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(54) **CATALYST TO IMPROVE LOW TEMPERATURE DENOX ACTIVITY IN A REFORMER-LNT EXHAUST AFTERTREATMENT SYSTEM**

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(57) **ABSTRACT**

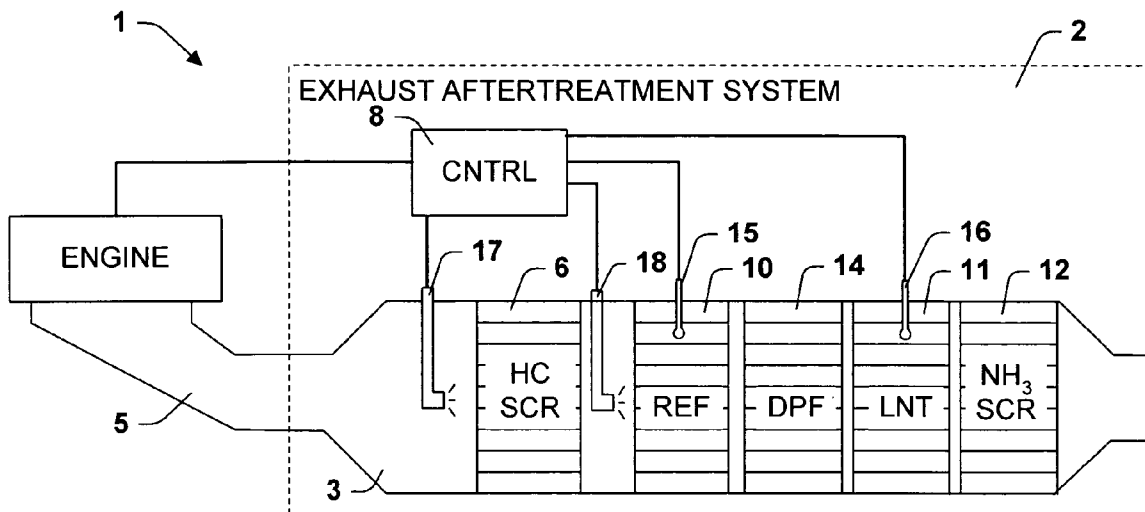
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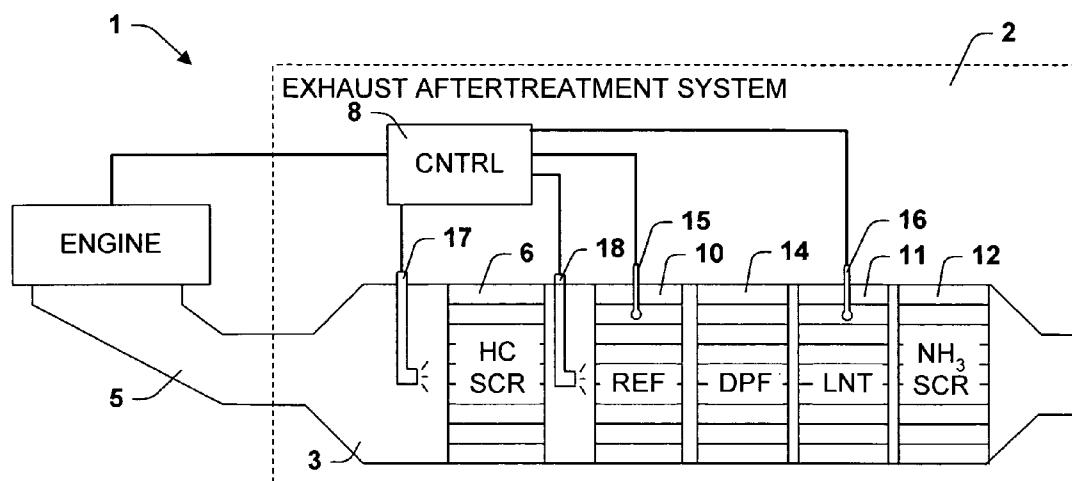
A low temperature lean NO_x catalyst is configured in a diesel exhaust treatment system upstream of a fuel reformer-LNT system to provide low temperature performance. During system warm-up and anytime the LNT falls below an effective operating temperature, the exhaust aftertreatment system is provided with hydrocarbons at a rate proportional to the exhaust NO_x flow rate, whereby NO_x is reduced over the lean NO_x catalyst. Optionally, the lean NO_x catalyst is also adapted for use warming up the fuel reformer and or catalyzing NO to NO₂ conversion. These concepts allow the reformer and LNT to be designed for high temperature performance and durability without also having to be adapted for NO_x mitigation at the exhaust system's lowest temperatures.

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Figure

**CATALYST TO IMPROVE LOW
TEMPERATURE DENOX ACTIVITY IN A
REFORMER-LNT EXHAUST
AFTERTREATMENT SYSTEM**

FIELD OF THE INVENTION

[0001] The present invention relates to pollution control systems and methods for diesel and lean burn gasoline engines.

