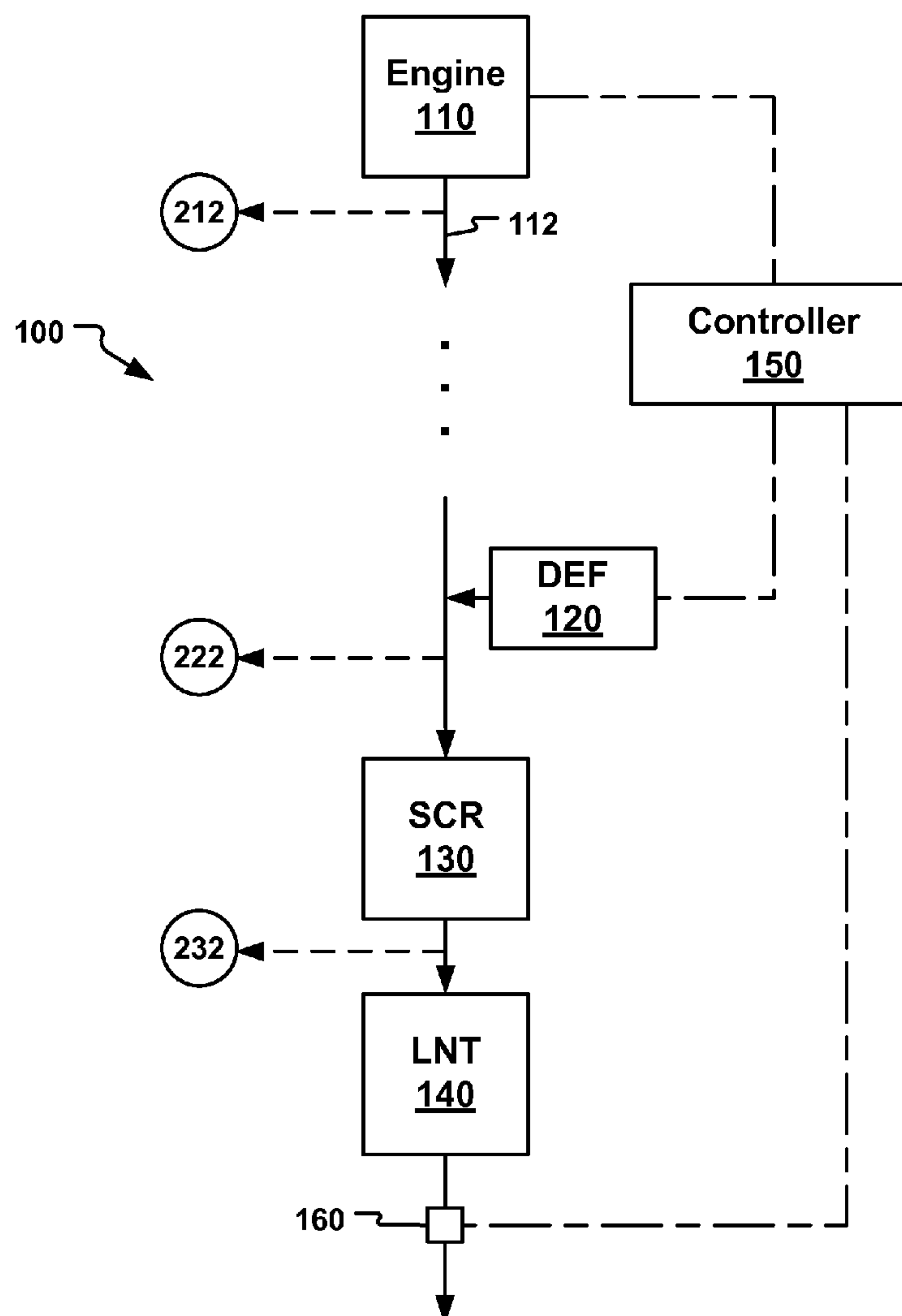


US 20110047970A1

(19) **United States**(12) **Patent Application Publication**
YEZERETS et al.(10) **Pub. No.: US 2011/0047970 A1**(43) **Pub. Date: Mar. 3, 2011**(54) **HIGH EFFICIENCY NOX REDUCTION
SYSTEM AND METHOD**(52) **U.S. Cl. 60/274; 60/301; 60/295; 60/276;
60/286**(75) **Inventors:** **Aleksey YEZERETS**, Columbus,
IN (US); **Neal W. CURRIER**,
Columbus, IN (US)(57) **ABSTRACT**(73) **Assignee:** **CUMMINS INTELLECTUAL
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An exhaust gas stream aftertreatment system and method achieves high efficiency NOx reduction in exhaust gas emissions by arranging a selective catalytic reduction (SCR) catalyst element upstream from a NOx adsorber catalyst. In an exemplary embodiment, a reductant is introduced into the exhaust gas stream, exposing the exhaust gas stream containing the reductant to a selective catalytic reduction (SCR) catalyst element, and exposing the exhaust gas stream that was exposed to the SCR catalyst element to a NOx adsorber catalyst element. The NOx adsorber catalyst element can be regenerated by temporarily reducing an oxygen concentration in an exhaust gas stream to reduce the λ of the exhaust gas stream. While the oxygen concentration is reduced, reductant is introduced into the exhaust gas stream at a rate that achieves a fuel-rich condition, and the fuel rich exhaust stream is exposed to the NOx adsorber catalyst element.

(21) **Appl. No.: 12/552,096**(22) **Filed: Sep. 1, 2009****Publication Classification**(51) **Int. Cl.**
F01N 3/10 (2006.01)
F01N 3/023 (2006.01)
F01N 11/00 (2006.01)
F01N 9/00 (2006.01)

