Title: BYPASS CONTROLLED REGENERATION OF NOX ADSORBERS

Abstract: A method and apparatus for regenerating a lean NOx adsorber is disclosed where the NOx adsorber issued to treat exhaust gases created during the combustion of gaseous fuels in general. A bypass line is issued to maintain a target regeneration flow of exhaust gas through the NOx adsorber during regeneration regardless of operating demands on the engine. A closed and open loop control is provided. The closed loop control uses sensors determining properties of the exhaust gas during regeneration and the controller using those properties to provide an efficient regeneration cycle. A regeneration map is also provided that allows creation of in-cylinder regeneration conditions for the exhaust gas in combination of inline regeneration conditions for the exhaust gas.
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BYPASS CONTROLLED REGENERATION OF NOₓ ADSORBERS

Field of the Invention

This invention relates to methods and apparatus for regenerating NOₓ absorbers used in association with internal combustion engines.

Background of the Invention

Emissions controls for internal combustion engines are becoming increasingly important in transportation and energy applications. One class of pollutants of concern are oxides of nitrogen (NOₓ). NOₓ form during combustion in internal combustion engines.

One effective NOₓ treatment system is a lean NOₓ adsorber (LNA), also known as NOₓ trap. LNA systems need to be periodically regenerated. That is, over time, a reductant is needed to treat NOₓ traps to permit further NOₓ removal to take place. It is desirable to provide an efficient means of regeneration.

As discussed in, by way of example, WO 00/76637, there are a variety of reductants available for NOₓ trap regeneration. By way of example, many hydrocarbons, carbon monoxide (CO) and hydrogen can be used as reductants. Hydrogen is especially effective as a reductant: see US 5,953,911. Also, hydrogen is advantageous in regard to the emissions generated when hydrogen is used as a reductant since the products are water and nitrogen. Other carbon-based reductants such as CO can also be useful, however, carbon-based reductants result in production of the greenhouse gas carbon dioxide.

Hydrogen is difficult to store and is generally not readily available. However, hydrocarbons are readily available since internal combustion engines typically use hydrocarbons as fuel. As hydrocarbons comprise hydrogen atoms, they provide a possible source of hydrogen. A hydrocarbon fuel may be passed through a reformer to yield hydrogen.

Further, while hydrogen is an excellent reductant, any regeneration process that takes advantage of hydrogen runs the risk of expelling hydrogen with exhaust gas when regeneration is complete. This is undesirable due to the flammability of hydrogen. Also, regeneration using hydrogen from a hydrocarbon source consumes a
potential fuel. Therefore, improving regeneration efficiency not only reduces expulsion of untreated NO\textsubscript{x}, it also helps to reduce consumption of hydrocarbons otherwise available as a fuel.

NO\textsubscript{x} emissions can also be reduced by managing combustion. NO\textsubscript{x} emissions can be reduced by using certain gaseous fuels in place of heavy hydrocarbons. Examples of such fuels include natural gas, methane and propane. Even with gaseous fuel, however, NO\textsubscript{x} emissions are not insignificant.

Developments in gaseous combustion processes have sought to address NO\textsubscript{x} emissions problems. Spark ignited gaseous fuel engines, wherein a premixed charge of air and gaseous fuel is ignited with a spark within the combustion chamber, have resulted in further reductions of NO\textsubscript{x}. Also, high pressure directly injected gaseous fuel, ignited by an ignition source such as a small quantity of a more readily auto-ignitable pilot fuel introduced within the engine combustion chamber, yields an improvement over diesel-fuelled engines by reducing the emissions levels of NO\textsubscript{x} depending on the gaseous fuel chosen. However some NO\textsubscript{x} is still generated in such engines and therefore, it is desirable to reduce this pollutant.

This invention provides an efficient means of regenerating NO\textsubscript{x} adsorbers.

**Summary of the Invention**

The invention is directed to an efficient method and apparatus for regenerating lean NO\textsubscript{x} adsorbers. A method is disclosed providing a bypass strategy for regenerating lean NO\textsubscript{x} adsorbers efficiently.

A method is disclosed for regenerating a lean NO\textsubscript{x} adsorber efficiently by providing an easily recognizable marker indicating the completion of a regeneration cycle. This allows for real time monitoring of regeneration or a closed-loop regeneration method.

A preferred method of regenerating a lean NO\textsubscript{x} adsorber that is used to remove NO\textsubscript{x} from exhaust gas generated by combustion of a fuel in a combustion chamber of an operating internal combustion engine comprises:

(a) determining a target regeneration flow of the exhaust gas through the lean NO\textsubscript{x} adsorber,
directing a regeneration flow of the exhaust gas through the lean NO\textsubscript{x} adsorber, the regeneration flow established by one of either bypassing a bypass flow of the exhaust gas around the lean NO\textsubscript{x} adsorber when the target regeneration flow is less than the flow of the exhaust gas from the engine, resulting in the regeneration flow being substantially the same as the target regeneration flow, or directing substantially all of the exhaust gas through the lean NO\textsubscript{x} adsorber when the target regeneration flow is greater than the exhaust gas flow from the engine; the flow of the exhaust gas from the engine and the bypass flow are determined by reference to at least one of: the speed of the engine, the load of the engine, the intake manifold temperature of the engine, the intake air mass flow, the fuel flow into the engine, the intake manifold pressure of the engine, the measured flow of the exhaust gas flow out of the engine, and the temperature and pressure of the exhaust gas

reacting, within the exhaust gas and upstream of the lean NO\textsubscript{x} adsorber, the first quantity of the reductant to maintain a lambda of the regeneration flow of less than one across the lean NO\textsubscript{x} adsorber.

The method can be practiced with the reductant being hydrogen. The method can also be practiced with the reductant being a hydrocarbon, and in a preferred example, the hydrocarbon is methane. A further aspect of the method can comprise reforming a second quantity of the hydrocarbon within the exhaust gas upstream of the lean NO\textsubscript{x} adsorber to introduce hydrogen into the regeneration flow.

In a preferred method the fuel that is burned in the engine is the same as, or is interchangeable with, the reductant. In a further embodiment, the bypass flow is directed through a second lean NO\textsubscript{x} adsorber.

A method is also provided of operating an internal combustion engine equipped with an aftertreatment system for removing NO\textsubscript{x} from exhaust gas generated by combustion of a fuel in at least one combustion chamber of the engine. The method
comprises directing all of the exhaust gas through a lean NO$_x$ adsorber during normal operation of the engine, and periodically regenerating the lean NO$_x$ adsorber during a regeneration cycle defined by a regeneration cycle start time and a regeneration cycle end time. The regeneration cycle includes:

5 (a) determining a target regeneration flow of the exhaust gas through the lean NO$_x$ adsorber,

(b) directing a regeneration flow of the exhaust gas through the lean NO$_x$ adsorber, the regeneration flow established by one of either bypassing a bypass flow of the exhaust gas around the lean NO$_x$ adsorber when the target regeneration flow is less than the flow of the exhaust gas from the engine, resulting in the regeneration flow being substantially the same as the target regeneration flow, and directing substantially all of the exhaust gas through the lean NO$_x$ adsorber when the target regeneration flow is greater than the flow of the exhaust gas from the engine.

10 the flow of the exhaust gas from the engine and the bypass flow are determined by reference to at least one of:

    the speed of the engine,
    the load of the engine,
    the intake manifold temperature of the engine,
    the intake air mass flow,
    the fuel flow into the engine,
    the intake manifold pressure of the engine,
    exhaust gas flow measured out of the engine, and
    the temperature and pressure of the exhaust gas,

20 The first quantity of the reductant is reacted within the exhaust gas and upstream of the lean NO$_x$ adsorber to maintain a lambda of the regeneration flow of less than one across the lean NO$_x$ adsorber.

    In a preferred method the fuel is the same as, or is interchangeable with, the reductant.

25 A further aspect of this method comprises introducing hydrogen into the regeneration flow by reforming a second quantity of the hydrocarbon within the exhaust gas upstream of the lean NO$_x$ adsorber. In a preferred example, the
hydrocarbon is methane. In a further embodiment, hydrogen is introduced into the regeneration flow by reforming the methane within the exhaust gas upstream of the lean NOₓ adsorber.

With regard to the introduction of a hydrocarbon comprising methane into the aftertreatment system, in one embodiment of the method, the hydrocarbon can be oxidized within the exhaust gas prior to directing the bypass flow around the lean NOₓ adsorber. However, in a preferred embodiment the hydrocarbon is oxidized within the regeneration flow. In these embodiments, the first quantity of the hydrocarbon can be directed into the exhaust gas by at least one of a valve or an injector.

In another embodiment of the method of operating an internal combustion engine equipped with an aftertreatment system, the regeneration cycle end time is based on the lambda of the regeneration flow downstream of the lean NOₓ adsorber being representative of an oxygen potential below a pre-determined threshold concentration. In a further embodiment, the regeneration cycle is based on a concentration of the reductant downstream of the lean NOₓ adsorber being above a pre-determined threshold concentration.

In another embodiment of the introduction hydrogen into the regeneration flow by reforming a second quantity of the hydrocarbon within the exhaust gas upstream of the lean NOₓ adsorber, the regeneration cycle end time is based on a concentration of at least one of CO or H₂ downstream of the lean NOₓ adsorber being above a pre-determined threshold concentration.

