An exhaust aftertreatment system and a method for treating exhaust produced by a lean-burn engine are provided. The exhaust aftertreatment system may include an exhaust gas treatment subsystem and a clean-up oxidation catalyst located downstream of the exhaust gas treatment subsystem. The clean-up oxidation catalyst can selectively oxidize $\text{NH}_3$ to $\text{N}_2$ in the hot, oxygen-abundant exhaust flow emanated from the lean-burn engine and passed through the exhaust gas treatment subsystem to help prevent ammonia slip to the atmosphere. The clean-up oxidation catalyst comprises perovskite oxide particles and/or manganese-containing mixed metal oxide particles dispersed on a selective catalytic reduction (SCR) catalyst.
CATALYST MATERIALS FOR AMMONIA OXIDATION IN LEAN-BURN ENGINE EXHAUST

TECHNICAL FIELD

[0001] The technical field relates generally to exhaust aftreatment systems that treat the exhaust produced by a lean-burn engine and, more particularly, to catalyst materials that may be used to oxidize ammonia, among others, and help prevent ammonia slip to the atmosphere.

BACKGROUND

[0002] Lean-burn engines such as diesel engines and certain spark-ignition engines are supplied with, and combust, a lean mixture of air and fuel (oxygen-rich mixture) to achieve more efficient fuel economy. The exhaust emitted from such engines during periods of lean-burn operation may include a relatively high content of nitrogen (N₂) and oxygen (O₂), a relatively low content of carbon monoxide (CO) and unburned/partially-burned hydrocarbons (HC’s), possibly some suspended particulate matter (i.e., in diesel engines), and small amounts of nitrogen oxides primarily comprised of NO and NO₂ (collectively referred to as NOₓ). The NOₓ constituency of the exhaust may fluctuate between about 50 and about 1500 ppm and generally comprises far greater amounts NO than NO₂ along with nominal amounts of N₂O. The hot engine exhaust, which can reach temperatures of up to about 900 °C, often needs to be treated before it can be released to the atmosphere.

[0003] An exhaust aftreatment system may be associated with the lean-burn engine to help remove unwanted gaseous emissions and particulate matter that may be present in the lean-burn engine exhaust. The exhaust aftreatment system may be configured to receive an exhaust flow from the lean-burn engine and generally aspires to cooperatively (1) oxidize CO into carbon dioxide (CO₂), (2) oxidize HC’s into CO₂ and water (H₂O), (3) convert NOₓ gases into nitrogen (N₂) and O₂, and (4) filter off or otherwise destroy any suspended particulate matter. A variety of exhaust aftreatment system architectures that employ specialty-catalyzed components have been devised and are able to sufficiently facilitate these reactions so that the exhaust expelled to the environment contains a much more desirable chemical makeup.

[0004] The normal operation of many exhaust aftreatment system designs can result in ammonia (NH₃) being introduced into the exhaust flow. Some exhaust aftreatment system designs, for example, deliberately introduce controlled amounts of NH₃ into the exhaust flow to provide a reductant species that reduces NOₓ to N₂ over a selective catalytic reduction (SCR) catalyst. A metering system that directly injects NH₃ or an NH₃ precursor (i.e., urea) into the exhaust flow may be employed to supply NH₃ to the SCR catalyst. Ammonia may also be passively generated from native NOₓ in the exhaust flow by periodically cycling a rich air/fuel mixture to the lean-burn engine and communicating the resultant engine exhaust over a close-coupled three-way-catalyst (TWC). The NH₃ produced may then be stored on a downstream SCR catalyst and consumed when the lean-burn engine iscombustion a lean air/fuel mixture. Other exhaust aftreatment design systems, as another example, may include one or more lean NOₓ traps (LNT) that occasionally have to be regenerated and desulfated which, in turn, may cause NH₃ to be introduced into the exhaust flow.

[0005] A clean-up oxidation catalyst is oftentimes included at or near the end of the exhaust aftreatment system to oxidize any residual NH₃ and other gaseous emissions that might otherwise escape to the atmosphere. Ammonia that manages to pass through the exhaust aftreatment system is often referred to as “ammonia slip.” The clean-up oxidation catalyst used at this particular juncture of the exhaust aftreatment system is traditionally formulated with about 5 to 10 g/ft³ of platinum group metals (PGM’s) dispersed on a high-surface area support material such as aluminas. Most or all of the clean-up oxidation catalyst’s PGM loading is generally attributable to platinum, although smaller amounts of palladium and rhodium may also be included, if desired. A honeycomb flow-through monolith structure may carry the clean-up oxidation catalyst within several hundred to several thousand parallel flow-through cells to ensure sufficient contact between the exhaust flow and the clean-up oxidation catalyst.

[0006] The PGM’s commonly used to make the clean-up oxidation catalyst, however, are quite expensive and have been shown, in some instances, to exhibit poor thermal durability when exposed to relatively high-temperature engine exhaust. The N₂ selectivity of PGM-based clean-up oxidation catalysts can also be affected by thermal aging and fluctuations in the temperature and chemical composition of the exhaust flow. Such effects on N₂ selectivity can cause the clean-up oxidation catalyst to oxidize NH₃ into NOₓ—instead of N₂—at an unacceptably high rate and thus lower the overall NOₓ conversion efficiency of the exhaust aftreatment system.

SUMMARY OF EXEMPLARY EMBODIMENTS

[0007] A clean-up oxidation catalyst that comprises a selective catalytic reduction (SCR) catalyst and metal oxide particles selected from the group consisting of perovskite oxide particles and manganese-containing mixed metal oxide particles, and mixtures thereof, dispersed on the SCR catalyst may be employed at or near the end of an exhaust aftreatment system to help prevent ammonia slip and the escape of unwanted gaseous emissions to the atmosphere. The clean-up oxidation catalyst can selectively oxidize NH₃ to N₂ in the hot, oxygen-abundant exhaust flow emanated from a lean-burn engine and communicated through the exhaust aftreatment system. The inclusion of platinum group metals, such as platinum and palladium, in the clean-up oxidation catalyst may be avoided. Other exemplary and more detailed embodiments of the invention will become apparent from the detailed description that follows.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Exemplary embodiments of the invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

[0009] FIG. 1 is a generalized and schematic depiction of an exhaust aftreatment system for a lean-burn engine that includes an exhaust gas treatment subsystem and a clean-up oxidation catalyst downstream from the exhaust gas treatment subsystem.

[0010] FIG. 2 is a generalized and schematic illustration of the relevant parts of one exemplary embodiment of the exhaust gas treatment subsystem.
FIG. 3 is a generalized and schematic illustration of the relevant parts of another exemplary embodiment of the exhaust gas treatment subsystem.

FIG. 4 is a graph that shows the oxidation capabilities of $La_2Sr_xCo_3$ particles for various reactions when exposed to simulated lean-burn engine exhaust.

FIG. 5 is a graph that shows the $NH_3$ oxidation performance, when exposed to simulated lean-burn engine exhaust, of a degreased Fe/β-zeolite SCR catalyst, $La_xSr_{1-x}Co_3$ particles, and three degreased clean-up oxidation catalysts each with a different $La_{1-x}Sr_{x}Co_3$ particle loading.