BACKGROUND

[0002] NO_x emissions from diesel engines are an environmental problem. Several countries, including the United States, have long had regulations pending that will limit NO_x emissions from trucks and other diesel-powered vehicles. Manufacturers and researchers have put considerable effort toward meeting those regulations.

[0003] In gasoline powered vehicles that use stoichiometric fuel-air mixtures, three-way catalysts have been shown to control NO_x emissions. In diesel-powered vehicles, which use compression ignition, the exhaust is generally too oxygen-rich for three-way catalysts to be effective.

[0004] Several solutions have been proposed for controlling NO_x emissions from diesel-powered vehicles. One set of approaches focuses on the engine. Techniques such as exhaust gas recirculation and partially homogenizing fuel-air mixtures are helpful, but these techniques alone will not eliminate NO_x emissions. Another set of approaches remove NO_x from the vehicle exhaust. These include the use of lean-burn NO_x catalysts, selective catalytic reduction (SCR), and lean NO_x traps (LNTs).

[0005] Lean-burn NO_x catalysts promote the reduction of NO_x under oxygen-rich conditions. Reduction of NO_x in an oxidizing atmosphere is difficult. It has proven challenging to find a lean-burn NO_x catalyst that has the required activity, durability, and operating temperature range. The introduction of a reductant, such as diesel fuel, into the exhaust is generally required and introduces a fuel economy penalty of 3% or more. Currently, peak NO_x conversion efficiencies for lean-burn NO_x catalysts are unacceptably low.

[0006] SCR generally refers to selective catalytic reduction of NO_x by ammonia. The reaction takes place even in an oxidizing environment. The ammonia can be temporarily stored in an adsorbent or can be fed continuously into the exhaust. SCR can achieve high levels of NO_x reduction, but there is a disadvantage in the lack of infrastructure for distributing ammonia or a suitable precursor. Another concern relates to the possible release of ammonia into the environment.

[0007] To clarify the state of a sometime ambiguous nomenclature, it should be noted that in the exhaust after-treatment art, the terms "SCR catalyst" and "lean NO_x catalyst" are occasionally used interchangeably. Where the term "SCR" is used to refer just to ammonia-SCR, as it often is, SCR is a special case of lean NO_x catalysis. Commonly when both types of catalysts are discussed in one reference, SCR is used with reference to ammonia-SCR and lean NO_x catalysis is used with reference to SCR with reductants other than ammonia, such as SCR with hydrocarbons.

[0008] LNTs are devices that adsorb NO_x under lean exhaust conditions and reduce and release the adsorbed NO_x under rich conditions. A LNT generally includes a NO_x adsorbent and a catalyst. The adsorbent is typically an

alkaline earth compound, such as BaCO_3 and the catalyst is typically a combination of precious metals, such as Pt and Rh. In lean exhaust, the catalyst speeds oxidizing reactions that lead to NO_x adsorption. In a reducing environment, the catalyst activates reactions by which adsorbed NO_x is reduced and desorbed. In a typical operating protocol, a reducing environment will be created within the exhaust from time-to-time to regenerate (denitrate) the LNT.

[0009] A LNT can produce ammonia during denitration. Accordingly, it has been proposed to combine a LNT and an ammonia-SCR catalyst into one system. Ammonia produced by the LNT during regeneration is captured by the SCR catalyst for subsequent use in reducing NO_x , thereby improving conversion efficiency over a stand-alone LNT with no increase in fuel penalty or precious metal usage. U.S. Pat. No. 6,732,507 describes such a system. U.S. Pat. Pub. No. 2004/0076565 describes such systems wherein both components are contained within a single shell or disbursed over one substrate.

[0010] In addition to accumulating NO_x , LNTs accumulate SO_x . SO_x is the combustion product of sulfur present in ordinary fuel. Even with reduced sulfur fuels, the amount of SO_x produced by combustion is significant. SO_x adsorbs more strongly than NO_x and necessitates a more stringent, though less frequent, regeneration. Desulfation requires elevated temperatures as well as a reducing atmosphere. The temperature of the exhaust can be elevated by engine measures, particularly in the case of a lean-burn gasoline engine, however, at least in the case of a diesel engine, it is often necessary to provide additional heat. Typically, this heat is provided through the same types of reactions as used to remove excess oxygen from the exhaust. The temperature of the LNT is generally controlled during desulfation as the temperatures believed to be required for desulfation are generally close to those at which the LNT catalyst undergoes thermal deactivation.

[0011] Creating a reducing environment for LNT regeneration involves eliminating most of the oxygen from the exhaust and providing a reducing agent. Except where the engine can be run stoichiometric or rich, a portion of the reductant reacts within the exhaust to consume oxygen. The amount of oxygen to be removed by reaction with reductant can be reduced in various ways. If the engine is equipped with an intake air throttle, the throttle can be used. However, at least in the case of a diesel engine, it is generally necessary to eliminate some of the oxygen in the exhaust by combustion or reforming reactions with reductant that is injected into the exhaust.