In another embodiment of the method of operating an internal combustion engine equipped with an aftertreatment system, the regeneration flow is controlled by at least one valve. In a particular embodiment, the regeneration flow is controlled by a bypass valve in a bypass line and an exhaust valve in an exhaust line. For greater control over the regeneration and bypass flows, each one or both of the bypass valve and the exhaust valve can be a variable control valve.

In another embodiment of the method of operating an internal combustion engine equipped with an aftertreatment system, the regeneration cycle start time is determined based on the measurement of a NOₓ concentration within the exhaust gas downstream of the lean NOₓ adsorber, with the start time occurring when the measured NOₓ concentration is higher than a threshold concentration, which is
determined by reference to a NO$_x$ concentration of the exhaust gas exiting from the engine.

In embodiments of the method that employ methane as the hydrocarbon, the method can further comprise burning fuel in the combustion chamber to generate the exhaust gas wherein the lambda of the exhaust gas is less than one when operating in a predefined low load, low speed mode.

In a preferred example the engine is a direct injection engine.

In another embodiment of the method of operating an internal combustion engine equipped with an aftertreatment system, exhaust gas is directed downstream of the lean NO$_x$ adsorber through a clean-up catalyst during the regeneration cycle. The clean up catalyst can remove NO$_x$ or reductant. In a preferred example, the clean up catalyst removes hydrogen sulfide from the exhaust gas.

The method may further comprise directing the exhaust gas through a particulate filter upstream of the lean NO$_x$ adsorber, or in another example, directing bypass flow through a second lean NO$_x$ adsorber.

A further method is disclosed for operating an internal combustion engine equipped with an aftertreatment system for removing NO$_x$ from exhaust gas generated by combustion of a fuel in at least one combustion chamber of the engine.

The method comprises:

(a) directing all of the exhaust gas through a lean NO$_x$ adsorber during normal operation of the engine;

(b) periodically regenerating the lean NO$_x$ adsorber using a predetermined regeneration strategy selected from one of a high load strategy, a midrange load strategy and a low load strategy, the regeneration strategy causing the exhaust gas pass through the lean NO$_x$ adsorber:

- during the high load strategy: reacting, upstream of the lean NO$_x$ adsorber, a reductant to maintain a lambda of the exhaust gas of less than one across the NO$_x$ adsorber;

- during the low load strategy:
burning the fuel in the combustion chamber generating the
exhaust gas wherein the lambda of the exhaust gas is less than
one, and
during the midrange load strategy, causing the lambda of the exhaust
gas to be less than one across the NO\textsubscript{x} adsorber by:
- burning the fuel with the combustion chamber in a rich
environment, and
- reacting a reductant upstream of the lean NO\textsubscript{x} adsorber.

An aftertreatment system is provided for removing NO\textsubscript{x} found in exhaust gas
produced during combustion of a fuel within a combustion chamber of an operating
internal combustion engine. This system comprises:
(a) an exhaust line for directing the exhaust gas from the engine,
(b) a lean NO\textsubscript{x} adsorber disposed in the exhaust line for removing NO\textsubscript{x},
(c) a regeneration catalyst disposed in the exhaust line upstream of the lean NO\textsubscript{x}
adSORber, with such regeneration catalyst capable of oxidizing a reductant,
(d) a reductant line for delivering the reductant from a reductant store to the
exhaust line upstream of the regeneration catalyst,
(e) a reductant flow control disposed in the reductant line for controlling reductant
flow into the exhaust line
(f) a bypass line for directing the exhaust gas around the lean NO\textsubscript{x} adsorber,
(g) at least one bypass flow control capable of controlling flow of the exhaust gas
through the bypass line,
(h) a controller, and
(i) at least one sensor providing control information to the controller, the
controller capable of adjusting the at least one valve in response to the control
information.

With this aftertreatment system, the reductant can be hydrogen and in a
preferred example, the reductant is a gaseous hydrocarbon. In this embodiment the
regeneration catalyst is capable of reducing the gaseous hydrocarbon to provide
hydrogen with the exhaust gas.

In a preferred embodiment of the aftertreatment system, the regeneration
catalyst comprises a reformer in series with an oxidation catalyst. The regeneration
catalyst can also be an oxidation catalyst. In another embodiment, the regeneration
catalyst comprises an oxidation catalyst combined with a reformer.

The aftertreatment system can further comprise a second close-coupled
catalyst proximate to the engine for oxidizing the reductant when the exhaust gas
proximate to the regeneration catalyst is at a temperature below a predetermined
threshold temperature. The predetermined threshold temperature is determined as the
temperature below which the reduction catalyst is unable to efficiently oxidize the
reductant.

The aftertreatment system can further comprise an injector for injecting the
reductant into the exhaust line.

The bypass valve can be a variable control valve for improved modulation of
flow through the by-pass line. In another embodiment the reductant store can be a fuel
system of the engine.

A further embodiment introduces a second quantity of the reductant such as
hydrogen or a hydrocarbon through a second gas line to deliver it to the oxidation
catalyst.

The system may further comprise a particulate filter disposed in the exhaust
line downstream of and proximate to the regeneration catalyst or a second lean NO$_x$
adsorber in the bypass line.

A second regeneration catalyst may also be disposed in the bypass line
upstream of the second lean NO$_x$ adsorber.

The aftertreatment system can further comprise a clean-up catalyst disposed
downstream of the lean NO$_x$ adsorber. The clean-up catalyst is capable of removing
NO$_x$ or reductant, and in a preferred example, hydrogen sulphide from the exhaust
gas.

Further aspects of the invention and features of specific embodiments of the
invention are described below.

**Brief Description of the Drawings**

In drawings which illustrate non-limiting embodiments of the invention:

Figure 1 shows a schematic of a NO$_x$ management system according to one
embodiment of the invention.
Figure 2 shows a graphical representation of properties of the exhaust gas plotted against time. Included are some system properties over a regeneration cycle.

Figure 3 shows an engine operating map of torque against speed with flow gradients over a regeneration cycle provided for use in a closed-loop control strategy.

Figure 4 shows a graph of flow versus temperature of the exhaust gas out of the engine and through the NOx catalyst during regeneration.

Figure 5 shows an alternate embodiment of the subject invention with a two bed by-pass aftertreatment system.

Figure 6 shows an alternate embodiment of a control strategy for the subject invention representing an engine operating map of torque against speed with flow gradients over a regeneration cycle provided for use in a closed-loop control strategy utilizing both in-line and in-cylinder regeneration.

**Detailed Description**

A method of regenerating a NOx adsorber that is used to treat exhaust gases created during combustion in the combustion chamber is disclosed. A hydrocarbon, preferably methane, is introduced into the exhaust line wherein the hydrocarbon is oxidized and reformed within the exhaust line to generate hydrogen which is used to regenerate the NOx absorber. CO, as well as hydrogen, is generated during reformation of methane resulting in a regeneration mixture that includes both hydrogen and CO. The aftertreatment system is capable of directing an amount of exhaust gas to by-pass the NOx adsorber during regeneration for the purposes of reducing regeneration flow, hydrocarbon consumption, emissions, and regeneration time. Specific markers, indicative of the properties of the exhaust gas, can be used to identify completion of regeneration.

Figure 1 is a schematic showing an aftertreatment system according to a preferred embodiment of the invention. An exhaust line 22 carries exhaust gases flowing in the direction of arrow 20 from an engine block 11 to an outlet in the direction of arrow 31. Components of a NOx aftertreatment system can be disposed in exhaust line 22 such that exhaust gases are carried to NOx adsorber 46 as indicated by arrow 56. Regeneration catalyst 42 is disposed in exhaust line 22 upstream of NOx adsorber 46.
By-pass line 12 is capable of carrying a portion of the exhaust gases around adsorber 46 as may be desirable while adsorber 46 is being regenerated. The exhaust gases can be directed through by-pass line 12 as indicated by arrow 18 by opening by-pass valve 14. By-pass valve 14 can be disposed anywhere along by-pass line 12. In the embodiment shown, by-pass line 12 branches off from exhaust line 22 at a junction 16 and rejoins exhaust line 22 at a junction 48 downstream from NO\textsubscript{x} adsorber 46.

Valves 13 and 14 are provided to help control the flow of exhaust gases through line 22 and by-pass line 12 during regeneration.

Although not preferred if operating of the subject method and apparatus is possible without it (see discussion below), Fig. 1 also shows a close coupled catalyst 74 in line 22 physically proximate to engine block 11. A hydrocarbon, preferably methane gas, can be introduced just prior to catalyst 42 and / or catalyst 74. Hydrocarbon valves 28 and 29 are disposed in respective main line 26 and close couple line 27, each of which branches off of store line 34. Store line 34 is connected to store 36 from which methane is allowed to flow as indicated by arrow 50. Flow direction 51 and 52 along lines 26 and 27 are also provided.