FIG. 6 is a graph that shows the $NH_3$ oxidation performance, when exposed to simulated lean-burn engine exhaust, of a high-temperature aged Fe/β-zeolite SCR catalyst, $La_xSr_{1-x}Co_3$ particles, and three high-temperature aged clean-up oxidation catalysts each with a different $La_{1-x}Sr_{x}Co_3$ particle loading.

FIG. 7 is a graph that shows how much of the $NH_3$ oxidation shown in FIG. 5 resulted in the formation of NOX.

FIG. 8 is a graph that shows how much of the $NH_3$ oxidation shown in FIG. 6 resulted in the formation of NOX.

FIG. 9 is a graph that shows the $NH_3$ oxidation performance and the $N_2$ selectivity, when exposed to simulated lean-burn engine exhaust, of a degreased and a high-temperature aged clean-up oxidation catalyst material having 12 wt. % $La_xSr_{1-x}Co_3$ particles loaded onto a Fe/β-zeolite SCR catalyst and, for comparison purposes, a conventional platinum-containing catalyst.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

The following description is merely exemplary in nature and is in no way intended to limit the claimed invention(s), its application, or its uses.

A clean-up oxidation catalyst that comprises metal oxides dispersed on a selective catalytic reduction (SCR) catalyst may be employed at or near the end of an exhaust aftertreatment system to help prevent ammonia slip and the escape of unwanted gaseous emissions to the atmosphere. The metal oxide particles may be selected from the group consisting of perovskite oxide particles, manganese-containing mixed metal oxide particles, and mixtures thereof. The clean-up oxidation catalyst can selectively oxidize $NH_3$ to $N_2$ in the hot, oxygen-abundant exhaust flow emanated from a lean-burn engine and communicate through an upstream portion of the exhaust aftertreatment system. The temperature at which optimum $NH_3$ oxidation occurs and the oxidation reaction’s $N_2$ selectivity can be influenced by the loading of the metal oxide particles as well as the aging of the clean-up oxidation catalyst. The inclusion of PGM’s in the clean-up oxidation catalyst, although not prohibited, is not needed to achieve satisfactory $NH_3$ oxidation over a robust temperature range. The opportunity to reduce the amount of PGM’s used in an exhaust aftertreatment system can contribute to significant cost savings and help counteract the durability and $N_2$ selectivity issues sometimes observed in PGM-based catalysts.

FIG. 1 depicts a generalized and schematic illustration of an exhaust aftertreatment system 10 for managing an exhaust flow 20 produced by a lean-burn engine 12 that is combusting a lean air/fuel (A/F) mixture 18. The exhaust aftertreatment system 10 receives the exhaust flow 20 from the lean-burn engine 12 and communicates a treated exhaust flow 24 downstream for expulsion to the atmosphere. The exhaust aftertreatment system 10, as illustrated here, may include an exhaust gas treatment subsystem 14 and a clean-up oxidation catalyst 16. The exhaust gas treatment subsystem 14 decreases to acceptable levels the amount of unwanted gaseous emissions and, if present, particulate matter that are contained in the exhaust flow 20. The clean-up oxidation catalyst 16 oxidizes any $NH_3$ contained in an intermediate exhaust flow 22 that flows from the exhaust gas treatment subsystem 14 to help prevent ammonia slip to the atmosphere. The treated exhaust flow 24 may flow through other mechanical equipment, such as a muffler, after engaging the clean-up oxidation catalyst 16 but generally does not interact with any additional catalysts before being released to the atmosphere.

The lean-burn engine 12 may be any engine that is constructed and designed to combust the lean A/F mixture 18 at least part of the time. The lean A/F mixture 18 supplied to the lean-burn engine 12 generally contains more air than is stoichiometrically needed to combust the associated fuel. Known mechanical or electronic mechanisms may be used to control the air to fuel mass ratio of the lean A/F mixture 18 which, in general, often ranges from about 15 to about 65 depending on the engine load, RPM, and the type of lean-burn engine 12 (i.e., diesel or spark-ignition) being operated. Examples of engines that may be employed as the lean-burn engine 12 include a charge compression-ignition (diesel) engine, a lean-burn spark-ignition (gasoline) engine such as spark-ignition direct injection (SIDI) engine, or a homogeneous charge compression ignition (HCCI) engine. The general construction and operating requirements of these types of engines are well known to skilled artisans and, as such, need not be described in further detail.

The combustion of the lean A/F mixture 18 in the lean-burn engine 12 generates mechanical power and the exhaust flow 20 that is supplied to the exhaust aftertreatment system 10. The exhaust flow 20 generally includes a relatively large amount of $N_2$ and $O_2$, possibly some suspended particulate matter composed of unburnt high-molecular weight hydrocarbons, and various unwanted gaseous emissions comprised of the following: (1) CO, (2) HCs’s, and (3) a NOx-contingent primarily comprised of NO and NO2. The NOx-contingent of the exhaust flow 20 may fluctuate between about 50 and about 1500 ppm. The proportion of NO and NO2 particles in the NOx-contingent usually ranges from approximately 80%-95% NO and approximately 5%-20% NO2. Such a NO/NO2 particle distribution corresponds to a molar ratio of NO to NO2 that ranges from about 4 to about 19. The exhaust flow 20 may reach temperatures of up to 900°C depending the distance between the lean-burn engine 12 and the exhaust aftertreatment system 10 as well as the presence of any intervening components such as a turbocharger turbine and/or an EGR bleed line. The temperature of the exhaust flow 20 along with the $O_2$ content, which is relatively high, and the CO and HCs’s content, which are relatively low, promote an oxidizing environment in the exhaust flow 20.

The exhaust gas treatment subsystem 14 encompasses a large variety of system architectures that operate to remove a substantial portion of the CO, HCs’s, NOx, and particulate matter, if present, from the exhaust flow 20. A NOx abatement component, such as a lean NOx trap or a selective catalytic reaction (SCR) catalytic converter, may be included in the exhaust gas treatment subsystem 14 to reduce NOx to $N_2$ in the oxidative environment of the exhaust flow 20. An assortment of other components such as, but not
limited to, diesel oxidation converters, three-way catalytic converters, diesel particulate filters, and reductant metering devices are available and can be assembled to operate with the NO\textsubscript{x} abatement component, either individually or in select combinations with one another, to constitute the exhaust gas treatment subsystem 14.

[0024] The intermediate exhaust flow produced by the exhaust gas treatment subsystem 14 primarily includes N\textsubscript{2}, O\textsubscript{2}, H\textsubscript{2}O, and CO\textsubscript{2}. The intended operation of the exhaust gas treatment subsystem 14 and, in particular, the NO\textsubscript{x} abatement component, may further result in NH\textsubscript{3} being present in the intermediate exhaust flow 22 as well as acceptable residual amounts of CO, HC’s, NO\textsubscript{x}, and particulate matter. A number of factors and component operating requirements related to the lean-burn engine 12 and the exhaust gas treatment subsystem 14 may be responsible for the presence of NH\textsubscript{3} in the intermediate exhaust flow 22 despite the sophisticated control strategies often associated with the exhaust aftertreatment system 10.