[0012] The reactions between reductant and oxygen can take place in the LNT, but it is generally preferred for the reactions to occur in a catalyst upstream of the LNT, whereby the heat of reaction does not cause large temperature increases within the LNT at every regeneration.

[0013] Reductant can be injected into the exhaust by the engine or a separate fuel injection device. For example, the engine can inject extra fuel into the exhaust within one or more cylinders prior to expelling the exhaust. Alternatively, or in addition, reductant can be injected into the exhaust downstream of the engine.

[0014] U.S. Pat. No. 6,832,473 describes a system wherein the reductant is reformat produced outside the exhaust stream and injected into the exhaust as needed. During desulfation, the reformat is injected upstream of an oxida-

tion catalyst. Heat generated by combustion of the reformat over the oxidation catalyst raises the LNT to desulfation temperatures.

[0015] U.S. Pat. Pub. No. 2004/0050037 (hereinafter “the ‘037 publication”) describes an exhaust treatment system with a fuel reformer placed in the exhaust line upstream of a LNT. The reformer includes both oxidation and steam reforming catalysts. The reformer both removes excess oxygen and converts the diesel fuel reductant into more reactive reformat. For desulfation, heat produced by the reformer is used to raise the LNT to desulfation temperatures.

[0016] WO 2004/090296 (the ‘296 application) describes a system with an inline reformer upstream of a LNT and a SCR catalyst. The reformer has an oxidation catalyst, but is not designed to catalyze steam reforming. This reformer also removes excess oxygen from the exhaust while converting diesel fuel reductant into more reactive reformat. For desulfation, the LNT is heated through engine measures.

[0017] The inline reformer of the ‘296 application has a high thermal mass and is intended to operate through reactions partial oxidation at exhaust gas temperatures. The inline reformer of the ‘037 publication, by contrast, is designed to operate above through oxidation and steam reforming at temperatures from about 500 to about 750° C., which are generally above exhaust gas temperatures. In order to achieve these temperatures quickly, the reformer of the ‘037 publication is designed with a low thermal mass. The reformer is heated by injecting fuel into the exhaust at a rate that leaves the exhaust lean, whereby combustion. After warm up, the fuel injection rate is increased to provide a rich exhaust. Neither reformer can be started or operated if it is too cool to effectively catalyze combustion.

[0018] In spite of advances, there continues to be a long felt need for an affordable and reliable exhaust treatment system that is durable, has a manageable operating cost (including fuel penalty), and is practical for reducing NO_x emissions from diesel engines to a satisfactory extent in the sense of meeting U.S. Environmental Protection Agency (EPA) regulations effective in 2010 and other such regulations.

SUMMARY

[0019] According to one of the inventor’s concepts a low temperature lean NO_x catalyst is configured in a diesel exhaust treatment system upstream of a fuel reformer-LNT system to provide low temperature performance. During system warm-up and anytime the LNT falls below its effective operating temperature range, the exhaust is provided with hydrocarbons at a rate proportional to the NO_x flow rate, whereby NO_x is reduced within the exhaust aftertreatment system by reacting with the hydrocarbons over the lean NO_x catalyst. Optionally, the lean NO_x catalyst is also adapted for use warming up the fuel reformer and/or catalyzing NO to NO₂ conversion. This concept allows the reformer and LNT to be designed for high temperature performance and durability without also having to be adapted for NO_x mitigation at the exhaust system’s lowest operating temperatures.

[0020] Another of the inventor’s concepts relates to a power generation system, comprising a diesel engine and an exhaust aftertreatment system. The exhaust aftertreatment system comprises a hydrocarbon SCR catalyst, a fuel reformer, and a LNT configured in that order within an

exhaust line. The hydrocarbon SCR catalyst is designed to be functional to catalyze selective catalytic reduction of NO_x with hydrocarbons in a lean environment at temperatures below 250° C. or even below 200° C. The system includes an adaptation to provide the hydrocarbon SCR catalyst with hydrocarbons during system warm-up. This adaptation may comprise an exhaust line fuel injector. Optionally, the system includes an additional fuel injector configured between the hydrocarbon SCR catalyst and the fuel reformer.

[0021] A further concept of the inventor relates to a method of operating a power generation system comprising starting a diesel engine, operating the diesel engine to produce an exhaust containing NO_x, and channeling the exhaust through an exhaust aftertreatment system. While the exhaust aftertreatment system is warming, the system is dosed with diesel fuel at a rate proportional to the NO_x flow rate in the exhaust, whereby a substantial portion of the NO_x is reduced over a lean NO_x catalyst contained in the exhaust aftertreatment system. When the exhaust system has warmed, the diesel dosing is discontinued.