Lambda sensor 71 is used to measure lambda. Lambda, is defined herein as a measure of the oxygen potential of the exhaust gas. A lambda sensor measures this potential. Generally, a lambda value above 1 denotes a high oxygen potential and a lambda value below 1 denotes a low oxygen potential. A rich exhaust gas environment is an environment with a lambda value below 1 while a lean exhaust gas environment is an environment with a lambda value above 1. Lambda sensor 71 measures lambda in the exhaust gas after adsorber 46 and also near engine block 11 as shown by the intersection point of feed lines 61 and 63 with exhaust line 22. NO\textsubscript{x} sensor 72 is used to measure NO\textsubscript{x} levels after adsorber 46 and near engine block 11 as shown by the intersection point of feed lines 62 and 64 with exhaust line 22. Temperature sensor 73 is also used to measure temperatures before and after catalyst 42 as shown by the intersection point of feed lines 65 and 66 with exhaust line 22.

Finally, each of sensors 71, 72 and 73 feed information to controller 70 through respective feed lines 67, 68 and 69. Line 60 provides engine data to controller 70.
Controller 70 drives valves 13 and 14, through feed lines 75 and 76, and valves 28 and 29, through feed lines 77 and 78.

Figure 2 provides a graph demonstrating a sample set of conditions within the exhaust gas at a typical mid-range engine speed and load plotted against time. Line 500 is lambda of the exhaust gas measured at point C (refer to Fig. 1). Line 502 is the temperature of the exhaust gas measured in degrees Celsius at point A (refer to Fig. 1). Line 504 is the flow of the exhaust gas at point B measured in kg/hr. Line 506 is the NO\textsubscript{x} concentration of the exhaust gas measured downstream of adsorber 46 at point D (refer to Fig. 1), in ppm. Line 508 is lambda of the exhaust gas at point B (refer to Fig. 1) and line 508 overlaps line 500 except for the dashed line indicated by reference number 508 between the start and end of the regeneration cycle. Line 510 represents a lambda value of 1, above which the exhaust gas has high oxygen potential and below which the exhaust gas has a low oxygen potential. Line S provides the approximate start time of a regeneration cycle. Line O provides the earliest end to a regeneration cycle. Line F provides the end of the regeneration cycle in the example shown.

Figure 3 provides an engine map of torque versus speed. Lines 900 through 906 provide gradient lines that demonstrate the boundaries at which 100\%, 50\%, 35\%, and 20\% of the total exhaust gas flow is directed through the NO\textsubscript{x} adsorber during regeneration. Line 908 defines the boundary of the engine operating map.

Figure 4 provides a graph of flow or space velocity of the exhaust gas plotted against temperature. Line 800 provides an example of exhaust gas properties out of engine block 11 over all operating conditions of the engine. Line 802 provides target properties of the exhaust gas through NO\textsubscript{x} adsorber 46 during regeneration.

Referring to Fig. 5, an alternate embodiment of the subject invention is provided wherein by-pass system 968 is a two bed system. Exhaust line 972 directs exhaust gas in direction 974 away from engine block 970. Reformers 976, 978 are disposed in lines 977, 979 wherein exhaust gas can be directed according to arrows 984 or 986. Adsorbers 980 and 982 are also disposed in lines 977, 979. The resulting exhaust gas is directed from system 968 in direction 988. Valves 990, 992 are
disposed in each of lines 977, 979. Valves 994, 996 are also provided in store lines 995, 997 to control flow of gas from store 993 in direction 998.

Figure 6 provides an alternate torque versus speed map for controlling the operation of the subject aftertreatment system. Line 950 defines transition region 952 for regeneration wherein a combination of in-cylinder and in-line regeneration is done. Lines 954, 956, 958 and 960 provide the same gradient lines, as found in Fig. 3, that demonstrate the boundaries at which 100%, 50%, 35% and 20% of the total exhaust gas flow is directed through the NOx adsorber during regeneration. Line 962 defines the boundary of the engine operating map.

In the NOx aftertreatment systems of Fig. 1, exhaust gas is generated by combustion events within one or more combustion chambers disposed upstream of engine exhaust line 22 in engine block 11. Exhaust gas results from the combustion of fuel (lean burn combustion when a NOx adsorber is used for aftertreatment purposes) such as natural gas or a mixed fuel that includes natural gas or methane. The fuel is, in general, either directly injected into the combustion chamber or pre-mixed with a quantity of air to create a fumigated charge or is a combination of the two wherein a premixed charge and directly injected charge drive the engine. In each case, spark ignition, hot surface ignition or compression ignition are utilized to initiate the combustion process within the combustion chamber.

During normal operation of the engine valve 14 is closed and exhaust gas flows along exhaust line 22. The exhaust gas also passes through NOx adsorber 46 which removes NOx. By way of example, during normal operation, NOx adsorber is under lean operating conditions, that is, with an excess of oxygen available in the exhaust gas, NOx is driven to (NO3)2 by way of the following reactions:

\[ \text{NO} + \frac{1}{2} \text{O}_2 (\text{Pt}) \rightarrow \text{NO}_2 \]  \hspace{2cm} (1)

\[ \text{XO} + 2 \text{NO}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{X(NO}_3)_2 \]  \hspace{2cm} (2)

where X is a washcoat, as is well known to those skilled in this technology.

Eventually NOx adsorber 46 will become less effective at removing NOx as X(NO3)2 uses up adsorbing sites in adsorber 46. NOx slip is used to express a percentage increase in NOx emissions above a base concentration of NOx. NOx slip can be used to
determine when an unacceptable level of NO\textsubscript{x} is being expelled. When this unacceptable level is reached, adsorber 46 is regenerated. Upon regeneration the NO\textsubscript{x} adsorber returns to removing NO\textsubscript{x} from the exhaust gas. Controller 70 determines when NO\textsubscript{x} adsorber 46 needs regenerating. This can be done through an open loop control, based on selected parameters from the engine map, or closed loop control, based, in part, on direct readings of the NO\textsubscript{x} concentration within the treated exhaust gas. By way of example, one such open loop control uses a calibration of the aftertreatment system over a range of engine operating conditions to estimate the time at which adsorber 46 needs regeneration. That is, the controller monitors such variables as the engine load and speed, determining from a look-up table, the time for regeneration. With this method, the system is calibrated such that the engine operating conditions, which are indicative of NO\textsubscript{x} production, are used to estimate when regeneration for the NO\textsubscript{x} adsorber is desirable. Conditions such as torque, speed, intake air mass flow, the fuel flow into the engine, intake manifold temperature, intake manifold pressure, as well as others, can be used for open loop control.

A closed loop control for determining the commencement of a regeneration cycle could also be used. By way of example, one such control monitors NO\textsubscript{x} levels within exhaust line 22 downstream of adsorber 46 with sensor 72 through line 64 and near the engine through line 62. Controller 70 can commence regeneration once the ratio of NO\textsubscript{x} at point C to NO\textsubscript{x} out of block 11 exceeds a predetermined threshold NO\textsubscript{x} slip level.

During the regeneration cycle, controller 70 needs to provide H\textsubscript{2} and/or CO to NO\textsubscript{x} adsorber 46 and do so in a rich exhaust gas environment (oxygen depleted environment). The controller can control exhaust gas flow and the introduction of methane to provide a regeneration strategy that will help reduce hydrocarbons used for regeneration, and reduce the time required for regeneration. One hydrocarbon that can be used is methane.

During regeneration, the following provides a set of reactions found across catalyst 42:

\[
\begin{align*}
\text{CH}_4 + 2\text{O}_2 & \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} \\
\text{CH}_4 + \frac{1}{2}\text{O}_2 & \rightarrow \text{CO} + 2\text{H}_2 \\
\text{CH}_4 + \text{H}_2\text{O} & \rightarrow \text{CO} + 3\text{H}_2
\end{align*}
\]
\[
\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2
\]

(6)

where reaction 6 can be held in equilibrium depending on exhaust gas temperature.

Note also, that equation 3 may occur but is not preferred. The CO and H\text{2} generated

according to equations 4 through 6 are then used for regeneration as follows:

\[
\begin{align*}
\text{X(NO}_3\text{)}_2 & \rightarrow \text{XO} + 2\text{NO} + \frac{3}{2} \text{O}_2 & \quad (7) \\
\text{X(NO}_2\text{)}_2 & \rightarrow \text{XO} + 2\text{NO}_2 + \frac{1}{2} \text{O}_2 & \quad (8) \\
\text{NO} + \text{H}_2 & \rightarrow \text{H}_2\text{O} + \frac{1}{2}\text{N}_2 & \quad (9) \\
\text{NO}_2 + 2\text{H}_2 & \rightarrow \frac{1}{2}\text{N}_2 + 2\text{H}_2\text{O} & \quad (10) \\
\text{NO} + \text{CO (Rh)} & \rightarrow \frac{1}{2}\text{N}_2 + \text{CO}_2 & \quad (11) \\
\text{NO}_2 + 2\text{CO} & \rightarrow \frac{1}{2}\text{N}_2 + 2\text{CO}_2 & \quad (12)
\end{align*}
\]

where X is provided in a washcoat. A lambda less than 1, which denotes a low oxygen

potential in the exhaust gas, favors reactions 7 through 12; this is not the case, in

general, when lambda is above 1.