[0025] One exemplary embodiment of the exhaust gas treatment subsystem 14, which is identified as 14a and depicted in FIG. 2, includes a diesel oxidation converter 30, an ammonia-SCR catalytic converter 32 located downstream of the diesel oxidation converter 30, a diesel particulate filter 34 located downstream of the ammonia-SCR catalytic converter 32, and a urea metering system 36. The exhaust gas treatment subsystem 14a shown and described here may be used when the exhaust aftertreatment system 10 is coupled to a diesel engine.

[0026] The diesel oxidation converter 30 receives the exhaust flow 20 from the lean-burn engine 12. The diesel oxidation converter 30 houses a diesel oxidation catalyst that may comprise a combination of platinum and palladium or some other suitable oxidation catalyst formulation. The exhaust flow 20 traverses the diesel oxidation converter 30 and achieves intimate exposure with the diesel oxidation catalyst to promote the oxidation of CO (to CO\textsubscript{2}), HC’s (to CO\textsubscript{2} and H\textsubscript{2}O) and NO (to NO\textsubscript{2}). The oxidation of NO by the diesel oxidation catalyst typically does not decrease the NO\textsubscript{x} content in the exhaust flow 20; instead, the molar ratio of NO to NO\textsubscript{2} is merely decreased as NO is oxidized to NO\textsubscript{2}. This downward adjustment to the NO:NO\textsubscript{2} molar ratio may be desirable since the downstream ammonia-SCR catalytic converter 32 may convert NO\textsubscript{x} to N\textsubscript{2} at lower temperatures more efficiently as the molar ratio of NO to NO\textsubscript{2} decreases from that which is typically generated by the lean-burn engine 12.

[0027] The exhaust flow 20 exiting the diesel oxidation converter 30 is then combined with NH\textsubscript{3} to form an exhaust mixture 44. The NH\textsubscript{3} may be supplied by the urea metering device 36 which includes an on-board and refillable urea storage tank 38 fluidly connected to a urea injector 40. Urea, which is stored in the urea storage tank 38, may be injected into the exhaust flow 20 exiting the diesel oxidation converter 30 through the urea injector 40. The urea then quickly evaporates and undergoes thermolysis and hydrolysis reactions in the hot and oxygen-abundant exhaust flow 20 to generate NH\textsubscript{3} and form the exhaust mixture 44. The amount of urea injected into the exhaust flow 20 may be monitored and controlled by known control techniques that attempt to regulate the amount of NH\textsubscript{3} present in the exhaust mixture 20 despite fluctuations in the temperature, chemical composition, and flow rate of the exhaust flow 20. A mixer 42 or other suitable device may be provided upstream of the ammonia-SCR catalytic converter 32 to help evaporate the injected urea and homogeneously distribute small particles of NH\textsubscript{3} throughout the exhaust mixture 44.

[0028] The ammonia-SCR catalytic converter 32 receives the exhaust mixture 44 and discharges a NO\textsubscript{x}-treated exhaust flow 46. The ammonia-SCR catalytic converter 32 houses an appropriate ammonia-SCR catalyst that can absorb NH\textsubscript{3} and facilitate the reduction of NO\textsubscript{x} in the oxidative environment fostered by the exhaust mixture 44. The exhaust mixture 44 traverses the ammonia-SCR catalytic converter 32 and achieves intimate exposure with the ammonia-SCR catalyst to enable the reduction of NO\textsubscript{x} largely to N\textsubscript{2} and H\textsubscript{2}O in the presence of NH\textsubscript{3} and O\textsubscript{2}. The newly-generated N\textsubscript{2} is then communicated from the ammonia-SCR catalytic converter 32 in the NO\textsubscript{x}-treated exhaust flow 46. The ammonia-SCR catalyst may comprise, for example, an ion-exchanged base-metal zeolite such as a Cu/zeolite or a Fe/zeolite. Several different zeolite crystal structures including β-zeolites and MFI-type zeolites are commonly used to make the ammonia-SCR catalyst. Supported base metal oxides, such as V\textsubscript{2}O\textsubscript{5}-WO\textsubscript{3}/Tio\textsubscript{2} and V\textsubscript{2}O\textsubscript{5}/Tio\textsubscript{2}, may also be employed to formulate the ammonia-SCR catalyst.

[0029] A number of factors may influence the dynamic operating conditions of the ammonia-SCR catalytic converter 32 and result in NH\textsubscript{3} being present in the NO\textsubscript{x}-treated exhaust flow 46 and ultimately the intermediate exhaust flow 22. Fast increases in the temperature or flow rate of the exhaust mixture 46 and/or the over-injection of urea into the exhaust flow 20, for instance, may trigger the release of significant amounts of NH\textsubscript{3} from the ammonia-SCR catalyst or simply allow NH\textsubscript{3} to pass through the ammonia-SCR catalytic converter 32 unabsorbed and unreacted.

[0030] The NO\textsubscript{x}-treated exhaust mixture 46 discharged from the ammonia-SCR catalytic converter 32 is then supplied to the diesel particulate filter 34 to remove any suspended particulate matter. The diesel particulate filter 34 may be constructed according to any known design. The intermediate exhaust flow 22 emerges from the diesel particulate filter 34.

[0031] Skilled artisans will appreciate that many modifications can be made to the exhaust gas treatment subsystem 14a. For example, ammonia may be directly injected into the exhaust flow 20 instead of urea to form the exhaust mixture 44. As another example, the diesel particulate filter 34 may be placed between the diesel oxidation converter 30 and the ammonia-SCR catalytic converter 32 or combined with the diesel oxidation converter 30. As yet another example, the exhaust gas treatment subsystem 14a may be altered to operate with a spark-ignition engine by substituting a catalytic converter that houses a three-way-catalyst (TWC) for the diesel oxidation converter 30 and removing the diesel particulate filter 34. The TWC may comprise a combination of platinum, palladium, and rhodium, or it may comprise some other suitable catalyst formulation.

[0032] Another exemplary embodiment of the exhaust gas treatment subsystem 14, which is identified as 14b and depicted in FIG. 3, includes a catalytic converter 50 and a lean-NO\textsubscript{x} trap (LNT) 52 located downstream of the catalytic converter 50. The exhaust gas treatment system 14b shown and described here may be used when the exhaust aftertreatment system 10 is coupled to a spark-ignition engine such as a SIDI engine.

[0033] The catalytic converter 50 receives the exhaust flow 20 from the lean-burn engine 12. The catalytic converter 50 houses a TWC catalyst that may comprise a combination of
platinum, palladium, and rhodium. Other suitable TWC formulations may of course be employed. The exhaust flow traverses the catalytic converter and achieves intimate exposure with the TWC catalyst to promote the oxidation of CO (to CO₂) and HC’s (to CO₂ and H₂O). The TWC catalyst generally does not include a high enough proportion of platinum loading to oxidize NO and significantly change the NO to NO₂ molar ratio in the exhaust flow. The TWC catalyst can also oxidize CO and HC’s and simultaneously reduce NO to N₂ during regenerative periods when the lean-burn engine is supplied with a rich A/F mixture to, for example, regenerate or desulfate the LNT during regeneration of the LNT catalyst. Desulfation of the LNT catalyst may cause NH₃ to be introduced into the intermediate exhaust flow in much the same way that regeneration of the LNT catalyst does. While the problem of accumulated SO₃ in the LNT catalyst is more prevalent when the lean-burn engine is a diesel engine, desulfation of the LNT catalyst or desulfation-like procedures may also be practiced under certain circumstances when the lean-burn engine is a spark-ignition engine.