[0022] The primary purpose of this summary has been to present certain of the inventor’s concepts in a simplified form to facilitate understanding of the more detailed description that follows. This summary is not a comprehensive description of every one of the inventor’s concepts or every combination of the inventor’s concepts that can be considered “invention”. Other concepts of the inventor will be conveyed to one of ordinary skill in the art by the following detailed description together with the drawings. The specifics disclosed herein may be generalized, narrowed, and combined in various ways with the ultimate statement of what the inventor claim as his invention being reserved for the claims that follow.

BRIEF DESCRIPTION OF THE DRAWING

[0023] The FIGURE provides a schematic illustration of an exemplary power generation system conceived by the inventor.

DETAILED DESCRIPTION

[0024] The FIGURE provides a schematic illustration of an exemplary power generation system 1 conceived by the inventor. The power generation system 1 comprises an engine 4 connected to an exhaust aftertreatment system 2 by a manifold 5. The exhaust aftertreatment system 2 includes a controller 8 and an exhaust line 3 defining a direction of exhaust flow beginning from the manifold 5. Arranged in series with respect to the direction of the exhaust flow in the exhaust line 3 are a first fuel injector 17, a hydrocarbon SCR catalyst 6, a second fuel injector 18, a fuel reformer 10, a diesel particulate filter (DPF) 14, a lean NO_x-trap (LNT) 11, and a SCR catalyst 12. The controller 8 may be an engine control unit (ECU) that also controls the exhaust aftertreatment system 2 or may include several control units.

[0025] The engine 4 is operative to produce an exhaust that contains NO_x and particulate matter. The hydrocarbon content of the exhaust can be selectively increased by altering operating parameters of the engine 4 such as the fuel-air ratio, the injection timing, and the extent of EGR. The hydrocarbon content of the exhaust can also be increased and the exhaust made rich as needed without

altering the operation of the engine 4, for example, by injecting fuel into the exhaust line 3 through one or both of the fuel injectors 17 and 18.

[0026] During lean operation (a lean phase), the LNT 11 adsorbs and stores a significant amount of NO_x from the exhaust, provided the LNT 11 is within an effective operating temperature range for NO_x mitigation. An additional portion of NO_x in the exhaust may also be reduced over the ammonia SCR catalyst 12, provided that the ammonia SCR catalyst 12 contains stored ammonia from a previous regeneration of the LNT 11. An effective operating temperature range for the LNT 11 is typically from about 300 to about 450° C., the actual operating temperature range depending on the LNT formulation.

[0027] If the LNT 11 is below its effective operating temperature range and there is no ammonia stored in the SCR catalyst 12, the exhaust aftertreatment system 2 can still mitigate NO_x emissions by reducing NO_x through selective catalytic reduction over the hydrocarbon SCR catalyst 6. In order to reduce a significant amount of NO_x in this manner, the exhaust is selectively dosed with hydrocarbons. Hydrocarbon dosing can be achieved by altering the operating of the engine 4, injecting fuel into engine cylinders during exhaust strokes, or by injecting hydrocarbons through the optional fuel injector 17.

[0028] The provision of hydrocarbons to act as a reductant for SCR over the hydrocarbon SCR catalyst 6 is controlled by the controller 8. For example, the controller 8 can determine that the LNT 11 is below its effective operating temperature range by interpreting signals from the temperature sensor 16. The LNT 11 is generally below its effective operating temperature range immediately following start of the engine 4 and may also fall below that temperature at various times during operation of the engine 4, such as during long periods of engine idling. In response to a determination that the LNT 11 is below its effective operating temperature range, the controller 8 initiates dosing of the exhaust upstream of the hydrocarbon SCR catalyst 6 with hydrocarbons. The dosing rate is preferably proportional to the NO_x flow rate in the exhaust.

[0029] In order to determine the amount of hydrocarbon required to reduce NO_x over the hydrocarbon SCR catalyst 6, the controller 8 obtains an estimate for the NO_x flow rate in the exhaust. Any suitable estimate can be used. For example, an estimate can be made based on a sensor measurement of NO_x concentration in the exhaust. Alternatively, an estimate can be made without measurement based solely on the operating state of the engine 4. The relationship between engine operating state and NO_x emissions can be determined, for example, by calibration.

[0030] The hydrocarbon SCR catalyst 6 is preferably operative to catalyze hydrocarbon SCR at 200° C. Preferably, the hydrocarbon SCR catalyst 6 is operative for SCR at temperatures up to at least about 250° C. Preferably, the hydrocarbon SCR catalyst 6 is operative for SCR at temperatures at least down to about 175° C. A suitable catalyst operative for hydrocarbon SCR over these preferred ranges is a platinum catalyst on a high surface area support, such as alumina.