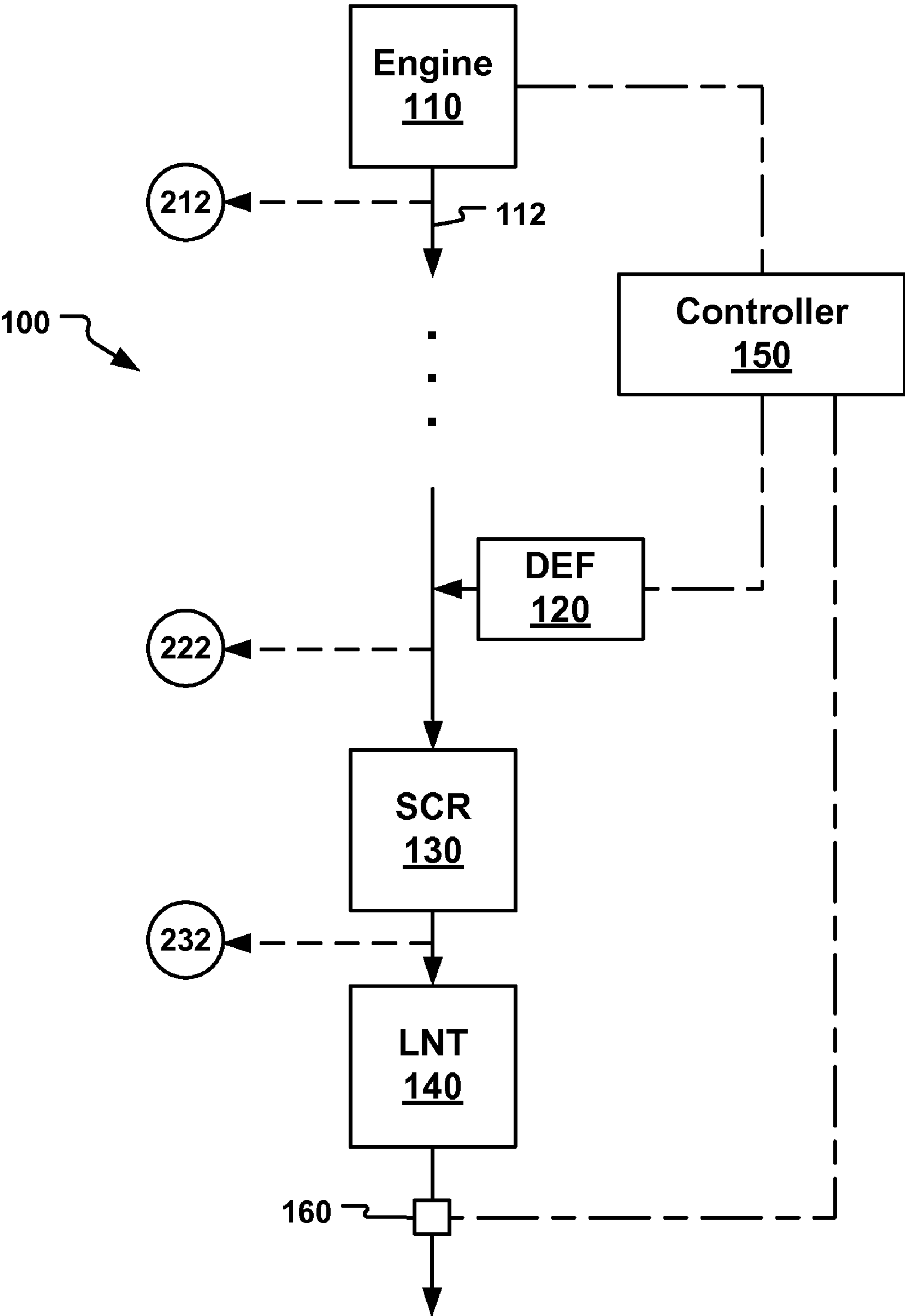


FIG. 1

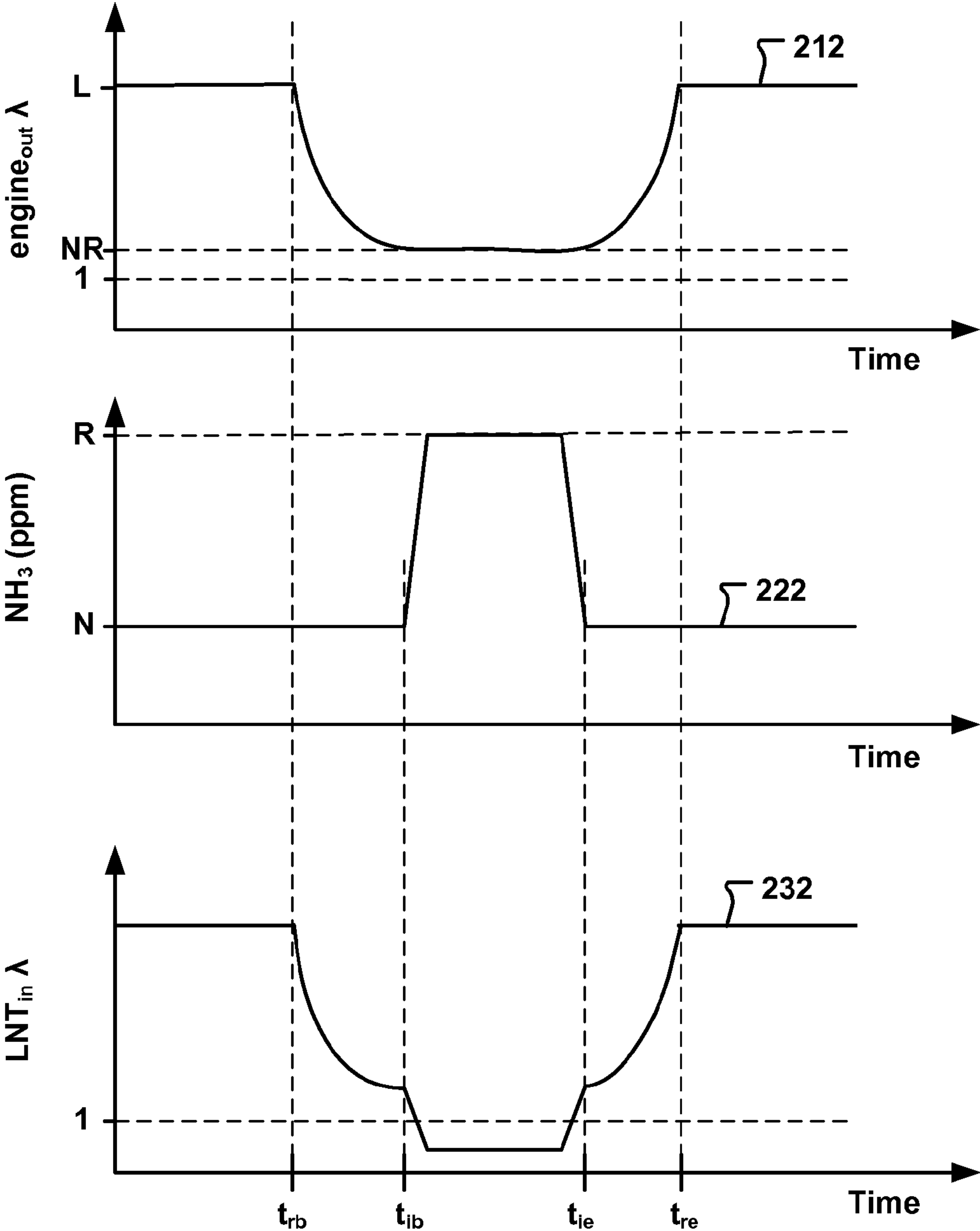


FIG. 2

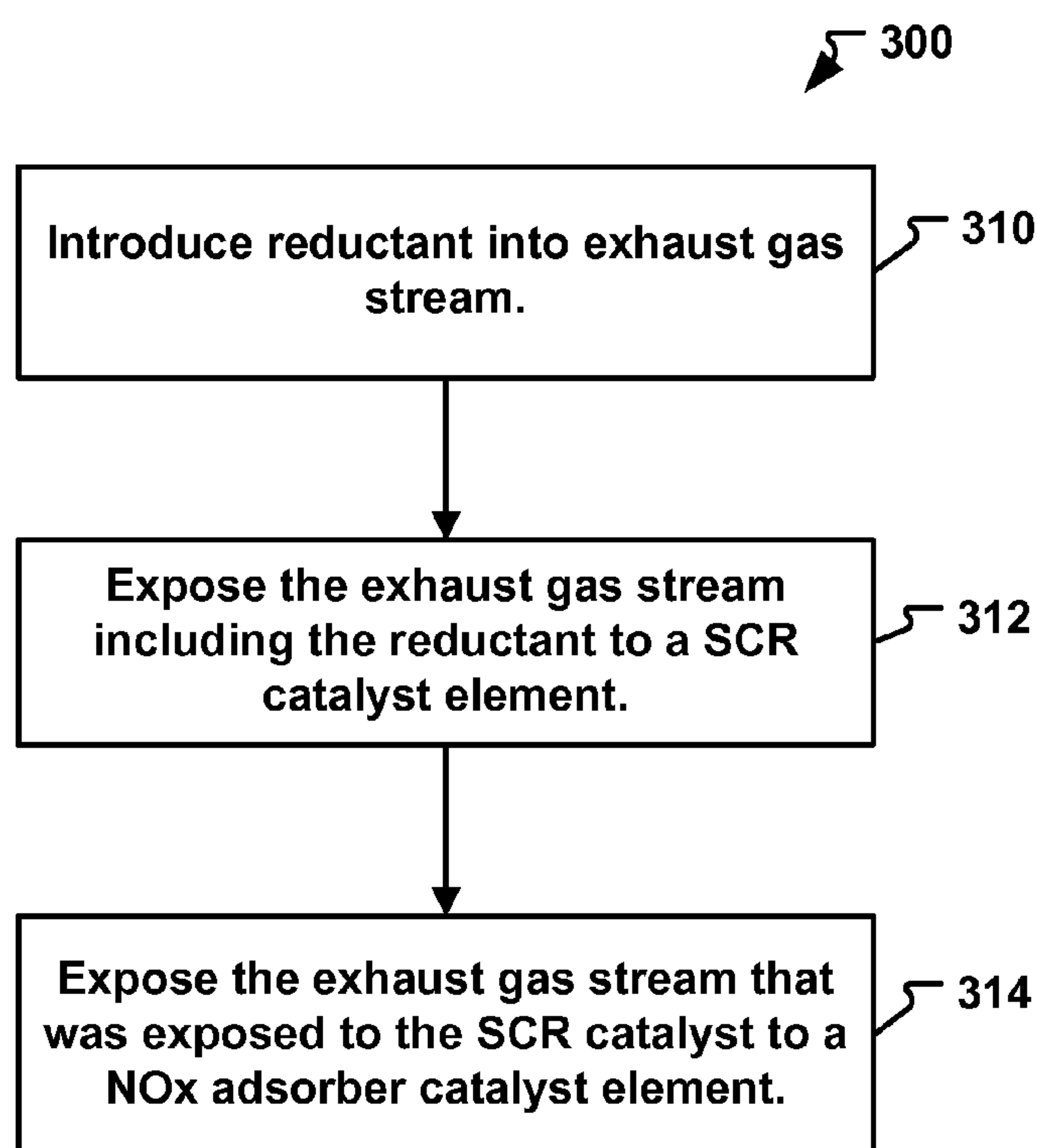


FIG. 3A

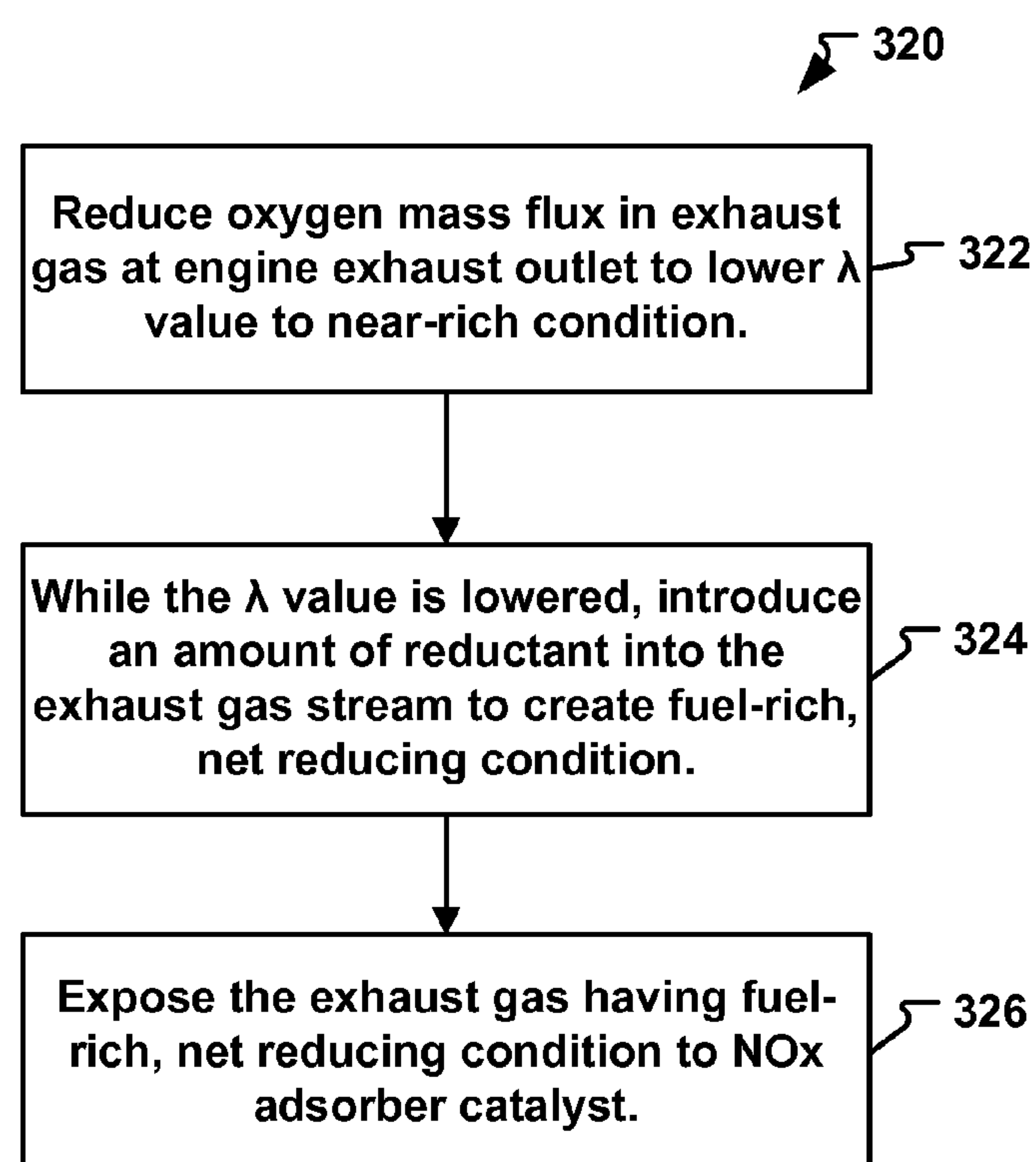


FIG. 3B

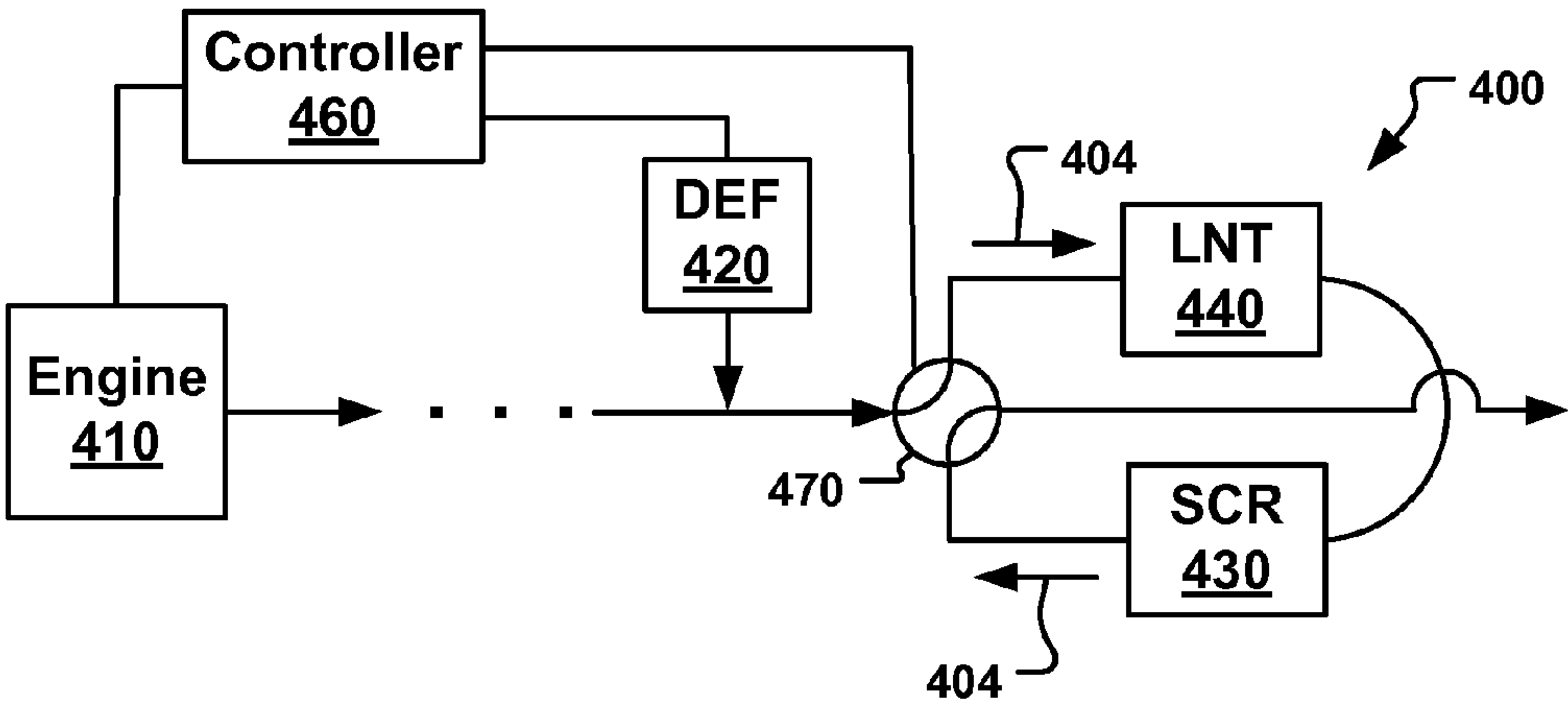
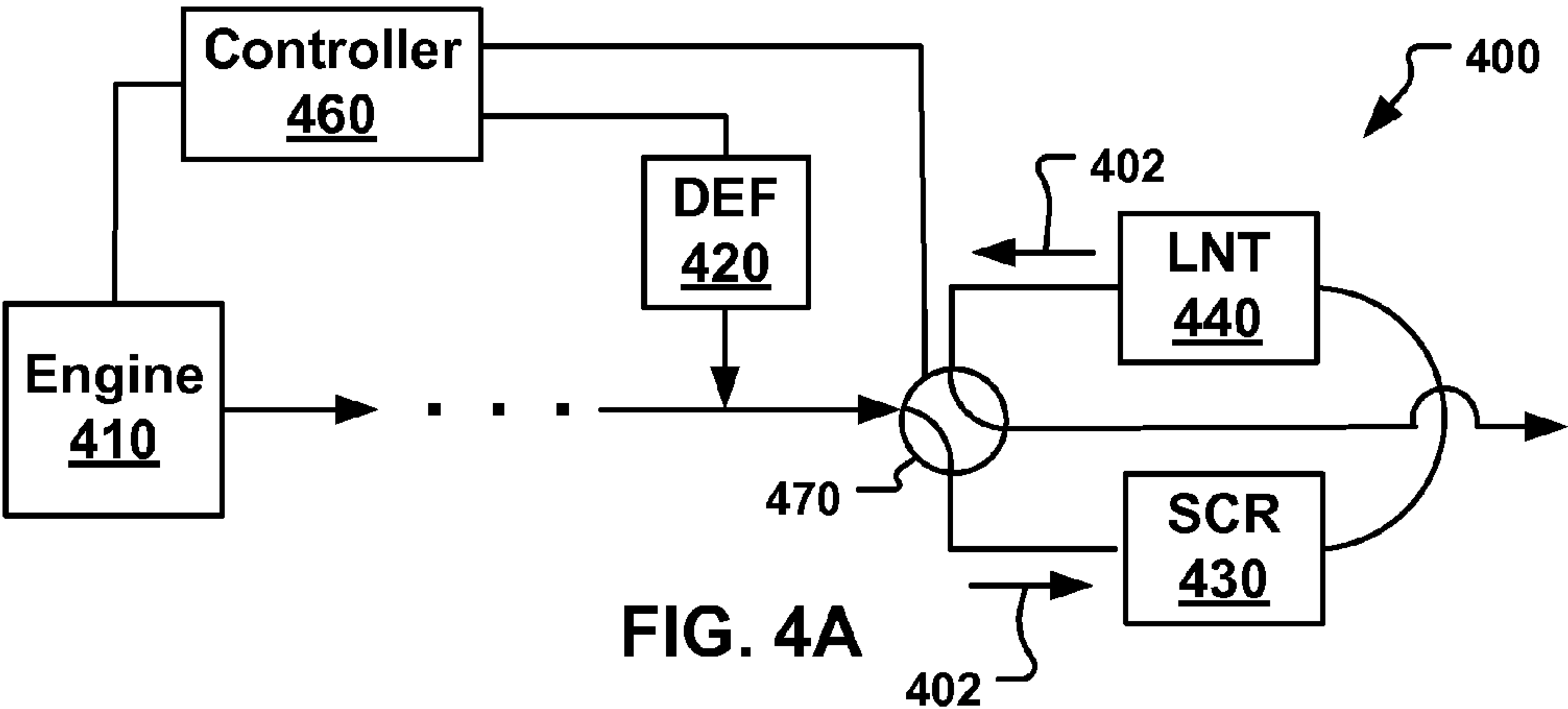


FIG. 4B

HIGH EFFICIENCY NOX REDUCTION SYSTEM AND METHOD

FIELD OF THE INVENTION

[0001] A system and method for reducing nitrogen oxides in exhaust gas are disclosed.

BACKGROUND

[0002] Nitrogen oxides (NOx), which include nitric oxide (NO) and nitrogen dioxide (NO₂), are formed during the high temperature and pressure combustion of an air and fuel mixture in an internal combustion engine. These oxides cause a number of concerns related to the environment, such as a source of ground-level ozone or smog, acid rain, excess aqueous nutrients, and can readily react with common organic chemicals, and even ozone, to form a wide variety of toxic products. Since the 1970's, government legislation has required increasing reductions of NOx in exhaust gas emissions.