[0034] The LNT receives the exhaust flow exiting the catalytic converter. The exhaust flow traverses the LNT and achieves intimate contact with a LNT catalyst housed in the LNT. The LNT catalyst exhibits NO₃ trapping and NO₂ conversion capabilities and generally comprises an oxidation catalyst, a NO₂ storage catalyst, and a NO₂ reduction catalyst. The oxidation catalyst oxidizes NO to NO₂, and the NO₂ storage catalyst traps or “stores” NO₂ as a nitrate species as the exhaust flow traverses the LNT. The oxidation catalyst may also oxidize other gaseous emissions such as CO and HC’s, if present. The NO₂ reduction catalyst, as described below, catalyzes the reduction of NO and NO₂ into N₂ during regeneration of the LNT. A typical LNT catalytic formulation may comprise, for example, an alumina washcoat appropriately loaded with platinum, rhodium, and barium carbonate (BaCO₃).

[0035] The NO₂ storage capacity of the LNT is not unlimited and at some point may need to be regenerated or purged of NO₂-derived nitrate compounds. The LNT catalyst may be regenerated by introducing reductants—such as CO, HC’s and H₂—into the exhaust flow. This may be accomplished by decreasing the air to fuel mass ratio of the lean A/F mixture 18 so that the lean-burn engine combusts a stoichiometric or rich A/F mixture. The resultant delivery of rich-burn exhaust effluents to the LNT 20 by way of the exhaust flow causes the NO₂-derived nitrate compounds stored in the LNT catalyst to become thermodynamically unstable which, in turn, triggers the release of NO₂ and the regeneration of future NO₂ storage sites. The liberated NO₂ is then reduced to N₂ by excess reductants. The newly-generated N₂ is communicated from the LNT 20 in the intermediate exhaust flow 28. Some NH₃ may also be introduced into the intermediate exhaust flow since it is possible for the NO₂ reduction catalyst to reduce NO₂ to NH₃—instead of N₂—during regeneration.

Skilled artisans will appreciate, much like before, that many modifications can be made to the exhaust gas treatment subsystem 140. For example, an oxidation catalyst, such as a diesel oxidation catalyst or a two-way-catalyst, may be provided upstream of the LNT in addition to the catalytic converter 50 to lower the NO to NO₂ molar ratio in the exhaust flow. This downward adjustment to the NO: NO₂ molar ratio may be desirable since the downstream LNT may convert NO to N₂ at lower temperatures more efficiently as the molar ratio of NO to NO₂ decreases from that which is typically generated by the lean-burn engine. As another example, the exhaust gas treatment subsystem may be altered to operate with a diesel engine by substituting a diesel oxidation converter that houses a diesel oxidation catalyst for the catalytic converter 50 and adding a diesel particulate filter. The combustion of diesel fuel in the lean-burn engine, however, may additionally require periodic desulfation of the LNT catalyst to remove accumulate sulfur oxides (SOₓ). The LNT catalyst may be desulfated, for example, by introducing reductants into the exhaust flow and heating the LNT catalyst to elevated temperatures of about 600 °C. The desulfation of the LNT catalyst may cause NH₃ to be introduced into the intermediate exhaust flow in much the same way that regeneration of the LNT catalyst does. While the problem of accumulated SO₂ in the LNT catalyst is more prevalent when the lean-burn engine is a diesel engine, desulfation of the LNT catalyst or desulfation-like procedures may also be practiced under certain circumstances when the lean-burn engine is a spark-ignition engine.

[0037] Referring back to FIG. 1, the clean-up oxidation catalyst receives the intermediate exhaust flow and oxidizes any residual NH₃ to N₂. Other unwanted gaseous emissions that may have slipped through the exhaust gas treatment subsystem may also be oxidized. The clean-up oxidation catalyst may, in one embodiment, be housed in a separate catalytic converter device that is fluidly connected to the end of the exhaust gas treatment subsystem. The clean-up oxidation catalyst may, for example, be carried on a support body contained within a canister. The canister may be constructed to communicate the intermediate exhaust flow across or through the substrate body to induce intimate exposure between the intermediate exhaust flow and the clean-up oxidation catalyst. Various constructions of the substrate body are possible. The substrate body may be a monolithic honeycomb structure that includes several hundred to several thousand parallel flow-through cells per square inch. Each of the flow-through cells may be defined by a wall surface to which the clean-up oxidation catalyst is washcoated. The monolithic honeycomb structure may be formed from a material capable of withstanding the temperatures and chemical environment associated with the intermediate exhaust flow. Some specific examples of materials that may be used include ceramics such as extruded cordierite, α-alumina, silicon carbide, silicon nitride, zirconia, mullite, spodumene, alumina-silica-magnesia, zirconium silicate, sillimanite, petalite, or a heat and corrosion resistant metal such as titanium or stainless steel. The clean-up oxidation catalyst may also, in another embodiment, be zone coated onto the trailing edge of the most-downstream component or components included in the exhaust gas treatment subsystem that communicate the intermediate flow such as, for example, and with reference to FIG. 2, the diesel particulate filter.

[0038] The clean-up oxidation catalyst comprises metal oxide particles selected from a group consisting of perovskite oxide particles and manganese-containing mixed metal oxide particles dispersed on a selective catalytic reduction (SCR) catalyst. The clean-up oxidation catalyst can catalyze the oxidation of appreciable amounts of any NH₃ contained in the intermediate exhaust flow into N₂ and H₂O. The metal oxide particle loading and the aging of the clean-up oxidation catalyst can influence the catalytic activity of the clean-up oxidation catalyst including the temperature at which optimum NH₃ oxidation occurs and the NH₃ oxidation reaction’s N₂ selectivity. The clean-up oxidation catalyst may also, in a related and coupled NH₃ reaction, catalytically reduce the amount of any residual NO₂ contained in the intermediate exhaust flow if both NO₂ and NH₃ are present. Any appropriate technique may be used to disperse the metal oxide particles onto the SCR catalyst including washcoating and incipient wet impregnation.
[0039] The perovskite oxide particles that may be dispersed on the SCR catalyst encompass a class of compounds defined by the general formula ABO₃. The “A” and “B” atoms may be complimentary cations of different sizes that coordinate with oxygen anions. A unit cell of the ABO₃ crystal structure may feature a cubic closest packing arrangement with the “A” cation, which is generally the larger of the two cations, centrally located and surrounded by eight “B” cations situated in the octahedral voids of the packing arrangement. The “A” and “B” cations in such a packing arrangement respectively coordinate with twelve and six oxygen anions. The unit cell of the ABO₃ crystal structure, however, is not necessarily limited to a cubic closest packing arrangement. Certain combinations of the “A” and “B” cations may indeed deviate from the cubic closest packing arrangement and assume, for instance, an orthorhombic, rhombohedral, or monoclinic packing structure. Small amounts of the “A” and/or “B” cations, moreover, may be substituted with different yet similarly sized “A’” and “B’” promoter cations to give a supercell crystal structure derived from the general ABO₃ crystal structure and designated by the general formula A₁₋ₓAlₓB₁₋ₓ₀ₓ₁₂O₃, where both X and Y range from 0 to 1.