[0031] Providing for low temperature SCR over the hydrocarbon SCR catalyst 6 reduces the need to design the LNT 11 to be effective for NO_x mitigation at lower temperatures. Reducing this requirement makes it easier to design the LNT

11 to be operational at high temperatures and also makes it easier to design the LNT 11 to be durable.

[0032] The hydrocarbon SCR catalyst 6 may perform additional functions as well as catalyzing low temperature hydrocarbon SCR. One possible function is catalyzing conversion of NO to NO₂. NO₂ is adsorbed more easily by the LNT 11 than NO. Converting NO to NO₂ over the hydrocarbon SCR catalyst 6 can therefore enhance the performance of the LNT 11. This is particularly useful if NO to NO₂ oxidation occurs near the low end of the operating temperature range of the LNT 11 where the effectiveness of the LNT 11 is flagging. NO to NO₂ catalysis can also facilitate continuous regeneration of the DPF 14. The hydrocarbon SCR catalyst 6 may also function as a low temperature oxidation catalyst that can be used to heat the fuel reformer 10.

[0033] From time-to-time, a rich phase is initiated to regenerate the LNT 11 to remove stored NO_x (denitration). Denitration may involve heating the reformer 10 to an operational temperature and then injecting fuel using the fuel injector 18 to make the exhaust rich. The fuel reformer 10 uses the injected fuel to consume most of the oxygen from the exhaust while producing reformat. The reformat thus produced reduces NO_x adsorbed in the LNT 11.

[0034] The time at which to regenerate the LNT 11 to remove accumulated NO_x can be determined by any suitable method. Examples of methods of determining when to begin a regeneration include initiating a regeneration upon reaching a threshold in any of NO_x concentration in the exhaust, total NO_x emissions per mile or per brake horsepower-hour over a period, such as the period since the last regeneration, total amount of NO_x produced by the engine since the last regeneration, estimated NO_x loading in the LNT 11, and estimated adsorption capacity remaining in the LNT 11. Regeneration can be periodic or determined by feed forward or feedback control. Regeneration can also be opportunistic, being triggered by engine operating conditions that favor low fuel penalty regeneration. A threshold for regeneration can be varied to give a trade off between urgency of the need to regenerate and favorability of the current conditions for regeneration. The time at which to regenerate the LNT 11 can be determined by the controller 8, which generates a control signal that initiates the regeneration process.

[0035] The reformer 10 preferably comprises a steam reforming catalyst and is adapted to produce reformat at least in part by steam reforming reactions. Steam reforming reactions generally do not occur at effective rates at temperature below about 550° C. Accordingly, when the control signal to denitrate the LNT 11 is received, it is generally necessary to first heat the fuel reformer 10 in response to the control signal prior to making the exhaust rich.

[0036] The reformer 10 is preferably heated by providing hydrocarbon to the exhaust at a rate that leaves the exhaust lean. If the reformer is sufficiently warm, the hydrocarbon will undergo complete combustion in the reformer 10, generating heat. The reformer 10, however, has a minimum start-up temperature. Below this minimum start-up temperature, the reformer 10 is too cool to effectively catalyze combustion and cannot be effectively heated simply by supplying it with lean exhaust. The minimum temperature can be lowered by providing the reformer 10 with more catalyst. The disadvantage of adding this catalyst is that it increases the cost of the reformer 10. Moreover, enhancing

the low temperature startup performance of the reformer **10** may come at the expense of high temperature performance and durability.

[0037] In a preferred embodiment, the low temperature startup of the reformer **10** is facilitated by the hydrocarbon SCR catalyst **6**. Below the reformer **10**'s minimum start-up temperature, hydrocarbon can be provided to the hydrocarbon SCR catalyst **6**, which is preferably functional to combust the hydrocarbon at temperatures below the reformer **10**'s minimum start-up temperature. Hydrocarbon combustion over the hydrocarbon SCR catalyst **6** can be used to heat the reformer **10** at least to its minimum start-up temperature.

[0038] Hydrocarbons for combustion in the hydrocarbon SCR catalyst **6** can be provided by the engine **4** or through the fuel injector **17**. These sources can also be used to provide hydrocarbon to the reformer **10** for combustion or reforming therein. Preferably, however, hydrocarbon for combustion or reforming in the reformer **10** is provided by the fuel injector **18**, whereby these hydrocarbons do not flow through the hydrocarbon SCR catalyst **6**. Injecting these hydrocarbons downstream of the hydrocarbon SCR catalyst **6** avoids the risk that combustion of these hydrocarbons in the hydrocarbon SCR catalyst **6** will overheat the hydrocarbon SCR catalyst **6**.

[0039] From time-to-time, the LNT **11** must also be regenerated to remove accumulated sulfur compounds (desulfated). Desulfation involves heating the reformer **10**, heating the LNT **11** to a desulfating temperature, and providing the heated LNT **11** with a rich atmosphere. Desulfating temperatures vary, but are typically in the range from about 550 to about 850° C., the exact range depending on the LNT composition. Below a minimum temperature, desulfation is very slow. Above a maximum temperatures, the LNT **11** may deteriorate and undergo a loss of activity.