Controller 70 determines a regeneration strategy based, generally,

- on the exhaust gas flow,
- the exhaust gas temperature,
- a desired exhaust gas flow chosen considering the reactive capacity of
catalyst 42 at a given exhaust gas temperature,
- lambda of the exhaust gas from the engine, adsorber 46 and/or catalyst
  42 throughout a regeneration cycle, and
- the type of adsorber 46 and catalyst 42.

The catalyst 42 is chosen to suit the engine used and the operating conditions

contemplated for the engine. The regeneration strategy for a given regeneration cycle
can be done by an open loop or closed loop strategy. The regeneration strategy can
control the quantity and rate of introducing the methane into the aftertreatment system
from store 36 and the quantity of by-pass flow by controlling valves 13 and 14. The
goal during regeneration is to efficiently provide an exhaust gas environment wherein
lambda is below one, thereby promoting reactions 7 through 12. This is realized when
reductants are provided to the NO\text{X} adsorber that remove oxygen released according to
the reactions above. However, oxidation through the NO\text{X} adsorber with other
reductants such as methane or other hydrocarbons can also provide the necessary rich
exhaust gas environment. It is also desirable to provide conditions where all hydrocarbons are used efficiently to reduce NO\textsubscript{x}, and minimize the time required for regeneration.

In an open loop strategy, the controller is preferably calibrated to direct flow of exhaust gas through the adsorber and methane into the exhaust gas based on the engine speed and load just prior to and during regeneration. Engine intake manifold temperature, intake air mass flow, the fuel flow into the engine or intake manifold pressure can also be used as indicators for controlling regeneration. A constant regeneration cycle time can also be used in certain static operating conditions when load and speed remain relatively constant over extended periods of time. Such an open loop strategy employs an engine calibration that considers one or more engine operating conditions, each of which is indicative of at least one of exhaust gas temperature, flow and lambda value. The controller is calibrated to direct a desired flow of exhaust gas through the NO\textsubscript{x} adsorber based on the characteristics of catalyst 42 and adsorber 46.

The flow through NO\textsubscript{x} adsorber 46 during regeneration is referred to herein as the regeneration flow. A look-up table is used to determine whether the exhaust gas flow exceeds the desired regeneration flow and, if so, directs excess exhaust gas around adsorber 46 via by-pass line 12. This is referred to as the by-pass flow if exhaust gas is by-passed during regeneration. The desired by-pass flow is achieved by adjusting valves 13 and 14 to match the target regeneration flow though adsorber 46.

Referring to the engine map of Fig. 3, the percentage flow of exhaust gas through NO\textsubscript{x} adsorber 46 is provided based on the torque and speed of the engine and this percentage is reduced as speed and torque increases, as is seen in contour lines 900 through 906. Operating conditions falling above or to the right of line 900 show a reduction in the proportion of the total exhaust gas that flows through adsorber 46. Below and to the left of line 900, controller 70 does not open valve 14 allowing all exhaust gas to flow through adsorber 46.

The look-up table for this open loop control also provides a target methane concentration upstream of catalyst 42. The engine operating conditions provide information about the exhaust gas temperature and lambda of the exhaust gas from block 11. The lambda of the exhaust gas, determined based on the engine operating
conditions, and the flow of the exhaust gas determines in part the amount of methane required to generate a sufficiently rich exhaust gas environment to support efficient regeneration.

A closed loop strategy could also be used. In a closed loop system lambda may be measured out of engine block 11 by sensor 71 and the temperature may be measured prior to catalyst 42 by sensor 73 through line 66 and after catalyst 42 through line 65. The load and speed of the engine may be used by the controller to infer the exhaust gas flow based on look-up tables or a flow meter within the exhaust line may also be used for complete closed loop control. The look-up table along with sensor information are used to determine the flow of methane to be introduced into exhaust line 22 and how much flow of exhaust gas, if any, to direct through valve 14 and line 12 during regeneration. When exhaust gas flow is too high for catalyst 42 to allow complete oxidation and reformation of methane or too high to regenerate catalyst 46 efficiently, some flow is directed into by-pass line 12 until the desired flow is met.

If temperature prior to and after catalyst 42 is too high or too low, the methane quantity can be increased or reduced according to those temperature readings. For example, if the temperature falls below a predetermined temperature set during calibration and based, in part, on the catalyst chosen, methane could be reduced to ensure that the exhaust gas temperature is elevated to an acceptable level to support the reformation reaction 5 set out above (assuming the inlet mixture to catalyst 42 originally had excess fuel). Further, if the post-catalyst temperature is too high, the methane quantity can be shut-off to avoid overheating the catalyst and damaging it during regeneration. Such a strategy can employ a series of cycles whereby the methane flow through valve 28 is opened and closed a few times through one regeneration cycle to ensure that adsorber 46 is regenerated while protecting catalyst 42.

Likewise, lambda sensor 71 can allow the controller to adjust the quantity of methane introduced through valve 28 to ensure that the exhaust gas was rich enough to approach target regeneration efficiency across adsorber 46 according to reactions 7 through 12 set out above.
Also, a lambda sensor could be provided after catalyst 42 and before adsorber 46 rather than, or in addition to, sensor 71 provided. This would monitor the oxygen potential out of catalyst 42 to provide for efficient regeneration through adsorber 46. That is, if the flow of methane through line 26 is unknown, then the lambda sensor could be used to close loop control the flow of methane to help provide for a target lambda in the regeneration flow prior to regeneration of NOx adsorber 46.

An optional close-coupled catalyst 74 is also available to increase exhaust gas temperatures when desired. The proximity of catalyst 74 to block 11, helps ensure that exhaust gas is never too cool to oxidize methane within the exhaust gas environment. Therefore, when the controller detects an exhaust gas temperature below a threshold amount, valve 29 will provide methane upstream of catalyst 74, heating and oxidizing the exhaust gas well upstream of adsorber 46. Catalyst 74 can also be used to produce CO and hydrogen for use in regeneration as was done with catalyst 42.

As noted above, these closed loop strategies are preferred but they are not necessary. The open loop strategy discussed above utilizing a calibration of the system that provides a target methane injection rate and quantity over a regeneration cycle that is based on the engine operating parameters such as load and speed, could eliminate dynamic monitoring and the added complexity in hardware and software for the system. However, the trade-off is that such a strategy is more likely to regenerate incompletely or to regenerate with a higher methane penalty.

The controller can determine completion of a regeneration cycle by reference to a closed or open loop control. In a closed loop control, the controller can use readings from lambda sensor 71 downstream of adsorber 46 to determine when the oxygen potential within line 22 downstream of adsorber 46 is decreasing. Referring to reactions 7 through 12, once most nitrogen has been released from adsorber 46, oxygen potential begins to decrease as oxygen is no longer being released from adsorber 46. Other sensors may be appropriate for closed loop monitoring of regeneration cycle completion, including a CO or H2 sensor that detects increases in CO or H2 downstream of adsorber 46. These increases would occur when oxygen is no longer released from the adsorber causing H2 and CO to pass through the adsorber unreacted.
An open loop control could also be used relying on the calibration of the
system wherein regeneration time is pre-determined based on engine operating
conditions such as speed, load, intake air mass flow, the fuel flow into the engine,
take manifold temperature and pressure.

Referring again to Fig. 3, as either or both speed and load of the engine at the
commencement of and during a regeneration cycle increase, controller 70 commands
valve 14 to open when load and speed fall above line 900. Valves 13 and 14 can be
variable control valves providing for a wide range of operating conditions as the
engine operating parameters continue to generate exhaust gas flows above a target
flow through catalyst 42 or adsorber 46 determined, in part, by the properties of
catalyst 42. Therefore, when controller 70 determines a desired exhaust gas flow,
valves 13 and 14 can be adjusted to maintain this pre-determined flow of exhaust gas
through line 22 during regeneration.

To simplify the system, an alternative to variable flow control valves used for
valve 13 and 14 are two position valves (or, for that matter, other multiple position
valves). Here, the controller can select from one of three possible settings. Valve 13
can be fully open or partially open. Valve 14 can be closed or fully open. Therefore,
controller 70 can select a position for each valve according to the engine operating
parameters in order to match exhaust flow through line 22 to a pre-determined target
value. That is, at low speed and load, valve 13 is open fully and valve 14 is closed. At
higher loads and speeds, valve 13 is fully opened and valve 14 is fully opened. At still
higher speeds and loads, valve 13 is partially closed and valve 14 is opened.

Other valve configurations can be used as well. More flexibility for the
controller to manage flow through line 22 during regeneration helps the controller to
meet a target pre-determined flow rate for each operating condition. One trade-off is
that such flexibility may result in a more expensive system that requires more
expensive valves and more complicated software to control those valves.

As would be understood by a person skilled in the technology, valves 13 and
14 can be any flow control mechanism and need not be limited to valves.

Referring to Fig. 4, flow and temperature over the range of engine operating
conditions are provided. Area 800 shows typical exhaust gas flow and temperature
conditions expelled from block 11. Area 802 provides the controller a desired operating range for temperature and flow of exhaust gas through regeneration catalyst 42 during regeneration – which provide the exhaust gas conditions which then allow the conditions necessary for regeneration of NOx adsorber 46. Therefore, when the flow out of block 11 is above area 802, flow through bypass line 12 can be used to bring the exhaust flow through adsorber 46 to within area 802 and below the upper limit flow of the range. Ideally, regeneration flow is targeted to a desired flow within this range, however, depending on such things as exhaust gas flow, valve reaction times in the system, pressure and temperature changes, a different regeneration flow within the range defined by 802 is all that can be maintained. When the temperature falls below area 802 (to the left of area 802) at catalyst 42, additional heat can be generated through the operation of the engine as described below or using close coupled catalyst 74, proximate to block 11, as described above and below.