[0040] The perovskite oxide particles may comprise the same perovskite oxide or a mixture of two or more perovskite oxides. A great many combinations of perovskite oxides are available for use in the clean-up oxidation catalyst 16 since no fewer than 27 cations may be employed as the “A” cation and no fewer than 36 cations may be employed as the “B” cation. A listing of the cations most frequently employed as the “A” cation includes those of calcium (Ca), strontium (Sr), barium (Ba), bismuth (Bi), cadmium (Cd), cerium (Ce), lead (Pb), yttrium (Y), and lanthanum (La) while a listing of the cations most commonly employed as the “B” cation includes those of cobalt (Co), titanium (Ti), zirconium (Zr), niobium (Nb), tin (Sn), cerium (Ce), aluminum (Al), nickel (Ni), chromium (Cr), manganese (Mn), copper (Cu), and iron (Fe). Some specific and exemplary perovskite oxides that may constitute all or part of the perovskite oxide particles include LaCoO₃, La₀.₅Sr₀.₅CoO₃, LaMnO₃, La₀.₅Sr₀.₅MnO₃, LaFeO₃, and La₀.₅Sr₀.₅FeO₃.

[0041] The manganese-containing mixed metal oxide particles that may be dispersed on the SCR catalyst may include at least one of manganese-cerium oxides, Mn₇Ce₀₂O₁₇, manganese-zirconium oxides, Mn₂ZrO₃, or manganese-cesium-zirconium oxides, Mn₇Ce₀₂O₁₇, with X ranging from 0.02 to 0.98, Y ranging from 0.02 to 0.98, W ranging from 0.02 to 0.98, and Z ranging from 1.0 to 3.0. Some specific examples of suitable manganese-containing metal oxides include, but are not limited to, 0.5MnO₂-0.5CeO₂ where V ranges from 2 to 3, 0.3MnO₂-0.7CeO₂ where W ranges from 2 to 3, 0.1MnO₂-0.9CeO₂ where V ranges from 2 to 3, Mn₀.₅Ce₀.₅O₂, Mn₀.₅Ce₀.₅O₁₋ₓ₂ₓ₂ₓ where 0 ≤ x ≤ 0.1, and Mn₀.₅Ce₀.₅O₁₋ₓ₂ₓ₂ₓ where 0 ≤ x ≤ 0.1.

[0042] The perovskite oxide particles and the manganese-containing mixed metal oxide particles, either alone or in combination, can help the clean-up oxidation catalyst 16 catalytically oxidize NH₃ to N₂ just as efficiently as platinum when exposed to the hot and oxygen-abundant intermediate exhaust flow 22. While not wishing to be bound by theory, it is believed that the perovskite oxide particles and the manganese-containing mixed metal oxide particles have the ability to donate oxygen anions to NH₃ molecules while temporarily forming oxygen vacancies in their crystal structures. Readily available oxygen contained in the engine exhaust then dissociates to fill those oxygen anion vacancies and possibly react with additional NH₃ molecules. The ability of the perovskite oxide particles and the manganese-containing mixed metal oxide particles to efficiently oxidize NH₃ may significantly diminish or altogether eliminate the need to include PGM’s such as platinum in the clean-up oxidation catalyst 16. The clean-up oxidation catalyst 16 may, as a result, provide the exhaust aftertreatment system 10 with a smaller amount of PGM’s than a comparable exhaust aftertreatment system that incorporates a conventional PGM-based clean-up oxidation catalyst 16 to prevent ammonia slip and the escape of other unwanted gaseous emissions.

[0043] The amount of the metal oxide particles present in the clean-up oxidation catalyst 16 may range from about 0.1 wt. % to about 20 wt. %, more specifically from about 0.5 wt. % to about 15 wt. %, and even more specifically from about 1.0 wt. % to about 12 wt. %, based on the weight of the clean-up oxidation catalyst 16. The specific metal oxide particle loading may be chosen, if desired, based on the normal expected operating temperature window of the exhaust flow 20 and the aging of the clean-up oxidation catalyst 16. A degreened (light-aging) clean-up oxidation catalyst 16 with a higher metal oxide particle loading (greater than about 5 wt. %), for example, tends to oxidize NH₃ to N₂ quite efficiently at lower exhaust temperatures (up to about 350°C) although, at higher temperatures (above about 350°C), it begins to oxidize some NH₃ to NOₓ, instead of N₂. As another example, a degreened clean-up oxidation catalyst 16 with a lower metal oxide particle loading (less than about 2 wt. %) tends to oxidize NH₃ to N₂ more consistently with complete or almost complete N₂ selectivity at both lower temperatures (up to about 350°C) and higher temperatures (above about 350°C). High-temperature aging can further affect the NH₃ oxidation efficiency and the N₂ selectivity of the clean-up oxidation catalyst 16. Such aging, in general, improves the N₂ selectivity of the clean-up oxidation catalyst 16 at higher temperatures at the expense of NH₃ oxidation efficiency at lower temperatures.

[0044] The SCR catalyst may be any material that can help facilitate the oxidation of NH₃ to N₂ when exposed to the intermediate exhaust 22. The SCR catalyst is generally a porous and high-surface area material—a wide variety of which are commercially available. The specific SCR catalyst used to formulate the clean-up oxidation catalyst 16 may be an ion-exchanged base metal zeolite or silver-supported alumina (Ag/Al₂O₃). The zeolite may be a β-type zeolite, a Y-type zeolite, or a MFI-type zeolite. Some specific examples of suitable ion-exchanged base metal zeolites that may be used include, but are not limited to, a β-zeolite that is ion-exchanged with Cu or Fe, a MFI-type zeolite that is ion exchanged with Cu or Fe, and a Y-type zeolite that is ion-exchanged with Na, Ba, Cu, or CuCo.

[0045] The particular composition of the clean-up oxidation catalyst 16 may be formulated based on a number of factors including the type and normal expected operating parameters of the lean-burn engine 12 and the design and construction of the exhaust gas treatment system 10. The clean-up oxidation catalyst 16 may, for example, comprise about 10-15 wt. % metal oxide particles washcoated onto a copper exchanged or iron exchanged β-zeolite. This particular catalyst composition may be employed if the lean-burn engine 12 is expected to generally operate at low speeds and/or with a low load demand. The clean-up oxidation catalyst 16 may also, as another example, comprise about 0.5-2.0 wt. % metal oxide particles washcoated onto a copper
exchanged or iron exchanged β-zeolite. This particular catalyst composition may be employed if the lean-burn engine is expected to generally operate at high speeds and/or with a high load demand. Other compositions of the clean-up oxidation catalyst may of course be formulated and utilized by skilled artisans who are familiar with lean-burn engine exhaust aftertreatment technology.