[0003] To comply with increasingly stringent government mandates, industry has developed several NOx reduction technologies to treat post combustion exhaust, of which NOx adsorber catalyst and selective catalytic reduction (SCR) technologies are actively pursued.

[0004] The NOx adsorber catalyst, sometimes referred to as an NAC, a lean NOx trap (LNT), a NOx storage reduction catalyst (NSR), and a NOx storage catalyst (NSC), performs the process of adsorbing, or "trapping" NOx using an alkali or alkaline earth storage material, such as a barium salt (e.g., barium carbonate), and reducing the bound nitrogen oxides using a catalytic surface comprised of precious metal (e.g., platinum, palladium, rhodium, and combinations thereof). More specifically, under lean air/fuel ratio that typifies diesel exhaust, the storage material M adsorbs NO₂ as a nitrate, MNO₃. After the NOx adsorber catalyst reaches or approaches a certain level of saturation, it is regenerated by creating or producing a fuel-rich environment, which can be either stoichiometric air/fuel mixture or fuel-rich of a stoichiometric mixture. A practical way of creating such an environment typically involves two steps: 1) reducing oxygen contained in the exhaust, and 2) consuming the residual of the remaining oxygen and injecting some extra fuel in the cylinder. Under these fuel-rich conditions, the NO_x adsorber catalyst promotes the decomposition and release of the nitrate as NO and catalyzes the reduction of NO to nitrogen and carbon dioxide.

[0005] The SCR process reduces NOx to diatomic nitrogen (N₂) and water (H₂O) using a catalyst and anhydrous ammonia (NH₃) or aqueous NH₃, or a precursor that is convertible to NH₃, such as urea. Typical SCR catalysts are a honeycomb or plate ceramic carrier (e.g., titanium oxide) and oxides of base metals (e.g., vanadium and tungsten), zeolites and other precious metals. Unreacted NH₃ is sometimes released from the SCR, and known as "NH₃ slip." To reduce NH₃ slip, an NH₃ slip catalyst can be provided downstream from the SCR.

SUMMARY

[0006] Embodiments consistent with the claimed invention relate to an exhaust gas stream aftertreatment system and method that achieves high efficiency NOx reduction in exhaust gas emissions by arranging a selective catalytic reduction (SCR) catalyst element upstream from a NOx adsorber catalyst.

[0007] In an exemplary embodiment consistent with the claimed invention, a method of reducing NOx in an exhaust gas stream emitted from an internal combustion engine includes introducing a reductant into the exhaust gas stream, exposing the exhaust gas stream containing the reductant to a selective catalytic reduction (SCR) catalyst element, and exposing the exhaust gas stream that was exposed to the SCR catalyst element to a NOx adsorber catalyst element.

[0008] In another embodiment consistent with the claimed invention, a NOx reduction system includes a gas flow circuit for treating an exhaust gas stream emitted from an internal combustion engine. The gas flow circuit comprises a reductant introduction port, an SCR catalyst element positioned downstream from the reductant introduction port, and a NOx adsorber catalyst element positioned downstream from the SCR catalyst element.

[0009] In yet another aspect, a method of regenerating a NOx adsorber catalyst element in an exhaust aftertreatment system including an SCR catalyst element positioned upstream from the NOx adsorber catalyst element includes temporarily reducing an oxygen concentration in an exhaust gas stream to reduce the λ of the exhaust gas stream. While the oxygen concentration is reduced, reductant is introduced into the exhaust gas stream at a rate that achieves a fuel-rich condition. The fuel-rich exhaust gas stream is then exposed to the NOx adsorber catalyst element.

[0010] It is to be understood that both the foregoing general description and the following detailed description are exemplary and exemplary only and are not restrictive of the invention, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The accompanying drawings, which are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate embodiments of the invention that together with the description serve to explain the principles of the invention. In the drawings:

[0012] FIG. 1 is a diagram of an exhaust treatment system in accordance with an exemplary embodiment.

[0013] FIG. 2 is a set of graphs showing λ values and ammonia injection rates versus time in the exhaust stream at different points along the exhaust treatment system of FIG. 1.

[0014] FIG. 3A is a flowchart of processes for treating exhaust gas during normal operation in accordance with an exemplary embodiment.

[0015] FIG. 3B is a flowchart of processes for treating exhaust gas during regeneration in accordance with an exemplary embodiment.

[0016] FIG. 4A is diagram of an exhaust treatment system including a valve configured for normal operation in accordance with exemplary embodiments.

[0017] FIG. 4B is a diagram of the exhaust treatment system of FIG. 4A with the valve is configured for a regeneration operation.

DETAILED DESCRIPTION

[0018] The various aspects are described hereafter in greater detail in connection with a number of exemplary embodiments to facilitate an understanding of the invention. However, the invention should not be construed as being limited to these embodiments. Rather, these embodiments are

provided so that the disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

[0019] Typical demonstrated efficiency of current NOx reduction technologies, such as NOx adsorber catalyst and SCR using urea or ammonia (NH₃) is limited to, at best, about 80 to 85% over the typical regulatory testing cycles. To achieve a target of 0.2 g/hp-hr NOx level at the tailpipe, for example, at an 80% NOx conversion efficiency the engine-out NOx levels would need to be reduced to 1 g/hp-hr. To meet such stringent NOx emission levels, exhaust gas recycling (EGR) or other mechanisms are utilized to reduce NOx exiting the engine (i.e., “engine-out NOx levels”). However, EGR negatively affects an engine’s fuel efficiency. At the same time, regulatory adjustment factors and engineering margins have been driving engine-out NOx to even lower levels. Thus, a different way to increase NOx conversion efficiency downstream of the engine would allow for both cleaner exhaust gases and improved engine performance. For example, if the downstream NOx conversion efficiency can be increased to 95%, this would permit engine-out NOx levels on the order of 4 g/hp-hr, which can provide margins for more fuel-efficient engine operation, improved passive regeneration of a diesel particle filter (DPF), and possible improvements to engine durability due to reduced EGR flow rates or elimination of EGR.

[0020] To provide more efficient reduction of NOx downstream of an engine, embodiments consistent with the claimed invention position a NOx adsorber catalyst downstream from an SCR catalyst. With this arrangement, the overall NOx reduction efficiency of an SCR system can be substantially improved by using the NOx adsorber catalyst to capture NOx slip from the SCR catalyst, oxidize the NH₃ slip from the SCR, and capture the NOx produced by the SCR process. This SCR-LNT sequential arrangement also can allow for more aggressive urea/NH₃ injection strategies, which result in higher SCR efficiency. Regeneration of the NOx adsorber catalyst can be accomplished using NH₃ to create a net reducing environment because NH₃ can be a hydrogen carrier in the NOx adsorber catalyst regeneration. For example, see L. Cumaranatunge et al., “Ammonia is a hydrogen carrier in the regeneration of Pt/BaO/Al₂O₃ NOx traps with H₂,” *Journal of Catalysis*, 246 (2007) 29-34.

[0021] While use of a LNT upstream from an SCR is known and has been commercialized, the LNT-SCR sequential system is fundamentally different from systems or methods consistent with the claimed invention utilizing the SCR to LNT arrangement. Namely, conventional LNT-SCR systems are NOx adsorber catalyst (LNT)-based system, with a downstream SCR catalyst merely enhancing its conversion efficiency at some conditions. When LNT is not working in the conventional LNT-SCR system, the SCR also does not work. There is no urea injection in those types of systems. In contrast, systems and methods consistent with the claimed subject matter are primarily SCR-based ones, with LNT acting as a NO_x and NH₃ slip control catalyst. These and other differences will become apparent in the following description of exemplary embodiments.