Referring to Fig. 2, selected properties of the system are plotted over the course of a partial adsorbing cycle and an entire regeneration cycle. Referring to Fig. 1, lambda at points B and C (lines 508 and 500, respectfully), temperature and space velocity at point A (lines 502 and 504 respectfully) and NOx at point D (line 506) are all shown, plotted against time. The example provided is representative of operation of the aftertreatment system when an engine is running at a typical midrange speed and load.

Referring to line 506, NOx concentrations increase gradually until the controller determines that the level has exceeded a pre-determined threshold – this could be done by monitoring the engine operating parameters or measuring the NOx concentration. Regeneration then commences with opening of valve 14.

Commencement of regeneration is shown at time S. Opening valve 14 drops the space velocity or flow through line 22, line 504, at time S. Methane is also directed into line 22 causing lambda to drop to a level below 1 between catalyst 42 and adsorber 46 (line 508). Lambda following the NOx adsorber also drops after regeneration is complete, (line 500), but during regeneration of the adsorber, it is maintained near a lambda value of 1 as the rich mixture entering the adsorber releases oxygen from the oxides of nitrogen resulting in a leaner mixture expelled from adsorber 46 than that
entering adsorber 46. Eventually, however, no further oxygen is released from adsorber 46 and lambda falls until the lambda out of adsorber 46 is the same as lambda into adsorber 46, (line 508). Once a threshold lambda out of adsorber 46 is detected, valve 14 is closed along with valve 28. Immediately, the flow begins to rise, line 504, as all exhaust gas is again routed through exhaust line 22. Soon, lambda begins to rise resulting in a lean exhaust gas environment, lines 500 and 508.

Note, that the regeneration cycle is complete at time F in Fig. 2. This is, in practice, a delayed end of the regeneration cycle. Preferably, the regeneration cycle would be completed sometime between time O and time F when lambda after the NOx adsorber (line 500) drops below a pre-determined threshold amount and before it matches lambda upstream of the NOx adsorber (line 508).

During the regeneration cycle, the NOx levels out of line 22 increase substantially, as the engine is continuing to operate without NOx treatment of the exhaust gas routed through by-pass line 12, line 504. Once regeneration is complete, however, NOx quickly falls as all exhaust gas is routed through recently regenerated adsorber 46. Therefore, as well as limiting fuel consumption (consumption of methane), short regeneration times also limit the amount of NOx emitted during regeneration through by-pass line 12. The longer the period of time needed for regeneration, the more cumulative exhaust gas flows through by-pass line 12. The target cycle is based on generating as much reductant per unit methane injected over the shortest time period. This is a function of variables such as the temperature of the exhaust gas, flow of exhaust gas, catalyst specifications, and lambda of exhaust gas, since a higher lambda requires more methane to burn off the oxygen present but more oxygen is available to generate CO. Preferably, regeneration cycles should be kept to less than 5% of operating time of the engine. Also, as noted above, a greater flow of exhaust gas routed through by-pass line 12, results in higher NOx emissions since by-pass line 12 does not generally include a separate NOx adsorber.

Figure 5, shows an alternative embodiment of the aftertreatment system. Here a second NOx adsorber and catalyst is disposed in the by-pass line to treat NOx through that line during regeneration. That is either one of line 977 or line 979 act as the bypass lines during regeneration of the either one of adsorber 980 or adsorber 982.
Valves 994, 996, 990 and 992 all work to control which of the adsorber is being regenerated. For example, for regeneration of adsorber 980, bypass line is line 979. Here, a regeneration cycle is begun when exhaust gas is directed according to a control strategy (see Fig. 3), through reformer 976. Excess exhaust gas is bypassed through adsorber 982 during regeneration in the same manner as exhaust gas was also bypassed through line 12 referring to Fig. 1. Here, however, the excess exhaust gas is treated by NOₓ adsorber 982.

In the example, the reductant source, methane, is directed from store 993 through valve 994 to line 977. At the same time, valves 990 and 992 are opened according to the desired split of exhaust gas through each valve for the purposes of regeneration. Eventually, NOₓ adsorber 982, as well, would need to be regenerated. In which case valve 994 would close and 996 would open and the acting bypass line would be 977.

This system in general could also be extended to a multi-bed system with 3 or 4 or 5 or more beds with one “off-line” at any one time. The benefit here is improved NOₓ conversion for the same catalyst volume.

Note also, for multi-bed systems – 2 or more beds – there is no need for 2 physically distinct adsorbers. Parts of a single physical adsorber could act as an isolated adsorber as well.

Also, while two reformers are shown in Fig. 5, one could be used. In fact, one reformer could be used for other multiple bed designs. Here the reformer would include lines that routed exhaust around the reformer to each adsorber as well as lines that routed exhaust gas from the reformer through to each adsorber. Valves would control the design of such a system.

In general, while these multi-bed systems provide better conversion, they also tend to add cost and complexity to the system both in terms of the architecture and in terms of the control mechanisms.

An alternative method of operating the aftertreatment system that can help to reduce regeneration time employs an additional exhaust line that routes exhaust gas around catalyst 42 and through adsorber 46 during regular operation. A valve disposed in this additional exhaust line could be used such that valve 13, closed during regular operation, would be opened just prior to commencement of regeneration, while
maintaining the catalyst bypass open. This would allow a flow of exhaust gas through line 22, lighting off catalyst 42 and warming the line prior to a regeneration cycle. When a valve used to bypass catalyst 42 is closed at the beginning of a regeneration cycle, there can be less time needed to heat line 22 and less time before regeneration can commence. Alternatively, in such an embodiment with an additional exhaust line around catalyst 42, the flow rate within reformer line 22 can be set to ensure a certain amount of exhaust gas is always flowing through line 22 eliminating the need for valve 13 by employing a valve to regulate flow through catalyst 42 by controlling flow through the additional exhaust line.

Catalyst 42 is generically describe as a bed that promotes reactions 3 through 5 to provide a desired exhaust gas with elevated concentrations of H₂ and/or CO and minimal amounts of oxygen. To varying extents, reactions 3 through 6, a combination of exothermic and endothermic reactions, drive the process across this catalyst. This catalyst can be a reformer that oxidizes methane and promotes reaction 5 to provide H₂ and CO. It can also be a partial oxidation catalyst, that partially oxidizes methane and reforms methane to provide H₂ and CO, see reaction 4. Catalyst 42 can also be a back-to-back oxidation catalyst and reformer sharing a common boundary surface. This catalyst would first oxidize methane until little oxygen remains within the exhaust gas and then, use excess methane to generate H₂ and CO within the reformer.

These two catalysts, the oxidation catalyst and reformer, can also be disposed in line 22 in series and need not share a common boundary surface. Also, a combination reformer and oxidation catalyst could be used that integrates the reformer and oxidation catalyst together in a mixed catalyst. Each option has balancing cost and efficiency considerations that weigh in any decision as to which catalyst to use depending on the aftertreatment system sought.

As noted briefly above, referring again to Fig. 1, an additional catalyst, close coupled catalyst 74, is shown positioned near engine block 11. Some systems need such a catalyst disposed close to the engine to ensure that the exhaust gas is hot enough to support oxidation of methane. That is, there are some aftertreatment system designs that would benefit from employing a close coupled catalyst near the engine block so that the exhaust gas temperature under low load and/or speed or idle conditions can be prevented from falling below a threshold limit at which stable
oxidation of methane in catalyst 42 would be compromised. Therefore, under such conditions, there are advantages in having close coupled catalyst 74 near engine block 11 with line 27 feeding methane upstream of such catalyst. This catalyst would then either oxidize the methane provided from store 36 to heat the exhaust gas to a temperature suitable to allow catalyst 42 to light off satisfactorily. Alternatively, catalyst 74 can provide the rich exhaust gas environment along with H₂ and CO needed to regenerate adsorber 46. It would be desirable here, however, to operate this way only when valve 14 is closed in order to prevent CO and H₂ from escaping through the by-pass line, since this would be inefficient.

An additional method of operating the regeneration cycle under low load conditions is to burn a fuel rich combustible mixture, preferably comprising methane, in the combustion chamber within engine block 11. Alternatively, a method wherein fuel burned lean with an injection of fuel late in the cycle. Fuel can oxidize in the combustion chamber, or in exhaust or over the catalyst. In each case, this will generate an excess of CO and some H₂ while creating a rich exhaust gas environment. With this method, no methane needs to be provided to catalyst 42 when the necessary reductants are present within a rich exhaust gas environment. Preferably, such a strategy would be limited to conditions when flow and temperature are low which is typically associated with light load and low speed conditions or idle conditions when full flow through adsorber 46 is desirable.

Use of in-cylinder techniques to generate the necessary conditions and reductants to regenerate the NOₓ adsorber can have drawbacks.