EXAMPLE

[0046] This Example demonstrates the catalytic activity of several exemplary clean-up oxidation catalysts that were evaluated in a laboratory reactor configured to flow a simulated lean-burn engine exhaust feedstream. Each of the exemplary clean-up oxidation catalysts evaluated had a different weight percent loading of La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles washed onto a Fe/β-zeolite and was either degreened or subjected to high-temperature aging. The weight percent loading of the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles for each exemplary clean-up oxidation catalyst is based on the weight of the clean-up oxidation catalyst (i.e., the total weight of the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles and the SCR catalyst). While this Example evaluates different loadings of La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles (perovskite oxide particles) on a Fe/β-zeolite SCR catalyst, it is expected that the general results and data would be achieved by either mixing the perovskite oxide particles with manganese-containing mixed metal oxide particles or completely substituting the perovskite oxide particles for manganese-containing mixed metal oxide particles.

[0047] A citric acid method was used to prepare a quantity of La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles. First, appropriate amounts of La(NO$_3$)$_3$·6H$_2$O, Co(NO$_3$)$_2$·6H$_2$O, and Sr(NO$_3$)$_2$·6H$_2$O were dissolved in distilled water with citric acid monohydrate. The amount of water used was 46.2 ml per gram of La(NO$_3$)$_3$·6H$_2$O, and the citric acid was added to the distilled water in a 10 wt. % excess to ensure complete complexation of the metal ions. The solution was set on a stirring and heating plate and stirred for 1 hour at room temperature. The solution was then heated to 80° C. under continuous stirring to slowly evaporate the water until the solution became a viscous gel and started evolving NO/NO$_2$ gases. The resulting spongy material was crushed and calcined at 700° C. for about 5 hours in static air. The temperature was then ramped down at a rate of 10° C. per minute. When the temperature reached just below 300° C., the citrate ions combusted vigorously and caused a large spike in temperature and powder displacement. The powder was thus covered with several layers of ZrO$_2$ balls to prevent such powder displacement yet still allow for gas mobility. The prepared La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles were characterized by N$_2$ physisorption for surface area measurements and X-ray diffraction for their bulk structure measurements.

[0048] The La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles were then ball milled with 6.33 ml of water per gram of the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles for 18 hours. Afterwards, the slurry was stirred continuously and 0.33 ml of HNO$_3$ (0.1 M) per gram of the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles and 5 ml of water per gram of the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles was added. The resulting washcoat solution had a concentration of 0.114 grams of La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles per ml. The slurry was washed onto a monolithic honeycomb core sample (½ inch diameter by 1 inch length with a flow-through cell density of 400 per square inch) that had already been washed coated with the Fe/β-zeolite. Next, after washingcoating of the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles, the monolithic honeycomb core sample was dried and calcined at 550° C. for 5 hours in static air.

[0049] This procedure was repeated several times to prepare monolithic honeycomb core samples that had a La$_{0.5}$Sr$_{0.5}$CoO$_3$ particle loading of either 1.0, 5.5, or 12 wt. %. Two core samples were prepared for each wt % loading of La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles. One clean-up catalyst at each La$_{0.5}$Sr$_{0.5}$CoO$_3$ particle loading was degreened and the other was high-temperature aged. The degreened clean-up oxidation catalysts were hydrothermally aged in air+10% H$_2$O for 5 hours at 550° C. The high-temperature aged clean-up oxidation catalysts were hydrothermally aged in air+10% H$_2$O for 48 hours at 700° C.

[0050] Monolithic core samples were also prepared that included only a Fe/β-zeolite SCR catalyst, only La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles, and a conventional platinum-containing catalyst, all for comparative evaluation purposes. The Fe/β-zeolite SCR catalysts were either degreened or high-temperature aged similar to the clean-up oxidation catalysts. The La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles alone were aged slightly different as indicated below.

[0051] FIG. 4 shows the catalytic performance of the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles for various reactions at temperatures ranging from 150° C. to 550° C. Temperature (°C.) is plotted on the X-axis and conversion (%) is plotted on the Y-axis. The conversion of NO (NO+O$_2$) is identified by numeral 60, the conversion of NH$_3$ (NH$_3$+O$_2$) is identified by numeral 62, and the conversion of NO$_x$ (NO+NH$_3$+O$_2$) is identified by numeral 64. The La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles were hydrothermally aged in air+$10\%$ H$_2$O for 5 hours at 700° C. The simulated exhaust feedstream passed over the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles to determine NO conversion (60) had a space velocity of about 30,000 h$^{-1}$ and comprised approximately 10% O$_2$, 400 ppm NO, and the balance N$_2$. The simulated exhaust feedstream passed over the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles to determine NH$_3$ conversion (62) had a space velocity of about 30,000 h$^{-1}$ and comprised approximately 10% O$_2$, 5% H$_2$O, 5% CO$_2$, 200 ppm NH$_3$, and the balance N$_2$. The simulated exhaust feedstream passed over the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles to determine NO$_x$ conversion (64) had a space velocity of about 30,000 h$^{-1}$ and comprised approximately 10% O$_2$, 5% H$_2$O, 5% CO$_2$, 200 ppm NO, 200 ppm NH$_3$, and the balance N$_2$.

[0052] As shown in FIG. 4, the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles oxidized NO and NH$_3$ rather well at temperatures above about 225° C. and 350° C., respectively. The undesirable oxidation of NH$_3$ into NO$_x$, however, occurred at temperatures of about 250° C. to about 450° C. At temperatures above about 450° C., as shown, the oxidation of NH$_3$ to N$_2$ was much preferred over the oxidation of NO$_x$ to N$_2$. This oxidation selectivity resulted in the overall NO$_x$ conversion being negative.

[0053] FIGS. 5-8 depict some catalytic performance data of the exemplary clean-up oxidation catalysts. The same catalytic performance data for the Fe/zeolite SCR catalyst and the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles are also shown for comparison purposes.

[0054] FIGS. 5 and 6 show the NH$_3$ oxidation performance, in the absence of NO, of the Fe/β-zeolite SCR catalyst alone, the La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles alone, and the clean-up oxidation catalysts at temperatures ranging from 150° C. to 550° C. Temperature (°C.) is plotted on the X-axis and NH$_3$ conversion (%) is plotted on the Y-axis. The Fe/β-zeolite SCR catalyst and the clean-up catalysts represented in FIG. 5 were degreened while the Fe/β-zeolite SCR catalyst and the clean-up oxidation catalysts represented in FIG. 6 were high-temperature aged. The La$_{0.5}$Sr$_{0.5}$CoO$_3$ particles in both of FIGS.
5 and 6 were hydrothermally aged for 5 hours at 700°C. The simulated exhaust feedstream passed over the Fe/β-zeolite SCR catalyst and the clean-up oxidation catalysts had a space velocity of about 30,000 h⁻¹ and comprised approximately 10% O₂, 5% H₂O, 5% CO₂, 200 ppm NH₃, and the balance N₂.