[0022] FIG. 1 is a diagram of an exhaust aftertreatment system 100 and according to an exemplary embodiment. As shown in FIG. 1, the exhaust aftertreatment system 100 includes a gas flow circuit that includes an exhaust gas channel 112 provided to an exhaust gas outlet of an internal combustion engine 110. The exhaust gas channel 112 can have

one or more segments that connect the engine 110 to a diesel exhaust fluid (DEF) port 120, an SCR catalyst element 130, and a LNT element 140, although additional aftertreatment elements (not shown) can be included in the exhaust aftertreatment system 100.

[0023] The exhaust aftertreatment system 100 can include a controller 150, which can be an electronic control unit (ECU) of the engine 110 that monitors the performance of the engine 110 and other elements of the exhaust aftertreatment system 100. The controller 150 can be a single unit or plural control units that collectively perform these monitoring and control functions. The controller 150 utilizes sensors to determine whether the exhaust aftertreatment system 100 is functioning properly. As shown in FIG. 1, the controller 150 can be connected to the DEF port 120, which can include an injecting device such as an atomizer to inject a reductant into the channel 112 downstream from the exhaust gas outlet of the engine 110. The reductant can be an NH₃ source, such as anhydrous NH₃, aqueous NH₃, or a precursor that is convertible to NH₃ such as urea. The controller 150 can control a timing and amount of reductant injected into the exhaust stream by the DEF port 120.

[0024] The exhaust gas stream treated with the reductant by the DEF port 120 is provided to an inlet of the SCR 130 at a location downstream of the DEF port 120. While the exhaust gas stream traverses the SCR catalyst element, the gas stream is exposed to the SCR catalyst. After exiting an outlet the SCR 130, the exhaust gas stream flows into the LNT element 140, where it is exposed to a NOx adsorber catalyst in the LNT element 140. The LNT 140 can comprise a housing defining an inlet at one end thereof configured to receive exhaust gas exiting the SCR 130, an outlet at an opposite end thereof, and a chamber between the inlet and the outlet that houses the catalyst. Alternatively, more than one element of the gas flow circuit of the exhaust aftertreatment system 100 can be contained within a single housing. For example, the SCR and LNT can be contained within the same housing in which the SCR element is provided upstream of the LNT element so the exhaust gas stream flows through a portion of the housing including the SCR element before flow through a portion of the housing including the LNT element.

[0025] Under normal operating conditions, the SCR element 130 is the primary element of the exhaust aftertreatment system for removing NOx from the exhaust gas stream. During normal operating conditions, the controller 150 receives signals from various sensors, such as the throttle sensor and air temperature sensor on the engine (not shown) or a NOx or ammonia sensor 160 provided in the exhaust aftertreatment system. From the sensed conditions, the controller 150 can determine various parameter values of engine 110 and elements of the exhaust aftertreatment system. More specifically, the controller 150 will cause the DEF port 120 to inject reductant at a rate needed to operate the SCR catalyst element 130 for a current operating condition of the engine 110. NOx that slips through the SCR catalyst element 130 can be captured by the LNT element 140.

[0026] Additionally, the LNT element 140 can oxidize NH₃ (if any) slipping from the SCR catalyst element 130 to N₂, which is benign, or to NOx, which the LNT element 140 also can trap and process. This allows the SCR catalyst 112 to be overdosed with reductant (e.g., NH₃), which can result in higher SCR conversion efficiency. For example, an ammonia dosing scheme will have a respective ammonia/NOx ratio (ANR), where an ANR equal to 1 would represent a stoichio-

metric ratio. As an example, typical average ANR values used under normal SCR system operation are between about 0.8 and 1.5 or higher, although it is to be understood that instantaneous ANR values can be greater or smaller than these averages. The LNT element acting as a slip clean-up catalyst in the described embodiments, enables the use more aggressive reductant schemes in which ANR values can be substantially higher than 1, for example, up to 5 or 10.

[0027] From time-to-time, the LNT element 140 must be actively regenerated because NOx adsorber capture efficiency declines as a function of the accumulation, or “storage” of NOx as a nitrate on the catalytic surface of the LNT element 140. By rapidly increasing the rate at which the reductant fluid is injected into the exhaust stream, the stored NOx on the catalytic surface of the LNT element 140 can be converted in an active regeneration process that promotes decomposition and release of the nitrate as NO. For example, a sharp increase in the rate at which the reductant fluid injected by the DEF port 120, and/or an introduction of additional reductant fluid at some other point upstream from the LNT element 140, can create a fuel-rich, net reducing condition necessary for regeneration of the LNT element 140. The reducing condition causes the release of NOx through decomposition of nitrates on the catalytic surface of the LNT 140 upon introduction of the reductant, which leads to reduction of the regenerated NOx to N₂. The regeneration process can be further facilitated by reducing oxygen mass flux in the exhaust gas stream. For example, an air intake of the engine 110 can be choked to reduce the oxygen content in the exhaust gas stream prior to rapidly increasing the rate that reductant is injected into the stream.

[0028] FIG. 2 includes a set of graphs showing characteristics of the exhaust gas stream at different points along the exhaust gas flow path before, during, and after regeneration of the LNT 140. Graphs 212 and 232 depict exemplary oxygen stoichiometry value, or “λ value”, versus time at different points along the exhaust stream. Graph 222 depicts levels of NH₃ injected by the DEF port 120 during the same time period covered by graphs 212 and 232. It is to be appreciated that the graphs of FIG. 2 are simplified for ease of illustrating concepts, and that the levels of reductant solution and λ value depicted can vary to some degree depending on how the engine 110 is operating. Further, while the graphs depict some events occurring simultaneously, it is to be understood that a small time delay (not shown) can occur for events at locations more downstream of others.

[0029] Referring again to FIG. 1, plural dotted arrows, each having an indicator designating one of the graphs 212, 222 and 232 of FIG. 2 are positioned at the different points along the flow path corresponding to exemplary exhaust gas characteristics depicted by the graphs 212, 222, and 232. Starting from the engine 110, the regeneration process can occur while choking air entering an intake of the engine 110 from time t_{rb} until a later time t_{re} . This choking is shown in graph 212 where the value of the exhaust exiting the engine 110 (i.e., the “engine_{out} λ”) is reduced from a fuel-lean “normal” operating condition L to a more rich condition while the air intake of the engine 110 is choked during the time period from t_{rb} to t_{re} . As shown in graph 212, the choking process reduces air in the value of exhaust gas stream in the channel 112 exiting the outlet of the engine 110 from the fuel-lean value L to a “near rich” value, NR, in which the λ value is reduced, but remains above a stoichiometric level of 1.