[0040] The time at which to desulfate the LNT **11** can be determined in any suitable fashion. Desulfation may be scheduled periodically, e.g., after every 30 hours of operation. Alternatively, desulfation may be scheduled based on an estimate of the amount on SO_x stored in the LNT **11**. The amount of stored SO_x can be assumed to increase in proportion to fuel usage and to decrease in a manner dependent on the extent of desulfations. A further option is to determine the need for desulfation based on system performance, e.g., based on the activity of the LNT **11** following an extensive denitration or based on the frequency with which denitration is required

[0041] The primary means of heating the LNT **11** is heat convection from the reformer **10**. To generate this heat, fuel can be supplied to the reformer **10** under lean conditions, whereby the supplied fuel undergoes complete combustion in the reformer **10**. Once the reformer **10** is heated, the fuel injection rate can be controlled to maintain the temperature of the reformer **10** while the LNT **11** is heating. Optionally, if the reformer **10** is below its minimum startup temperature, the reformer **10** can be heated using the hydrocarbon SCR catalyst **6**, if the hydrocarbon SCR catalyst **6** is suitably formulated, as described previously.

[0042] The exhaust aftertreatment system **2** also includes a DPF **14** for particulate matter control. The DPF **14** can be placed at any suitable location in the exhaust aftertreatment system **2**. The illustrated location has the advantage that it protects the LNT **11** from temperature excursion during

denitration. Reducing the number or magnitude of temperature excursions experienced by the LNT **11** can extend its life.

[0043] The DPF **14** can be a wall flow filter or a pass through filter and can use primarily either depth filtration or cake filtration. Cake filtration is the primary filter mechanism in a wall flow filter. In a wall flow filter, the soot-containing exhaust is forced to pass through a porous medium. Typical pore diameters are from about 0.1 to about 1.0 μm. Soot particles are most commonly from about 10 to about 50 nm in diameter. In a fresh wall flow filter, the initial removal is by depth filtration, with soot becoming trapped within the porous structure. Quickly, however, the soot forms a continuous layer on an outer surface of the porous structure. Subsequent filtration is through the filter cake and the filter cake itself determines the filtration efficiency. As a result, the filtration efficiency increases over time.

[0044] In contrast to a wall flow filter, in a flow through filter the exhaust is channeled through macroscopic passages and the primary mechanism of soot trapping is depth filtration. The passages may have rough walls, baffles, and bends designed to increase the tendency of momentum to drive soot particles against or into the walls, but the flow is not forced through micro-pores. The resulting soot removal is considered depth filtration, although the soot is generally not distributed uniformly with the depth of any structure of the filter. A flow through filter can also be made from temperature resistant fibers, such as ceramic or metallic fibers, that span the device channels. A flow through filter can be larger than a wall flow filter having equivalent thermal mass

[0045] The DPF **14** must be regenerated to remove accumulated soot. Two general approaches to DPF regeneration are continuous and intermittent regeneration. In continuous regeneration, a catalyst is provided upstream of the DPF **14** to convert NO to NO₂. NO₂ can oxidize soot at typical diesel exhaust temperatures and thereby effectuate continuous regeneration. Intermittent regeneration involves heating the DPF **14** to a temperature at which soot combustion is self-sustaining in a lean environment. Typically this is a temperature from about 400 to about 600° C., depending in part on what type of catalyst coating has been applied to the DPF to lower the soot ignition temperature. The reformer **10** can be used to heat the DPF **14** to the required temperature.

[0046] While the engine **4** is preferably a compression ignition diesel engine, the various concepts of the inventor are applicable to power generation systems with lean-burn gasoline engines or any other type of engine that produces an oxygen rich, NO_x-containing exhaust. For purposes of the present disclosure, NO_x consists of NO and NO₂.

[0047] The power generation system can have any suitable type of transmission. A transmission can be a conventional transmission such as a counter-shaft type mechanical transmission, but is preferably a CVT. A CVT can provide a much larger selection of operating points than a conventional transmission and generally also provides a broader range of torque multipliers. The range of available operating points can be used to control the exhaust conditions, such as the oxygen flow rate, exhaust temperature, and the exhaust hydrocarbon content. A given power demand can be met by a range of torque multiplier-engine speed combinations. A point in this range that gives acceptable engine performance while best meeting a control objective, such as matching the hydrocarbon content to the NO_x flow rate as nearly as possible.

[0048] In general, a CVT will also avoid or minimize interruptions in power transmission during shifting. Examples of CVT systems include hydrostatic transmissions; rolling contact traction drives; overruning clutch designs; electric; multispeed gear boxes with slipping clutches; and V-belt traction drives. A CVT may involve power splitting and may also include a multi-step transmission.