[0055] The NH₃ conversion of the Fe/β-zeolite SCR catalyst is identified by numeral 70 in FIG. 5 and numeral 70' in FIG. 6, the NH₃ conversion of the La₀.₇Sr₀.₃CoO₃ particles is identified by numeral 72 in FIG. 5 and numeral 72' in FIG. 6, the NH₃ conversion of the clean-up oxidation catalyst having 1.0 wt. % perovskite oxide particles is identified as numeral 74 in FIG. 5 and numeral 74' in FIG. 6, the NH₃ conversion of the clean-up oxidation catalyst having 5.5 wt. % perovskite oxide particles is identified as numeral 76 in FIG. 5 and numeral 76' in FIG. 6, and the NH₃ conversion of the clean-up oxidation catalyst having 12.0 wt. % perovskite oxide particles is identified as numeral 78 in FIG. 5 and numeral 78' in FIG. 6.

[0056] As shown in FIGS. 5 and 6, the degreened clean-up oxidation catalysts having a 5.5 wt. % and 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loading (FIG. 5) oxidized NH₃ more effectively than the La₀.₇Sr₀.₃CoO₃ particles alone while the high-temperature aged clean-up oxidation catalysts with the same La₀.₇Sr₀.₃CoO₃ particles loadings (FIG. 6) oxidized NH₃ quite comparably to the La₀.₇Sr₀.₃CoO₃ particles alone. The clean-up oxidation catalysts having a 1.0 wt. % La₀.₇Sr₀.₃CoO₃ particle loading—both degreened and high-temperature aged—and the Fe/β-zeolite SCR catalyst alone oxidized NH₃ to a lesser extent.

[0057] FIGS. 7 and 8 are related to FIGS. 5 and 6, respectively, and show how much of the oxidized NH₃ formed NOₓ, Temperature (°C) is plotted on the X-axis and NOₓ selectivity (%)—i.e., the conversion of NH₃ to NOₓ—is plotted on the Y-axis. The Fe/β-zeolite SCR catalyst and the clean-up oxidation catalysts represented in FIG. 7 were degreened while the Fe/β-zeolite SCR catalyst and the clean-up oxidation catalysts represented in FIG. 8 were high-temperature aged. The La₀.₇Sr₀.₃CoO₃ particles in both FIGS. 7 and 8 were hydrothermally aged for 5 hours at 700°C.

[0058] The NOₓ selectivity of the Fe/β-zeolite SCR catalyst is identified by numeral 80 in FIG. 7 and numeral 80' in FIG. 8, the NOₓ selectivity of the La₀.₇Sr₀.₃CoO₃ particles is identified by numeral 82 in FIG. 7 and numeral 82' in FIG. 8, the NOₓ selectivity of the clean-up oxidation catalyst having a 1.0 wt. % perovskite oxide particles is identified as numeral 84 in FIG. 7 and numeral 84' in FIG. 8, the NOₓ conversion of the clean-up oxidation catalyst having 5.5 wt. % perovskite oxide particles is identified as numeral 86 in FIG. 7 and numeral 86' in FIG. 8, and the NOₓ conversion of the clean-up oxidation catalyst having 12.0 wt. % perovskite oxide particles is identified as numeral 88 in FIG. 7 and numeral 88' in FIG. 8.

[0059] As can be seen, the La₀.₇Sr₀.₃CoO₃ particles alone began to oxidize NH₃ to NOₓ quite readily at temperatures above about 300°C. While the Fe/β-zeolite SCR catalyst—both degreened and high-temperature aged—produced essentially no NOₓ. The degreened and the high-temperature aged clean-up oxidation catalysts having a 0.1 wt. % La₀.₇Sr₀.₃CoO₃ particle loading also generated very little NOₓ, if any. The degreened and the high-temperature aged clean-up oxidation catalysts having 5.5 wt. % and 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loadings, however, showed an uptick in NOₓ selectivity once temperatures eclipsed about 400°C. This increase in NOₓ selectivity was less pronounced for the high-temperature aged 5.5 wt. % and 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loaded clean-up oxidation catalysts than for the corresponding degreened clean-up oxidation catalysts.

[0060] FIG. 9 relates to FIGS. 5-8 and compares the NH₃ oxidation performance and the NOₓ selectivity of the degreened and high-temperature aged 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loaded clean-up oxidation catalysts with that of the conventional platinum-containing catalyst. Temperature (°C) is plotted on the X-axis and both NH₃ conversion (%) and NOₓ selectivity (%) are plotted on the Y-axis. The conventional platinum-containing catalyst included 5 g/pℓ of platinum supported on alumina. The 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loaded clean-up oxidation catalysts were exposed to the same simulated exhaust feedstream as recited in the description of FIGS. 5-6. The conventional platinum-containing catalyst was exposed to a simulated exhaust feedstream at a space velocity of about 60,000 h⁻¹ that comprised approximately 12% O₂, 4.5% H₂O, 4.5% CO₂, 200 ppm NH₃, and the balance N₂.

[0061] The NH₃ conversion of the degreened 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loaded clean-up oxidation catalyst is identified by numeral 90, the NOₓ selectivity of the degreened 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loaded clean-up oxidation catalyst is identified by numeral 92, the NH₃ conversion of the high-temperature aged 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loaded clean-up oxidation catalyst is identified by numeral 94, the NOₓ selectivity of the high-temperature aged 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loaded clean-up oxidation catalyst is identified by numeral 96, the NH₃ conversion of the conventional platinum-containing catalyst is identified by numeral 98, and the NOₓ selectivity of the conventional platinum-containing catalyst is identified by numeral 100.

[0062] As shown, both of the degreened and the high-temperature aged 12 wt. % La₀.₇Sr₀.₃CoO₃ particle loaded clean-up oxidation catalysts demonstrated at least comparable and, in many respects superior, NOₓ selectivity and NH₃ oxidation performance to that of the conventional platinum-containing catalyst.

[0063] The above description of embodiments is merely exemplary in nature and, thus, variations therefrom are not to be regarded as a departure from the spirit and scope of the invention.

What is claimed is:

1. An exhaust aftertreatment system for removing gaseous emissions and suspended particulate matter, if present, contained in exhaust produced by a lean-burn engine that is combusting a lean mixture of air and fuel, the exhaust aftertreatment system comprising:

- an exhaust gas treatment subsystem that receives an exhaust flow from the lean-burn engine and communicates an intermediate exhaust flow, the exhaust gas treatment subsystem comprising a NOₓ abatement component and operating to oxidize carbon monoxide and unburned and/or partially burned hydrocarbons, remove suspended particulate matter if present, and reduce NOₓ so that the intermediate exhaust flow comprises a lesser amount of carbon monoxide, unburned and/or partially burned hydrocarbons, suspended particulate matter if present, and NOₓ than the exhaust flow; and
- a clean-up oxidation catalyst that receives the intermediate exhaust flow from the exhaust gas treatment subsystem and communicates a treated exhaust flow, the treated exhaust flow being communicated to the atmosphere.
without being exposed to another catalyst material after the clean-up oxidation catalyst, the clean-up oxidation catalyst comprising (1) a selective catalytic reduction catalyst and (2) metal oxide particles dispersed on the selective catalytic reduction catalyst, wherein the metal oxide particles are selected from the group consisting of perovskite oxide particles, manganese-containing mixed metal oxide particles, and mixtures thereof, and wherein the metal oxide particles are present in an amount that ranges from about 0.1 wt. % to about 20 wt. % based on the weight of the clean-up oxidation catalyst.

