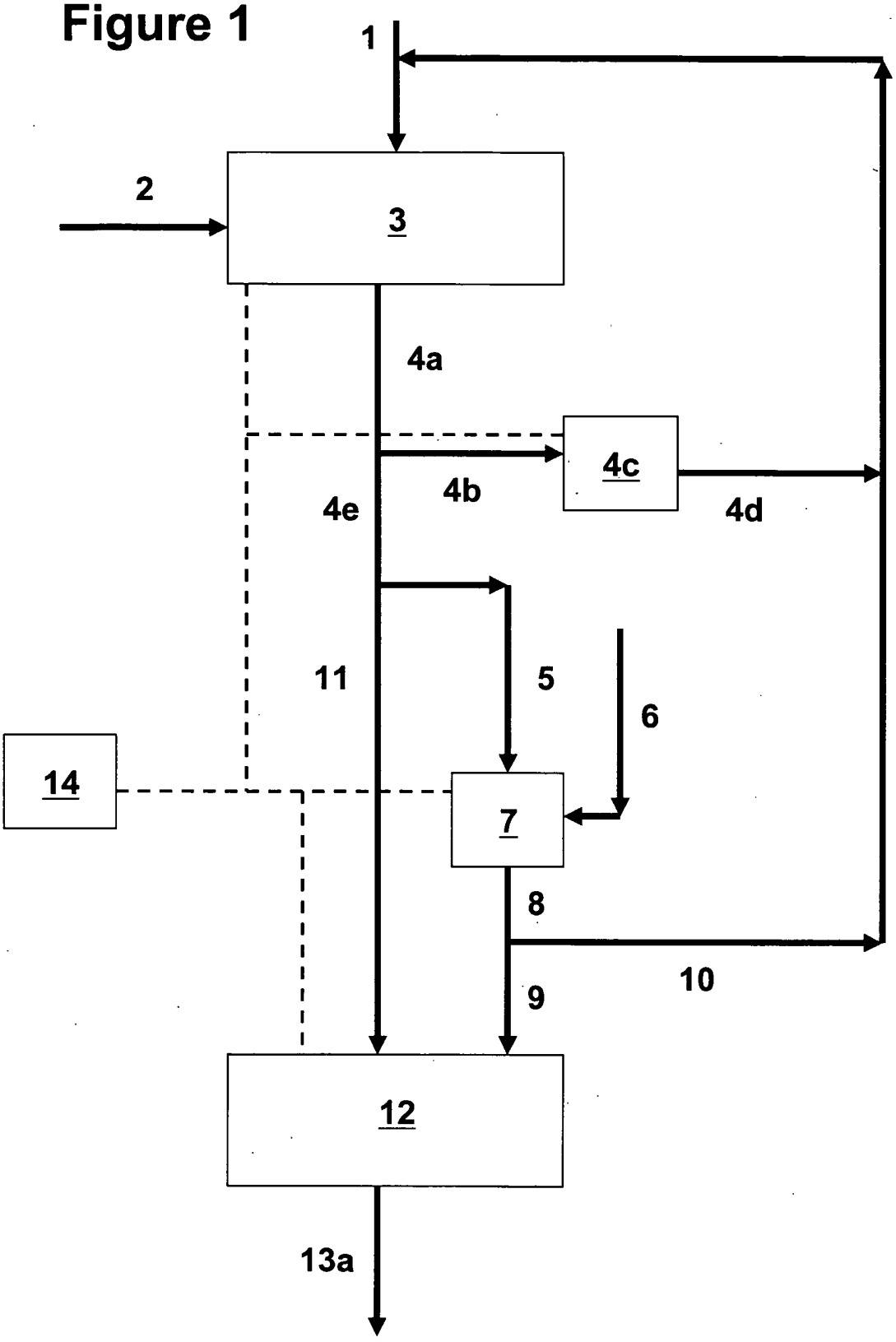


Figure 2

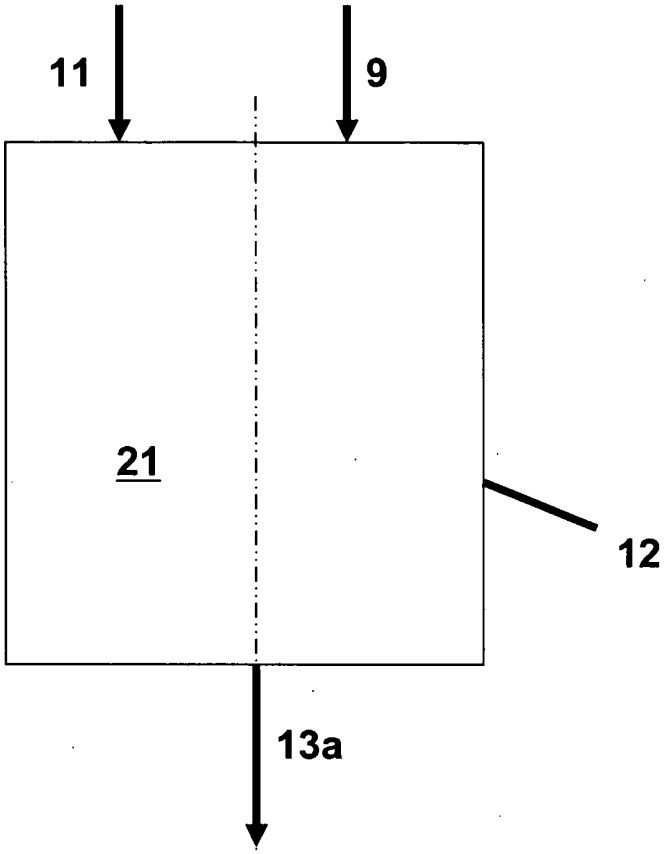


Figure 3

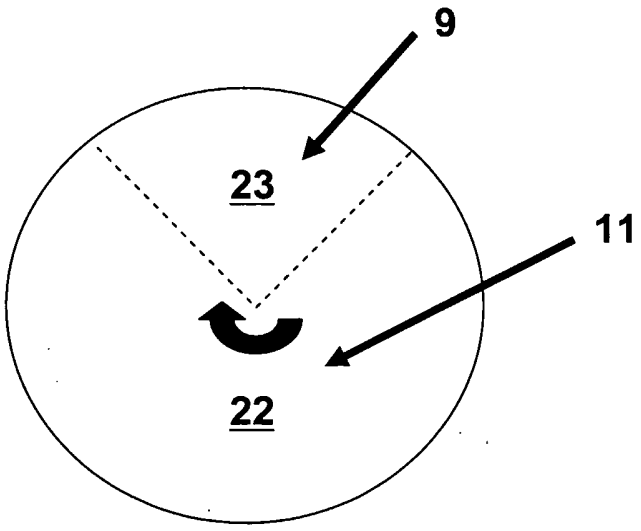


Figure 4