[0049] A preferred CVT provides a wide range of torque multiplication ratios, reduces the need for shifting in comparison to a conventional transmission, and subjects the CVT to only a fraction of the peak torque levels produced by the engine. This can be achieved using a step-down gear set to reduce the torque passing through the CVT. Torque from the CVT passes through a step-up gear set that restores the torque. The CVT is further protected by splitting the torque from the engine, and recombining the torque in a planetary gear set. The planetary gear set mixes or combines a direct torque element transmitted from the engine through a stepped automatic transmission with a torque element from a CVT, such as a band-type CVT. The combination provides an overall CVT in which only a portion of the torque passes through the band-type CVT.

[0050] The hydrocarbon SCR catalyst can have any suitable formulation. Suitable catalysts include platinum group metal (PGM) catalysts, with platinum being most preferred. Where a low temperature oxidation function is desired for reformer heating, a PGM catalyst can also be used, with Pt and Pd being preferred. NO to NO₂ oxidation can also be effectuated with a PGM catalyst, Pt again being preferred. A PGM catalyst typically includes a high surface area support. Examples of high surface area supports include alumina, silica, TiO₂, and other metal oxide supports commonly used in emission control catalysts.

[0051] The fuel reformer **10** is a device that converts heavier hydrocarbons into lighter compounds without fully combusting the fuel. The fuel reformer **10** can be a catalytic reformer or a plasma reformer. Preferably, the fuel reformer **10** comprises both partial oxidation and steam reforming catalysts and is capable of auto-thermal operation. Examples of reformer catalysts include precious metals, such as Pt, Pd, and Rh, and oxides of Al, Mg, and Ni, the later group being typically combined with one or more of CaO, K₂O, and a rare earth metal such as Ce and La to increase activity. The fuel reformer **10** is preferably small in size as compared to an oxidation catalyst or a three-way catalyst designed to perform its primary functions at temperatures below 450° C. The reformer **10** is generally operative at temperatures within the range from about 450 to about 1100° C.

[0052] The LNT **11** can comprise any suitable NO_x-adsorbing material. Examples of NO_x adsorbing materials include oxides, carbonates, and hydroxides of alkaline earth metals such as Mg, Ca, Sr, and Ba or alkali metals such as K or Cs. Further examples of NO_x-adsorbing materials include ceria, alumina, and activated carbon. Still further examples include metal phosphates, such as phosphates of titanium and zirconium. Generally, the NO_x-adsorbing material is an alkaline earth oxide. The adsorbent is typically combined with a binder and applied as a coating over an inert substrate.

[0053] The LNT **11** also comprises a catalyst for the reduction of NO_x in a reducing environment. The catalyst can be, for example, one or more transition metals, such as Au, Ag, and Cu, group VIII metals, such as Pt, Rh, Pd, Ru,

Ni, and Co, Cr, or Mo. A typical catalyst includes Pt and Rh. Precious metal catalysts also facilitate the adsorbent function of alkaline earth oxide absorbers.

[0054] Adsorbents and catalysts according to the present invention are generally adapted for use in vehicle exhaust systems. Vehicle exhaust systems create restriction on weight, dimensions, and durability. For example, a NO_x adsorbent bed for a vehicle exhaust systems must be reasonably resistant to degradation under the vibrations encountered during vehicle operation.

[0055] The ammonia-SCR catalyst **12** is a catalyst functional to catalyze reactions between NO_x and NH₃ to reduce NO_x to N₂ in lean exhaust. Examples of SCR catalysts include oxides of metals such as Cu, Zn, V, Cr, Al, Ti, Mn, Co, Fe, Ni, Pd, Pt, Rh, Rd, Mo, W, and Ce, zeolites, such as ZSM-5 or ZSM-11, substituted with metal ions such as cations of Cu, Co, Ag, Zn, or Pt, and activated carbon. Preferably, the ammonia-SCR catalyst **12** is designed to tolerate temperatures required to desulfate the LNT **11**.

[0056] Although not illustrated in any of the figures, a clean-up catalyst can be placed downstream of the other aftertreatment devices. A clean-up catalyst is preferably functional to oxidize unburned hydrocarbons from the engine **4**, unused reductants, and any H₂S released from the LNT **11** and not oxidized by the ammonia-SCR catalyst **12**. Any suitable oxidation catalyst can be used. To allow the clean-up catalyst to function under rich conditions, the catalyst may include an oxygen-storing component, such as ceria. Removal of H₂S, where required, may be facilitated by one or more additional components such as NiO, Fe₂O₃, MnO₂, Co₂O₃, and CrO₂ supported by refractory inorganic oxide.