2. The exhaust aftertreatment system set forth in claim 1, wherein the perovskite oxide particles comprise at least one of LaCoO₃, La₅₋ₓSrxCo₂O₄, LaMnO₃, La₅₋ₓSrₓMnO₃, LaFe₂O₄, or LaSr₁₋ₓFeₓO₄, and wherein the manganese-containing mixed metal oxide particles comprise at least one of MnₓCo₁₋ₓO₂, MnₓYₓZr₁₋ₓO₂, or MnₓCe₁₋ₓZr₁ₓO₂ in which X ranges from 0.02 to 0.98, Y ranges from 0.02 to 0.98, W ranges from 0.02 to 0.98, and Z ranges from 1.0 to 3.0.

3. The exhaust aftertreatment system set forth in claim 1, wherein the selective catalytic reduction catalyst comprises silver-supported alumina, an ion-exchanged base-metal zeolite, or a base metal oxide selected from the group consisting of V₂O₅-WO₃/TiO₂, V₂O₅/TiO₂, and mixtures thereof.

4. The exhaust aftertreatment system set forth in claim 3, wherein the ion-exchanged base-metal zeolite comprises at least one of a β-zeolite that is ion-exchanged with at least one of a Cu or Fe, a MFI-type zeolite that is ion-exchanged with at least one of a Cu or Fe, or a Y-type zeolite that is ion-exchanged with at least one of a Na, Ba, Cu, Co, or CuO.

5. The exhaust aftertreatment system set forth in claim 1, wherein the amount of metal oxide particles dispersed on the selective catalytic reduction catalyst ranges from about 0.5 wt. % to about 15 wt. % based on the weight of the exhaust flow.

6. The exhaust aftertreatment system set forth in claim 1, wherein the amount of metal oxide particles dispersed on the selective catalytic reduction catalyst ranges from about 1.0 wt. % to about 12 wt. % based on the weight of the clean-up oxidation catalyst.

7. The exhaust aftertreatment system set forth in claim 1, wherein the NOₓ abatement component is a lean NOₓ trap that comprises a LNT catalyst.

8. The exhaust aftertreatment system set forth in claim 7, wherein the exhaust gas treatment subsystem further comprises at least one of a diesel oxidation converter or a catalytic converter located upstream of the lean-NOₓ trap, wherein the diesel oxidation converter comprises a diesel oxidation catalyst and the catalytic converter comprises a three-way-catalyst.

9. The exhaust aftertreatment system set forth in claim 1, wherein the NOₓ abatement component is an ammonia-SCR catalytic converter that comprises an ammonia-SCR catalyst.

10. The exhaust aftertreatment system set forth in claim 9, wherein the exhaust gas treatment subsystem further comprises at least one of a diesel oxidation converter or a catalytic converter located upstream of the ammonia-SCR catalytic converter, wherein the diesel oxidation converter comprises a diesel oxidation catalyst and the catalytic converter comprises a three-way-catalyst.

11. The exhaust aftertreatment system set forth in claim 9, wherein the exhaust gas treatment subsystem further comprises a urea-metering device that introduces urea into the exhaust flow to form an exhaust mixture that comprises ammonia and the exhaust flow, and wherein the ammonia-SCR catalytic converter receives the exhaust mixture.

12. The exhaust aftertreatment system set forth in claim 1, wherein the clean-up oxidation catalyst is carried on a support body and housed in a canister that is fluidly connected to the exhaust gas treatment subsystem.

13. A method for removing gaseous emissions and suspended particulate matter, if present, contained in exhaust produced by a lean-burn engine that is combusting a lean mixture of air and fuel, the method comprising:

- supplying a lean-burn engine with a lean mixture of air and fuel;
- combusting the lean mixture of air and fuel in the lean-burn engine to produce an exhaust flow;
- delivering the exhaust flow to an exhaust gas treatment subsystem that comprises a NOₓ abatement component that can catalytically reduce NOₓ to N₂;
- operating the exhaust gas treatment subsystem to produce an intermediate exhaust flow that comprises a lesser amount of carbon monoxide, unburned and/or partially burned hydrocarbons, suspended particulate matter if present, and NOₓ than the exhaust flow; and
- delivering the intermediate exhaust flow to a clean-up oxidation catalyst to oxidize ammonia, if present, and produce a treated exhaust flow, the clean-up oxidation catalyst comprising (1) a selective catalytic reduction catalyst and (2) metal oxide particles dispersed on the selective catalytic reduction catalyst, wherein the metal oxide particles are selected from the group consisting of perovskite oxide particles, manganese-containing mixed metal oxide particles, and mixtures thereof.

14. The method set forth in claim 13, further comprising communicating the treated exhaust flow to the atmosphere without exposing the treated exhaust flow to another catalyst material after the clean-up oxidation catalyst.

15. The method set forth in claim 13, wherein operating the exhaust gas treatment subsystem comprises:

- delivering the exhaust flow to a diesel oxidation converter or a catalytic converter, the diesel oxidation converter comprising a diesel oxidation catalyst and the catalytic converter comprising a three-way-catalyst; and
- delivering the exhaust flow to a lean-NOₓ trap that includes a LNT catalyst that includes an oxidation catalyst, a NOₓ storage catalyst, and a NOₓ reduction catalyst.

16. The method set forth in claim 13, wherein operating the exhaust gas treatment subsystem comprises:

- delivering the exhaust flow to a diesel oxidation converter or a catalytic converter, the diesel oxidation converter comprising a diesel oxidation catalyst and the catalytic converter comprising a three-way-catalyst; introducing ammonia into the exhaust flow to form an exhaust mixture; and
- delivering the exhaust mixture to an ammonia-SCR catalytic converter that comprises an ammonia-SCR catalyst.

17. The method set forth in claim 13, wherein the metal oxide particles comprise at least one of LaCoO₃, La₅₋ₓSrₓCo₂O₄, LaMnO₃, La₅₋ₓSrₓMnO₃, LaFe₂O₄, LaSr₁₋ₓFeₓO₄, MnₓCe₁₋ₓZr₁ₓO₂, or MnₓCe₁₋ₓZr₁ₓO₂ in which X ranges from 0.02 to 0.98, Y ranges from 0.02 to 0.98, W ranges from 0.02 to 0.98, and Z ranges from 1.0 to 3.0.
18. The method set forth in claim 13, wherein the selective catalytic reduction catalyst comprises at least one of silver-supported alumina, an ion-exchanged base-metal zeolite, or a base metal oxide selected from the group consisting of $\text{V}_2\text{O}_5$, $\text{WO}_3/\text{TiO}_2$, $\text{V}_2\text{O}_5/\text{TiO}_2$, and mixtures thereof.

19. The method set forth in claim 18, wherein the ion-exchanged base-metal zeolite comprises at least one of a β-zeolite that is ion-exchanged with at least one of a Cu or Fe, a MFI-type zeolite that is ion-exchanged with at least one of a Cu or Fe, or a Y-type zeolite that is ion-exchanged with at least one of a Na, Ba, Cu, Co, or CuCo.

20. The method set forth in claim 13, wherein the metal oxide particles are dispersed on the selective catalytic reduction catalyst in an amount that ranges from about 0.1 wt. % to about 20 wt. % based on the weight of the clean-up oxidation catalyst.

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