For example, a spark ignited engine running under lean conditions has an engine out NOₓ that is relatively low when compared to that resulting from operation under stoichiometric conditions. In general, the peak in NOₓ production occurs at conditions slightly lean of stoichiometric where engine out NOₓ can be an order of magnitude larger than that produced near the lean limit. Thus, transitioning from lean to rich operation to create the conditions conducive to NOₓ adsorber regeneration also results in a substantial increase in engine out NOₓ emissions. While operating under rich conditions, the NOₓ adsorber reduces both the engine out and adsorber released NOₓ to nitrogen. However, when transitioning back to lean operation, the substantial
amounts of NO\textsubscript{x} created during operation just lean of stoichiometric are captured by the NO\textsubscript{x} adsorber.

Under light load/low speed conditions, for example, idle, the mass flow rate of NO\textsubscript{x} is relatively low and the storage capacity of the NO\textsubscript{x} adsorber is relatively high. Adsorption phases in excess of 1000 seconds can be realized. Under this condition, the influence of the NO\textsubscript{x} adsorbed during the transition from rich to lean operation has relatively little impact. For example, if the transition from lean to rich takes five seconds to accomplish, and the NO\textsubscript{x} produced is an order of magnitude larger than that of lean operation, the adsorption phase would be reduced by 5% to 950 seconds in the example provided. However, as the mass flow rate of the engine out NO\textsubscript{x} increases with speed and load, the relative impact of the additional NO\textsubscript{x} produced during the transition starts to have an impact on the system operation. For example, at an engine operating condition at a higher speed and load relative to idle, the engine out NO\textsubscript{x} flow rate doubles. Under these conditions, the fill time of the NO\textsubscript{x} adsorber, based on lean engine out NO\textsubscript{x} emissions and temperatures, is reduced to 500 seconds. When using in-cylinder regeneration, the 5 second transition now reduces the fill time by 10% to 450 seconds. Continuing along this line, at some point, the in-cylinder technique is not an effective means to regenerate the NO\textsubscript{x} adsorber.

Similar results would be expected for a fumigated or port-injected lean burn engine. However, the port-injected lean burn engine is expected to be more tolerant to in-cylinder regeneration because the transition time from lean to rich is expected to be shorter.

Retarding the spark timing would help the situation, possibly extending the region where the in-cylinder regeneration could be used. Similarly, if increasing EGR rates were available to reduce the in-cylinder oxygen concentration, the concern considered above would still exist, but be ameliorated.

This issue is not expected to arise for engines using the direct injection of gaseous fuels. For direct injection engines, the use of an injector provides more flexibility in transition to rich operation. For example, a combination of increasing the EGR rates, retarding of the gas injection timing, multiple injections and throttling of the engine is available. These conditions would not lead to significant increases in the
engine out NOₓ levels. Rather, engine out NOₓ levels would decrease (with a potential increase in particulate matter emissions).

Where in-cylinder regeneration is not effective, one can resort to the use of the in-line regeneration technique. However, under full flow conditions at relatively low exhaust gas temperatures the in-line regeneration method may not be efficient. The fuel penalty and hydrocarbon slip can be significantly higher than that associated with the in-cylinder regeneration. As mentioned above, the in-line regeneration efficiency can be improved with the use of a close-couple catalyst, but may still not be satisfactory.

Therefore, the system needs special management consideration when the speed load region where efficient in-cylinder regeneration is possible does not overlap with the region where efficient in-line regeneration can be realized.

Therefore, referring to Fig. 6, the region where effective in-cylinder can be realized is below line 950 in Fig. 6. The region where effective in-line regeneration can be realized is above line 950. The region where neither in-cylinder nor in-line regeneration is efficient is defined as area 952 bounded by line 950 in Fig. 6. Within area 952, the use of a combination of in-cylinder and in-line regeneration allows this region of the engine map to be managed. One embodiment of the combined method provides for the engine an enrichment of the combustion environment during regeneration to reduce the oxygen concentration in the exhaust. At the same time, the spark timing may or may not be retarded to increase exhaust gas temperature (and reduce engine out NOₓ emissions). A quantity of reductant is injected upstream of the regeneration catalyst to react with the species in the exhaust gas to reduce the oxygen potential further and create conditions conducive to regenerating the NOₓ adsorber.

The benefits associated with this technique include:

- the NOₓ spike associated with the rich to lean transition of the engine is avoided, and
- the fuel penalty and hydrocarbon slip are reduced.

A second possible embodiment of the method involves using the in-cylinder transition from lean to rich operation to regenerate the NOₓ adsorber catalyst. During the time when the transition back to lean operation is desired, a quantity of reductant is injected upstream of the regeneration catalyst. The injected reductant is used to
maintain a rich atmosphere over the NO\textsubscript{x} adsorber during the rich to lean transition such that the high engine out NO\textsubscript{x} emissions are reduced over the NO\textsubscript{x} adsorber. This embodiment has similar benefits to that outlined for the first embodiment.

As noted above, the first region below line 950, region 951, and represented by low load and, in general, low speed, demonstrates the operating range wherein in-cylinder regeneration is desired. As exhaust gas is cooler when the engine is operating under these conditions, in-cylinder generation of a rich environment with excess CO and some H\textsubscript{2} is, generally, more efficient than would be the case if catalyst 42 (or close coupled catalyst 74) were needed to generate the desirable condition in-line for regeneration.

The region outside of region 952 with high speed or load and bounded by line 954 shows a range of torque and speed at which full flow of exhaust gas though the adsorber is preferred. Beyond this region to high speeds or torque or both as represented by lines 956, 958, 960, bypass flow is accommodated as demonstrated and discussed above in relation to Fig. 3.

Note when this method of control of the aftertreatment system is used for a high pressure direct injection engine the range of region 951 tends to be larger, pushing line 950 higher on the load / speed plot as compared to a spark ignited engine that uses fumigated fuels to operate. That is, the effective expansion ratio tends to be larger resulting in cooler exhaust gas in general being expelled from the engine than is the case for a spark-ignited engine.

Note also, in-cylinder regeneration as demonstrated in fig. 6 need not rely on a by-pass flow during regeneration. That is, the high load region bounded by line 954 could be the extent of operation of the regeneration control map. Here three regions would exist for regeneration of a lean NO\textsubscript{x} adsorber. Low load strategy represented by region 951, midrange load strategy represented by region 952 and high load strategy bounded by line 954 would represent the entire regeneration control map. Each region would use in-cylinder and inline regeneration strategies as taught above with no need for by-pass.

As noted above, the regeneration cycle is dependant on the exhaust gas temperature. It is important that the exhaust gas introduced into catalyst 42 have a temperature above a minimum temperature to ensure that the catalyst is “lit-off”
initially. An additional way of controlling the regeneration process from the combustion chamber is to choose a combustion strategy or combustion timing that ensures either relatively late heat release, as might be the case with spark ignited engines, or a delayed or second direct injection of fuel into the combustion chamber late in the power stroke when regeneration is required. This can also reduce NO\textsubscript{x} levels with associated benefits during regeneration as a quantity of exhaust gas can be directed through the by-pass line without NO\textsubscript{x} treatment. A reduced NO\textsubscript{x} level has benefits here. Other strategies are well known to persons skilled in the art.

As natural gas is, overwhelmingly, methane with a few additional heavier hydrocarbons, C\textsubscript{2} and C\textsubscript{3} hydrocarbons in general, the methane store 36 can be the fuel storage tanks if the engine is fueled by natural gas. That is, methane store 36 can be a natural gas source such as the engine fuel tanks.

Also, valves 28 and 29 can be injectors that would directly inject methane into exhaust line 22. An injector as the reductant flow control would provide greater control over the timing and quantity of methane and, therefore, greater control over the regeneration cycle.

A metal substrate for carrying the catalyst is generally preferred, rather than, for example, a ceramic substrate, if the metal substrate improves thermal response to catalyst 42. As noted above, the quicker the thermal response the quicker the regeneration process can be completed, thereby reducing the amount of untreated exhaust gas allowed to flow through by-pass line 12.

An additional embodiment of the aftertreatment system can include a valve for introducing methane downstream from an oxidation catalyst and upstream of a reformer with catalyst 42 comprising an oxidation catalyst and reformer in series but not sharing a common interface. Flow of methane through such a downstream valve can be controlled in response to the quantity of methane needed within the exhaust gas entering a reformer. After the exhaust gas has passed through an oxidation catalyst its properties are changed. There will be less oxygen within the gas and less methane. This is because oxidation of methane occurs within the catalyst. This consumes oxygen. As methane serves to provide the source for H\textsubscript{2} and CO, which are preferred components in the regeneration process (see reactions 4 and 5 above), the quantity of methane needed within the reformer is determined by the amount present within the
exhaust stream upstream of the reformer. The amount of methane preferred is
determined by that present in the gases which are exiting the oxidation catalyst and the
H₂ and CO concentrations preferred in light of this initial quantity of methane present,
which is the methane not oxidized within oxidation catalyst.