[0057] The invention as delineated by the following claims has been shown and/or described in terms of certain concepts, components, and features. While a particular component or feature may have been disclosed herein with respect to only one of several concepts or examples or in both broad and narrow terms, the components or features in their broad or narrow conceptions may be combined with one or more other components or features in their broad or narrow conceptions wherein such a combination would be recognized as logical by one of ordinary skill in the art. Also, this one specification may describe more than one invention and the following claims do not necessarily encompass every concept, aspect, embodiment, or example described herein.

1. A power generation system, comprising:
 - a diesel engine operative to produce exhaust containing NO_x; and
 - an exhaust aftertreatment system configured to treat the exhaust with a hydrocarbon SCR catalyst, a fuel reformer, and a LNT configured in that order within an exhaust line;
 - wherein the hydrocarbon SCR catalyst is functional to catalyze selective catalytic reduction of NO_x with hydrocarbons in a lean environment at 200° C.
 - the fuel reformer is functional to produce reformat when the fuel reformer is sufficiently warm, the exhaust is rich, and the exhaust contains diesel fuel; and

- the LNT is adapted to store NO_x when the exhaust from the fuel reformer is lean and to reduce stored NO_x and regenerate when the exhaust from the fuel reformer is rich and contains reformate.
- 2. The power generation system of claim 1, further comprising a fuel injector configured to inject fuel into the exhaust line upstream of the hydrocarbon SCR catalyst.
- 3. The power generation system of claim 2, further comprising a second fuel injector configured to inject fuel into the exhaust line downstream of the hydrocarbon SCR catalyst, but upstream of the fuel reformer.
- 4. The power generation system of claim 1, further comprising a fuel injector configured to inject fuel into the exhaust line downstream of the hydrocarbon SCR catalyst, but upstream of the fuel reformer.
- 5. The power generation system of claim 2, further comprising:
 - a controller configured to selectively inject fuel through the fuel injector while the exhaust aftertreatment system is warming up.
- 6. The power generation system of claim 2, further comprising:
 - a controller configured to selectively inject fuel through the fuel injector in order to induce combustion within the hydrocarbon SCR catalyst in order to warm the fuel reformer as needed prior to initiating a rich regeneration phase.
- 7. The power generation system of claim 1, wherein the fuel reformer is adapted to produce reformate by steam reforming reactions.
- 8. The power generation system of claim 1, further comprising:
 - an ammonia SCR reactor configured in the exhaust line to receive at least a portion of the exhaust passing through the LNT;
 - wherein the ammonia SCR reactor is adapted to store ammonia produced by the LNT during regeneration and to reduce NO_x contained in the exhaust by catalyzing reactions between the NO_x and stored ammonia when the exhaust is lean.
- 9. The power generation system of claim 1, wherein the hydrocarbon SCR catalyst is a PGM catalyst also functional to catalyze oxidation of NO to NO₂ at 200° C.
- 10. The power generation system claim 1, wherein the hydrocarbon SCR catalyst comprises an effective amount of platinum.

- 11. A method of operating a power generation system, comprising:
 - starting a diesel engine;
 - operating the diesel engine to produce an exhaust containing NO_x;
 - channeling the exhaust through an exhaust aftertreatment system;
 - while the exhaust system is warming, dosing the exhaust with diesel fuel at a rate proportional to the NO_x flow rate in the exhaust, whereby a substantial portion of the NO_x is reduced over a lean NO_x catalyst contained in the exhaust aftertreatment system; and
 - in response to the exhaust system warming, discontinuing the diesel dosing to the exhaust system.
- 12. The method of claim 11, further comprising:
 - within the exhaust system, passing the exhaust first through the lean NO_x catalyst, then through a fuel reformer, and then through a LNT.
- 13. The method of claim 12, further comprising:
 - generating a control signal to regenerate the LNT;
 - in response to the control signal, dosing the exhaust aftertreatment with diesel fuel and combusting the dosed diesel fuel over the lean NO_x catalyst in order to heat the reformer; and
 - subsequently providing additional diesel dosing to make the exhaust rich, whereby the reformer produces reformate and regenerates the LNT.
- 14. The method of claim 13, wherein providing additional diesel dosing comprises injecting diesel fuel into the exhaust aftertreatment system downstream of the lean NO_x catalyst, but upstream of the fuel reformer.
- 15. The method of claim 13, wherein the fuel reformer functions to produce reformate by steam reforming reactions during LNT regeneration.
- 16. The method of claim 12, wherein the lean NO_x catalyst is effective for oxidizing NO to NO₂ at 200° C.
- 17. The method of claim 12, wherein the lean NO_x catalyst comprises an effective amount of platinum.
- 18. The method of claim 12, further comprising passing the exhaust over an ammonia SCR catalyst after passing the exhaust through the LNT.
- 19. The method of claim 11, further comprising:
 - in response to the LNT falling below a critical temperature, reinitiating diesel dosing to the exhaust system at a rate proportional to the NO_x flow rate in the exhaust.

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