[0030] As shown by graph 222 of FIG. 2, prior to regeneration, a reductant solution is injected into the exhaust stream by the DEF port 120 at a level N that is sufficient for operating the SCR 130. Typically, a value of N can be about 300 ppm, although N can take on any value of a range of values, for example a range of about 50 to 1000 ppm, because instantaneous amounts of reductant introduced into the exhaust stream can vary often in accordance with operating conditions. During regeneration event, the rate of injected reductant fluid (e.g., from the DEF port 120) can be rapidly increased and held at a level R between time t_{ib} and t_{ie} within the time period from t_{rb} to t_{re} when the engine 110 is choked. For example, the level of NH₃ introduced can be increased from about 300 ppm used to operate the SCR to concentrations of at least 3000 to 5000 ppm during the rich pulse R (assuming about 0.5% residual oxygen). Thus, the reductant concentration can increase an order of magnitude, or about 10-50 times the normal concentrations of NH₃ for SCR. In a case where residual O₂ is greater than about 2%, the reductant concentration can increase to four or more times the numbers for the 0.5% O₂ case. Hence, an amount R of reductant introduced during a regeneration event can be about 10 to 1000 times the amount N used to normally operate an SCR catalyst element. Further, the amount R need not be held to a single value during the entire regeneration event, but may increase or decrease in correspondence with an amount N used to operation of the engine around the time of regeneration.

[0031] At about the same time the reductant level is increased, as shown by the graph 232, the value of the exhaust entering LNT 140 (i.e., the “LNT_{in} λ”) breaks through the stoichiometry line at λ=1 to create a fuel-rich condition in the exhaust gas stream, although it is to be understood that reductant can be introduced at a rate at or near stoichiometry to produce a fuel-rich reducing condition. It is during this time interval of a large increase in the DEF injection (i.e., when the exhaust gas is rich) that regeneration of the LNT 140 actually occurs. Because the LNT 140 can be regenerated without necessarily injecting extra fuel into the exhaust stream or over-injecting fuel into the cylinders of the engine 110 as in conventional LNT aftertreatment systems, performance of the overall engine and exhaust aftertreatment system can be improved.

[0032] Embodiments of system and methods for reducing NOx described herein operate differently from known generic NH₃ slip catalysts. One difference is embodiments have a mode of operation that involves an intermittent (e.g., periodic) cleaning up of a NOx adsorber catalyst (LNT) using NH₃ as the reductant. More specifically, the NOx adsorber catalyst removes both NOx and NH₃ slip from an SCR by accumulating them, and then periodically the NOx adsorber catalyst must be cleaned by first choking the engine to some degree to reduce the air-fuel ratio and injecting a massive amount of a reductant, such as NH₃, and/or introducing additional fuel into exhaust stream by some mechanism, such as an injection port, to regenerate it. By first reducing oxygen in the exhaust gas exiting the engine, the amount of NH₃ that would be required as a reductant for a regeneration event can be reduced to a practical level. By contrast, known slip catalysts work continuously to remove NH₃ slippage from an SCR. Another difference is the use of a reductant (e.g., NH₃) to create a net reducing condition and eliminate or reduce the necessity of injecting fuel in the way a known lean NOx trap is operated.

[0033] An intermittent regeneration event can be triggered by either a physical or virtual sensor (not shown) recognizing that the NOx adsorber catalyst is full, or approaching a saturation point. For example, FIG. 1 shows a NOx and/or NH₃ sensor 160 located after the outlet of the NOx adsorber catalyst that can trigger regeneration based on feedback information related to sensed NOx and/or ammonia concentrations. Alternatively, intermittent regeneration can be triggered using a time based sensor, for example, a timer that triggers regeneration processes in a periodic manner (e.g., once every minute, once every ten minutes etc.). Time between intermittent regeneration may be determined by any, or a combination of controlling variables, such as sensed operating environment (e.g., city versus highway), heavy duty versus light duty operation, and “real time” or recent driving history. A scheme can be designed to regenerate the NOx adsorber catalyst at such a frequency, manner, and/or extent to achieve a prescribed emissions criterion while minimizing a performance penalty.

[0034] FIG. 3A depicts an exemplary process flow 300 performed by an embodiment of an exhaust aftertreatment system including an LNT element located downstream from an SCR catalyst element. In process 310, an emitted exhaust gas stream, for example, from a diesel internal combustion engine, is treated with a reductant solution containing urea and/or ammonia by introducing the reductant solution into the exhaust gas stream. For example, a rate at which a reductant is introduced into the exhaust gas can be increased from an amount that would be required to operate the SCR element when operating the engine under normal conditions. The exhaust gas stream including the reductant is then exposed to an SCR catalyst in process 312. In process 314, the exhaust gas stream that was exposed to the SCR catalyst is exposed to the to a NOx adsorber catalyst.

[0035] FIG. 3B illustrates an exemplary process flow 320 that can occur when the controller determines a regeneration event has been triggered. At process 322, the air mass flux in the exhaust is reduced to lower the exhaust gas λ value and create a near-rich condition. For example, the air intake of the engine can be choked to lower the air/fuel ratio to a lean level in which the oxygen stoichiometry is close to 1. While the λ value is lowered, an amount of reductant introduced into the exhaust gas stream in process 324 to create a fuel-rich, net reducing condition for the exhaust gas. In process 326, the exhaust gas having the fuel rich, net reducing condition is exposed to a NOx adsorber catalyst. At the end of a regeneration event, process 320 reduces the rate that the reductant solution is introduced into the exhaust gas stream and increases the air mass present in the exhaust gas stream to levels that are adequate for at the current engine operating condition.

[0036] The end of a regeneration event can be commanded based on the pre-set timer value (e.g., two to four seconds), an open loop virtual sensor such as one based on the exhaust conditions at the time of regeneration and/or integrated since the last regeneration event, or a closed loop virtual sensor, such as one based on measurements of some catalyst properties, such as detection of depletion of oxygen storage capacity using a λ -sensor.

[0037] With reference now to FIGS. 4A and 4B, an embodiment of a system 400 for reducing NOx in exhaust gas includes a mechanism that reverses the exhaust gas flow through a segment of the system 400 to facilitate precise

control of NH₃ slip during regeneration of the NOx adsorber catalyst, and thus an overall increase in the efficiency of operation.

[0038] FIG. 4A depicts the direction of exhaust gas flow during a normal operating mode. As indicated by the arrows 402, a reductant solution (e.g., NH₃ or aqueous urea) is injected by a DEF port 420 into an exhaust gas flowing from an engine 410 at a level sufficient for operating an SCR catalyst element 430 downstream of the engine 410. After the exhaust gas stream is exposed to the SCR catalyst element 430, the exhaust gas is exposed to a catalyst of a LNT element 440. NH₃ slip from the SCR catalyst element 430 is removed by the LNT element 440. A controller 460 controls the DEF 420, the engine 410 and a four port, or four-way valve 470. The controller 460 can set the valve 470 at one of two possible states. In a first state illustrated in FIG. 4A, the exhaust gas flows into the valve 470, through the SCR catalyst element 430, through the LNT element 440 downstream from the SCR catalyst element 430, and then again through the valve 470 before exiting the system.

[0039] FIG. 4B shows the system 400 operating during a regeneration operating mode. In this operating mode, the controller 460 sets the valve 470 in a second state, which changes the order that the exhaust stream flows through the SCR and NOx adsorber catalyst elements. More particularly, valve 470 is set so that the LNT 440 is connected upstream from the SCR catalyst element 430, as indicated by arrows 404. During regeneration, exhaust gas rich in reductant fluid (e.g., urea or NH₃) is first sent through the LNT 440 and thereafter through the SCR catalyst element 430 because, while controlling NH₃ slip under normal operating conditions is less difficult when only several hundred ppm of NH₃ is injected into the exhaust flow (i.e., a percentage of NH₃ that would slip through would be low), increasing an amount of reductant to a relatively high level at the time of regeneration, for example, going from 300 ppm to 2% or more concentration of NH₃, presents a higher risk of large NH₃ slip. By switching the order of elements during a regeneration event, the SCR catalyst element 430 can better act as a slip control device for NH₃ passing through the LNT element 440.