Once forced through the oxidation catalyst, the exhaust gas, supplemented
with methane via a downstream valve, is forced through the reformer. The reformer
utilizes the high temperature of exhaust gas heated in the oxidation catalyst and the
combustion chamber to drive reformation of methane within the reformer in line 22 to
provide H₂ and CO downstream from catalyst 42. This stream is directed into NOₓ
adsorber 46 when H₂ and CO regenerate NOₓ adsorber 46.

An oxidation catalyst can be a component of catalyst 42, and can be any
oxidation catalyst suitable for oxidizing the exhaust gas to reduce the oxygen
content. By way of example, a suitable oxidation catalyst can promote the following
reactions:

\[
\begin{align*}
\text{CxHy + (x+y/4) O}_2 \text{(Pt)} & \rightarrow x\text{CO}_2 + y/2 \text{H}_2\text{O} \\
\text{CxHy + (x+y/4) O}_2 \text{(Pd)} & \rightarrow x\text{CO}_2 + y/2 \text{H}_2\text{O} \\
\text{CxHy + (x/2) O}_2 \text{(Pd)} & \rightarrow x\text{CO} + y/2 \text{H}_2 \\
\text{CO} + \frac{1}{2} \text{O}_2 & \rightarrow \text{CO}_2
\end{align*}
\]

By way of example only, for the operating conditions known for this application, a
suitable washcoat formulation comprises Al₂O₃. Other suitable washcoat formulations
may also be used, as would be understood by a person skilled in the art.

A reformer can be a component of catalyst 42, and reformers suitable for this
application are well known. The reformer is preferably suitable to convert methane
with water to CO and H₂. By way of example, the reformer can be a precious metal-
based catalyst with washcoat materials including Al₂O₃.

NOₓ adsorber 46 typically adsorbs and stores of NOₓ in the catalyst washcoat
while operating under lean conditions and NOₓ can be released and reduced to N₂
under rich operating conditions when a regeneration mixture, that includes hydrogen
and rich exhaust gas, is passed through the adsorber. As noted above, the following
shows typical operation of the NO NOₓ x adsorber under lean conditions:

\[
\begin{align*}
\text{NO} + \frac{1}{2} \text{O}_2 \text{(Pt)} & \rightarrow \text{NO}_2 \\
\text{XO} + 2 \text{NO}_2 + \frac{3}{2} \text{O}_2 & \rightarrow \text{X(NO}_3)_2
\end{align*}
\]
and under rich conditions:

\[
\begin{align*}
X(NO_3)_2 & \rightarrow XO + 2NO + 3/2 O_2 \\
X(NO_3)_2 & \rightarrow XO + 2NO_2 + 1/2 O_2 \\
NO + CO (Rh) & \rightarrow \frac{1}{2} N_2 + CO_2 \\
2NO_2 + 4H_2 & \rightarrow N_2 + 4H_2O
\end{align*}
\]

where X is provided in the washcoat and is typically an alkali (e.g., K, Na, Li, Ce), an alkaline earth (e.g., Ba, Ca, Sr, Mg) or a rare earth (e.g., La, Yt).

An inline external heater can be used to help light off catalyst 42 and promote reformation and oxidation of exhaust gas during regeneration. While, it is preferable that the majority of heat is provided by the exhaust gas, things such as, by way of example and not limited to:

- transient response,
- efficiency considerations,
- combustion strategies that utilize a quick heat release,
- valve timing or
- cylinder design that takes advantage of a large expansion ratio

can release exhaust gas that could benefit from such a heater in order to initiate oxidation prior to or during regeneration.

A heat exchanger could direct a quantity of heat from the outlet of catalyst 42 or heat from gases unused after regeneration out of adsorber 46 back through to a point along line 22 upstream of catalyst 42. This could be used to help reduce the load on such heater after it initially lights the catalyst off.

Note that for reforming, as noted above, steam is required in order to generate H\textsubscript{2} and CO for regeneration. This need tends to be met as exhaust gas has sufficient quantities of water. However, if water levels are low, a partial oxidation catalyst (POX) catalyst can be employed to reform the gas without the need for supplemental water: see reaction 4. Other reformers could be used as understood by a person skilled in the art.

Steam is made more available by oxidizing methane as compared to other hydrocarbons. This is an additional advantage in light of the above.

A further advantage can be realized if a fuel is used that combines methane and hydrogen as two major components. By way of example, natural gas with 10 to
50% hydrogen might be appropriate as an engine fuel and appropriate for regeneration. Such a fuel could then be utilized in the embodiments discussed wherein the hydrogen introduced with the fuel prior to the oxidation catalyst could help to light off those catalysts and help to provide an exhaust gas environment with a lambda less than 1. Further, by providing a quantity of hydrogen into the exhaust stream, the burden on catalyst 42 is reduced. Less reforming is required for regeneration due to the presence of hydrogen in the injected fuel.

The method taught above for bypassing exhaust gas can also be used if hydrogen is injected into the exhaust gas. Here, the regeneration strategy is driven by a target regeneration flow through the NOₓ adsorber that would efficiently regenerate while limiting the associated fuel penalty and release of untreated NOₓ and NOₓ slip during regeneration. This is that much more beneficial if the engine is fueled by hydrogen, with the fuel providing a ready source of reductant, but this method would be useful, as well, if an external reformer can be used. Further, use of a two-bed aftertreatment system, as discussed above and demonstrated in Fig. 5, would be useful if hydrogen can be directly injected into the exhaust gas upstream of a NOₓ adsorber during a regeneration cycle after determining a target regeneration flow.

A further embodiment of the invention includes an aftertreatment system that has an in-line particulate filter. Referring to Fig. 1, a particulate filter may be disposed in line 22 near and downstream of reformer 42. The particulate filter could then benefit from the excess heat generated in line 22 during regeneration that, upon reintroduction of oxygen to this line after completion of a regeneration cycle, would generate an exotherm across the particulate filter that could burn off soot collected here extending or eliminating the regeneration cycles for the particulate filter. Note, however, one issue which arises is that the effectiveness of the particulate filter in reducing particulate matter emission is lowered because part of the flow is diverted around the particulate filter during the regeneration event.

In a further embodiment of the invention, a clean-up catalyst is used in the aftertreatment system. Referring to Fig. 1, a clean-up catalyst (not shown) may be provided in line 22 beyond junction 48. The catalyst could be selected to reduce NOₓ (lean NOₓ catalyst) from bypass line 12 (resulting during a regeneration cycle) or selected to remove reductant (CO or H₂) or other hydrocarbons that pass through the
aftertreatment system during regeneration or selected to remove hydrogen sulfide the might result during any desulfation process of the adsorbers.

Whenever flow is referred to in this disclosure, it is the mass or molar flow rate of the gas in question.

Exhaust gas recirculation (EGR) can also be utilized to help reduce NO\textsubscript{x} emissions during regeneration when a by-pass line is opened. Increased EGR rates during regeneration can reduce NO\textsubscript{x} generated in the combustion chamber resulting in less NO\textsubscript{x} flowing through by-pass line 12 and into the atmosphere. Further, increases in EGR can also be used to reduce the concentration in oxygen in the exhaust gas during regeneration, reducing, in turn the burden on the oxidation catalyst to reduce oxygen during a regeneration cycle as well as reduce the amount of methane needed to burn off oxygen.

While methane is the preferred source for hydrogen, as would be understood by a person skilled in the art, other lighter hydrocarbons, generally, gaseous hydrocarbons, could be used including but not limited to other gaseous hydrocarbons such as ethane, propane and butane.

While particular elements, embodiments and applications of the present invention have been shown and described, it will be understood, of course, that the invention is not limited thereto since modifications may be made by those skilled in the art without departing from the scope of the present disclosure, particularly in light of the foregoing teachings.
What is claimed is:

1. A method of regenerating a lean NO\textsubscript{x} adsorber, said lean NO\textsubscript{x} adsorber used to remove NO\textsubscript{x} from exhaust gas generated by combustion of a fuel in a combustion chamber of an operating internal combustion engine, said method comprising:

   (a) determining a target regeneration flow of said exhaust gas through said lean NO\textsubscript{x} adsorber,

   (b) directing a regeneration flow of said exhaust gas through said lean NO\textsubscript{x} adsorber, said regeneration flow established by one of:

       - bypassing a bypass flow of said exhaust gas around said lean NO\textsubscript{x} adsorber when said target regeneration flow is less than exhaust gas flow from said engine, resulting in said regeneration flow being substantially the same as said target regeneration flow, and

       - directsubstantially all of said exhaust gas through said lean NO\textsubscript{x} adsorber when said target regeneration flow is greater than said exhaust gas flow from said engine,

   5 said exhaust gas flow from said engine and said bypass flow established by reference to at least one of:

       - engine speed,

       - engine load,

       - intake manifold temperature of said engine,

       - intake air mass flow,

       - fuel flow into said engine,

       - intake manifold pressure of said engine,

       - a measured flow of said exhaust gas out of said engine,

       - exhaust gas temperature, and

       - exhaust gas pressure,

   (c) reacting, within said exhaust gas and upstream of said lean NO\textsubscript{x} adsorber, a reductant to maintain a lambda of said regeneration flow of less than one across said lean NO\textsubscript{x} adsorber.

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2. The method of claim 1 wherein said reductant is hydrogen.

3. The method of claim 1 wherein said reductant is a hydrocarbon.
4. The method of claim 3 wherein said hydrocarbon comprises methane.

5. The method of claim 4 further comprising introducing hydrogen into said regeneration flow by reforming said methane within said exhaust gas upstream of said lean NO\textsubscript{x} adsorber.

6. The method of claim 1 wherein said fuel and said reductant are interchangeable.

7. The method of claim 1 wherein said bypass flow is directed through a second lean NO\textsubscript{x} adsorber.

8. A method of operating an internal combustion engine equipped with an aftertreatment system for removing NO\textsubscript{x} from exhaust gas generated by combustion of a fuel in at least one combustion chamber of said engine, said method comprising:
   - during normal operation of said engine, directing all of said exhaust gas through a lean NO\textsubscript{x} adsorber;
   - periodically regenerating said lean NO\textsubscript{x} adsorber by a regeneration cycle defined by a regeneration cycle start time and a regeneration cycle end time, during said regeneration cycle:
     (a) determining a target regeneration flow of said exhaust gas through said lean NO\textsubscript{x} adsorber,
     (b) directing a regeneration flow of said exhaust gas through said lean NO\textsubscript{x} adsorber, said regeneration flow established by one of:
        - bypassing a bypass flow of said exhaust gas around said lean NO\textsubscript{x} adsorber when said target regeneration flow is less than exhaust gas flow from said engine, resulting in said regeneration flow being substantially the same as said target regeneration flow, and
directing substantially all of said exhaust gas through said lean NO\textsubscript{x} adsorber when said target regeneration flow is greater than said exhaust gas flow from said engine, said exhaust gas flow from said engine and said bypass flow determined by reference to at least one of:

- engine speed,
- engine load,
- intake manifold temperature,
- intake air mass flow,
- fuel flow into said engine,
- intake manifold pressure,
- a measured flow of said exhaust gas out of said engine,
- exhaust gas temperature, and
- exhaust gas pressure,

reacting, within said exhaust gas and upstream of said lean NO\textsubscript{x} adsorber, a reductant to maintain a lambda of said regeneration flow of less than one across said lean NO\textsubscript{x} adsorber.

9. The method of claim 8 wherein said reductant is hydrogen.

10. The method of claim 8 wherein said reductant is a hydrocarbon.

11. The method of claim 10 wherein said hydrocarbon comprises methane.

12. The method of claim 11 further comprising introducing hydrogen into said regeneration flow by reforming said methane within said exhaust gas upstream of said lean NO\textsubscript{x} adsorber.

13. The method of claim 8 wherein said fuel and said reductant are interchangeable.
14. The method of claim 11 wherein reacting of said hydrocarbon occurs within said exhaust gas prior to directing said bypass flow around said lean NO\textsubscript{x} adsorber.

15. The method of claim 11 wherein reacting of said hydrocarbon occurs within said regeneration flow.

16. The method of claim 11 wherein said hydrocarbon is directed into said exhaust gas by at least one of a valve and an injector.

17. The method of claim 8 wherein said regeneration cycle end time is determined when said lambda of said regeneration flow downstream of said lean NO\textsubscript{x} adsorber is below a pre-determined threshold concentration.

18. The method of claim 8 wherein said regeneration cycle end time is determined when a concentration of said reductant downstream of said lean NO\textsubscript{x} adsorber is above a pre-determined threshold concentration.

19. The method of claim 12 wherein said regeneration cycle end time is determined when a concentration of at least one of CO or H\textsubscript{2} downstream of said lean NO\textsubscript{x} adsorber is above a pre-determined threshold concentration.

20. The method of claim 8 wherein said regeneration flow is controlled by at least one valve.

21. The method of claim 8 wherein said regeneration flow is controlled by a bypass valve in a bypass line and an exhaust valve in an exhaust line.

22. The method of claim 21 wherein said bypass valve is a variable control valve.

23. The method of claim 21 wherein said exhaust valve is a variable control valve.

24. The method of claim 8 wherein said regeneration cycle start time is determined when a NO\textsubscript{x} concentration within said exhaust gas downstream of said lean NO\textsubscript{x} adsorber.
adsorber is in excess of a threshold concentration as compared to a \( \text{NO}_x \) concentration out of said engine.

25. The method of claim 11 further comprising, when operating said engine in a predefined low load, low speed mode, wherein said lambda of said exhaust gas is less than one as a result of combustion of said fuel within said combustion chamber.

26. The method of claim 25 wherein said engine is a direct injection engine.

27. The method of claim 8 further comprising during said regeneration cycle directing said exhaust gas downstream of said lean \( \text{NO}_x \) adsorber through a clean-up catalyst.

28. The method of claim 27 wherein said clean-up catalyst removes \( \text{NO}_x \) from said exhaust gas.

29. The method of claim 27 wherein said clean-up catalyst removes reductant from said exhaust gas.

30. The method of claim 27 wherein said clean-up catalyst removes hydrogen sulfide from said exhaust gas.

31. The method of claim 8 further comprising directing said exhaust gas through a particulate filter upstream of said lean \( \text{NO}_x \) adsorber.

32. The method of claim 8 wherein said bypass flow is directed through a second lean \( \text{NO}_x \) adsorber.

33. A method of operating an internal combustion engine equipped with an aftertreatment system for removing \( \text{NO}_x \) from exhaust gas generated by combustion of a fuel in at least one combustion chamber of said engine, said method comprising:
(a) during normal operation of said engine, directing all of said exhaust gas through a lean NO\textsubscript{x} adsorber;

(b) periodically regenerating said lean NO\textsubscript{x} adsorber using a predetermined regeneration strategy selected from one of a high load strategy, a midrange load strategy and a low load strategy, said regeneration strategy causing said exhaust gas pass through said lean NO\textsubscript{x} adsorber, during said high load strategy:

reacting, upstream of said lean NO\textsubscript{x} adsorber, a reductant to maintain a lambda of said exhaust gas of less than one across said NO\textsubscript{x} adsorber during said low load strategy:

burning said fuel in said combustion chamber generating said exhaust gas wherein said lambda of said exhaust gas is less than one;

15 during said midrange load strategy, causing said lambda of said exhaust gas to be less than one across said NO\textsubscript{x} adsorber by:

burning said fuel with said combustion chamber in a rich environment, and

reacting, upstream of said lean NO\textsubscript{x} adsorber, a reductant.

34. An aftertreatment system for removing NO\textsubscript{x} from exhaust gas produced during combustion of a fuel within a combustion chamber of an operating internal combustion engine, said aftertreatment system comprising:

25 (a) an exhaust line for directing said exhaust gas from said engine,

(b) a lean NO\textsubscript{x} adsorber disposed in said exhaust line for removing said NO\textsubscript{x},

(c) a regeneration catalyst disposed in said exhaust line upstream of said lean NO\textsubscript{x} adsorber, said catalyst capable of promoting oxidizing or reforming of reductant,

30 (d) a reductant line for delivering said reductant from a reductant store to said exhaust line upstream of said catalyst,
(e) a reductant flow control disposed in said reductant line for controlling flow of said reductant into said exhaust line,

(f) a bypass line for directing said exhaust gas around said lean NOx adsorber,

(g) at least one bypass flow control capable of controlling flow of said exhaust gas through said bypass line,

(h) a controller,

(i) at least one sensor providing control information to said controller, said controller capable of adjusting said at least one valve in response to said control information.

35. The aftertreatment system of claim 34 wherein said reductant is hydrogen.

36. The aftertreatment system of claim 34 wherein said reductant is a gaseous hydrocarbon, said catalyst capable of reducing said gaseous hydrocarbon to provide hydrogen with said exhaust gas.

37. The aftertreatment system of claim 34 wherein said catalyst is a reformer in series with an oxidation catalyst.

38. The aftertreatment system of claim 34 wherein said catalyst is an oxidation catalyst.

39. The aftertreatment system of claim 34 wherein said catalyst comprises an oxidation catalyst combined with a reformer.

40. The aftertreatment system of claim 34 further comprising a second close coupled catalyst proximate to said engine for oxidizing said reductant when said exhaust gas proximate to said regeneration catalyst is at a temperature below a predetermined threshold temperature, said predetermined threshold temperature below which said catalyst is unable to efficiently promote reaction of said reductant.
41. The aftertreatment system of claim 34 further comprising an injector for injecting said reductant into said exhaust line.

42. The aftertreatment system of claim 34 wherein said by-pass flow control is a valve.

43. The aftertreatment system of claim 34 wherein said reductant store is a fuel system of said engine.

44. The aftertreatment system of claim 34 further comprising a particulate filter disposed in said exhaust line downstream of and proximate to said regeneration catalyst.

45. The aftertreatment system of claim 34 further comprising a second lean NO\textsubscript{X} adsorber in said bypass line.

46. The aftertreatment system of claim 45 further comprising a second regeneration catalyst disposed in said bypass line upstream of said second lean NO\textsubscript{X} adsorber.

47. The aftertreatment system of claim 34 further comprising a clean-up catalyst disposed downstream of said lean NO\textsubscript{X} adsorber, said clean-up catalyst capable of removing, from said exhaust gas, at least one of:

(a) said NO\textsubscript{X},

(b) said reductant, and,

hydrogen sulfide.