[0040] Embodiments described herein having the NOx adsorber catalyst arranged downstream from the SCR can allow for more efficient operation of the engine because use of EGR, which reduces engine efficiency (e.g., fuel efficiency, horsepower, and engine performance) can either be reduced significantly or eliminated altogether. Additionally, a reduction in EGR also decreases overall operating costs. Also, positioning a NOx adsorber catalyst after the SCR in the normal operating mode allows for higher concentrations of ammonia during a normal operating mode of the engine, and thus greater SCR efficiency.

[0041] It will be appreciated that the embodiments described and shown herein may be modified in a number of ways. For instance, in any embodiment consistent with the claimed invention, the exhaust system can include other elements such as a diesel oxidation catalyst (DOC) and/or a DPF in the stream of the exhaust gas flow from the engine. Additionally, a reductant fluid injection point may be provided at any location after the engine and upstream of the SCR. It will be appreciated that a reductant other than those described above can be used, such as gaseous NH₃ or some source of bound NH₃ other than urea solution.

[0042] Additional embodiments can include, but are not limited to one or more additional reductant (e.g., urea or NH₃)

injection location upstream of the NOx adsorber catalyst. Embodiments also can include alternative way of regenerating the NOx adsorber catalyst. In addition, LNT regeneration can be accomplished in a traditional way, albeit much less frequently since it is used only as a slip catalyst, by achieving rich conditions in-cylinder or with a supplemental fuel doser. Even with such a classical mode of LNT regeneration, an application of a LNT can provide a combined reductant (e.g., NH₃) slip and NOx slip catalyst for an SCR catalyst element. [0043] Further, while the embodiments are depicted as separate devices in the figures, other embodiments can include an SCR and NOx adsorber catalysts being zone-coated on the same substrate or the SCR and NOx adsorber catalysts arranged as layers on the same substrate. Hence, while embodiments described above include a separate chamber for each of the SCR and NOx adsorber catalyst (LNT), other embodiments can include both the SCR and LNT in a same chamber. The exhaust in all such embodiments would flow in a direction from the SCR to the LNT within the chamber. Furthermore, while the exemplary embodiments are sometimes described in the context of a diesel internal combustion engine, the same concepts can be applied in a lean burn gasoline powered internal combustion engine.

[0044] Although a limited number of exemplary embodiments is described herein, one of ordinary skill in the art will readily recognize that there could be variations to any of these embodiments and those variations would be within the scope of the appended claims. Thus, it will be apparent to those skilled in the art that various changes and modifications can be made to the NOx reduction system and method described herein without departing from the scope of the appended claims and their equivalents.

What is claimed is:

1. A method of reducing NOx in an exhaust gas stream emitted from an internal combustion engine, comprising:
 - introducing a reductant into the exhaust gas stream;
 - exposing the exhaust gas stream containing the reductant to a selective catalytic reduction (SCR) catalyst element; and
 - exposing the exhaust gas stream that was exposed to the SCR catalyst element to a NOx adsorber catalyst element.
2. The method of claim 1, further comprising intermittently regenerating the NOx adsorber catalyst by temporarily reducing the oxygen mass flux in the exhaust gas stream and increasing a rate that the reductant is introduced into the exhaust stream while the oxygen mass flux is reduced to create a net reducing condition in the NOx adsorber catalyst element.
3. The method of claim 2, wherein temporarily reducing the oxygen mass flux in the exhaust gas stream comprises choking the air intake of the engine.
4. The method of claim 2, wherein the intermittent regeneration of the NOx adsorber catalyst is performed periodically.
5. The method of claim 2, further comprising sensing an amount of NOx in the exhaust stream downstream from the NOx adsorber catalyst, and triggering the intermittent regeneration when the sensed amount indicates the adsorber catalyst is at least one of full and approaching a saturation point.
6. The method of claim 2, further comprising sensing an amount of reductant in the exhaust stream downstream from the NOx adsorber catalyst, and triggering the intermittently

regeneration when the sensed amount of reductant indicates the adsorber catalyst is at least one of full and approaching a saturation point.

7. The method of claim 1, wherein the reductant is ammonia or urea.

8. The method of claim 2, wherein an intermittent regeneration further comprises reversing the order in which the exhaust gas stream is exposed to the SCR catalyst element and the NOx adsorber catalyst element.

9. A NOx reduction system comprising a gas flow circuit for treating an exhaust gas stream emitted from the outlet of an internal combustion engine, said gas flow circuit comprising:

- a reductant introduction port;
- a selective catalytic reduction (SCR) catalyst element positioned downstream from the reductant introduction port; and
- a NOx adsorber catalyst element positioned downstream from the SCR catalyst element.

10. The system of claim 9, further comprising a controller that monitors whether an intermittent regeneration triggering event occurs, and initiates regeneration of the NOx adsorber catalyst element after sensing a triggering event.

11. The system of claim 10, wherein regeneration of the NOx adsorber catalyst element includes temporarily reducing the oxygen mass flux in the exhaust gas stream exiting the internal combustion engine and increasing a rate of injection of a reductant injected from the reductant injection port while the oxygen mass flux is reduced.

12. The system of claim 10, wherein said intermittent regeneration triggering event comprises monitoring at least one sensor positioned downstream from the NOx adsorber catalyst and initiating the regeneration of the NOx adsorber catalyst when a sensed amount indicates the adsorber catalyst is at least one of full and approaching a saturation point.

13. The system of claim 12, wherein the sensor is a NOx sensor.

14. The system of claim 12, wherein the sensor is an ammonia sensor.

15. The system of claim 10, further comprising a valve that can be switched from a first state in which the SCR catalyst element is connected upstream from the NOx adsorber catalyst, and a second state in which the NOx adsorber catalyst is connected upstream from the SCR catalyst element.

16. The system of claim 15, wherein the controller switches the valve to the second state after determining that a triggering event has occurred.

17. A method of regenerating a NOx adsorber catalyst element in an exhaust aftertreatment system including a selective catalytic reduction (SCR) catalyst element positioned upstream from the NOx adsorber catalyst element, comprising:

- temporarily reducing an oxygen concentration in an exhaust gas stream to reduce the λ of the exhaust gas stream;
- while the oxygen concentration is reduced, introducing a reductant into the exhaust gas stream at a rate that achieves a fuel-rich condition; and
- exposing the fuel-rich exhaust gas stream to the NOx adsorber catalyst.

18. The method of claim 17, further comprising sensing an amount of NOx in the exhaust gas stream downstream from

the NOx adsorber catalyst, and triggering regeneration when the sensed amount indicates the adsorber catalyst is at least one of full and approaching a saturation point.

19. The method of claim **17**, further comprising sensing an amount of reductant in the exhaust stream downstream from the NOx adsorber catalyst, and triggering regeneration when

the sensed amount of reductant indicates the adsorber catalyst is at least one of full and approaching a saturation point.

20. The method of claim **17**, wherein regeneration of the NOx adsorber catalyst is performed periodically.

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