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(54) SELECTIVE CATALYTIC REDUCTION DEVICE CONTROL

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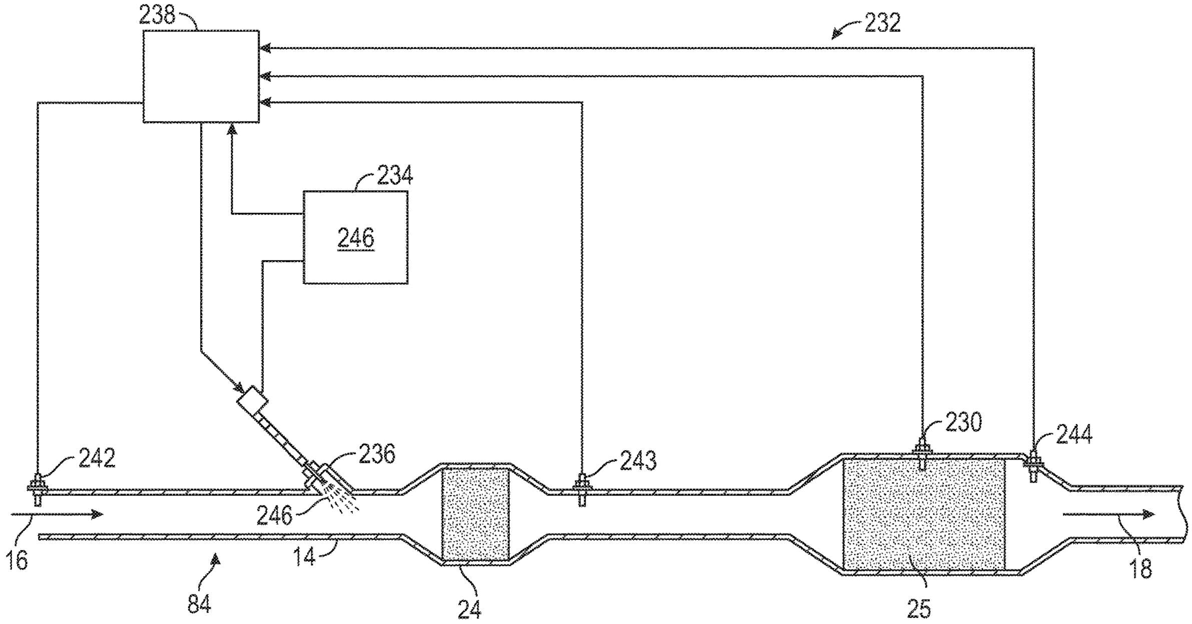
(57) ABSTRACT

Technical solutions described herein include an emissions control system for treating exhaust gas in a motor vehicle including an internal combustion engine. The emissions control system includes a model-based controller to control reductant injection into the exhaust gas. Controlling the reductant injection includes determining an amount of NOx and an amount of NH3 at an outlet of the first SCR device, and at an outlet of the second SCR device. The controlling further includes computing an amount of reductant to inject to maintain a first predetermined ratio between the amount of NH3 and the amount of NOx at the outlet of the first SCR device and to maintain a second predetermined ratio between the amount of NH3 and the amount of NOx at the outlet of the second SCR device. Further, the controlling includes sending a command for receipt by the reductant injector to inject the computed amount of reductant.



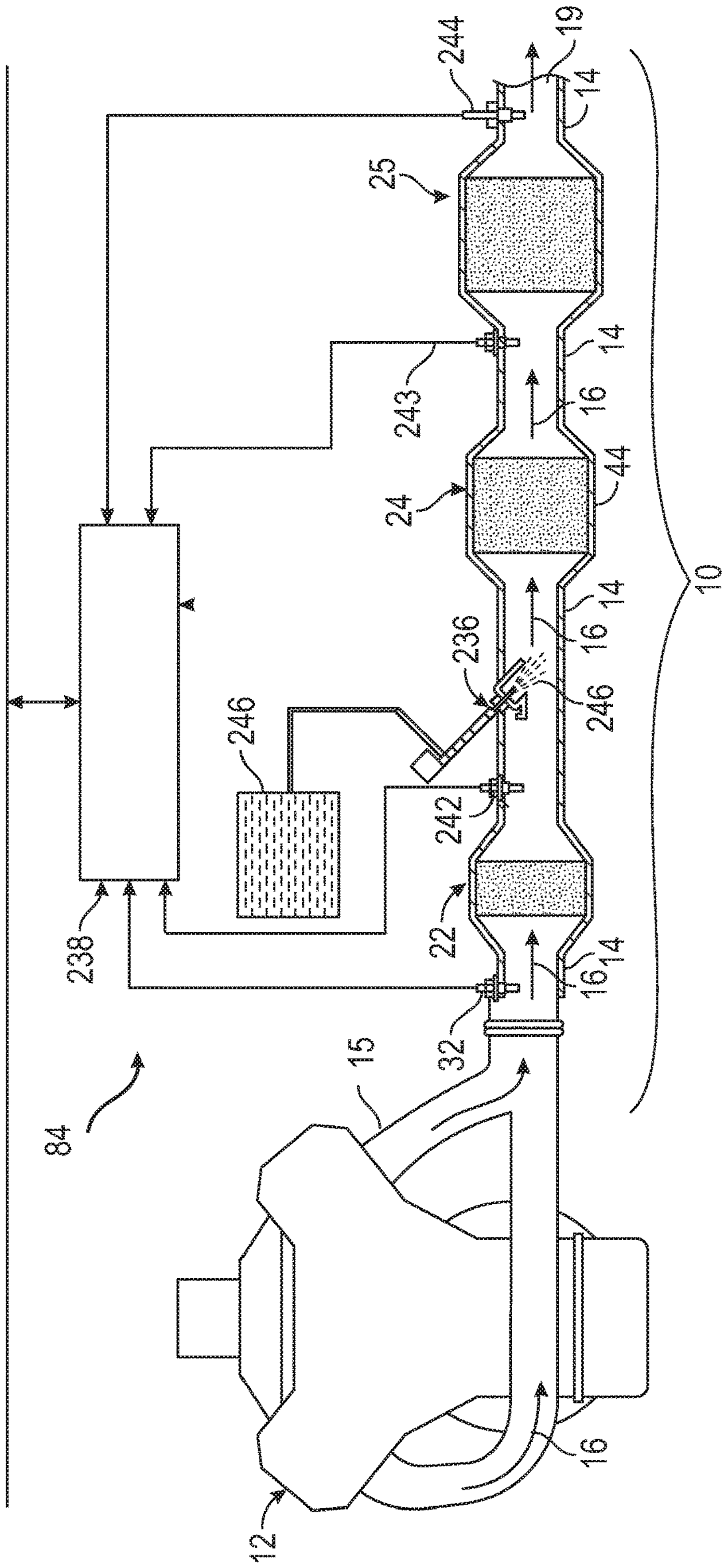

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FIG. 1

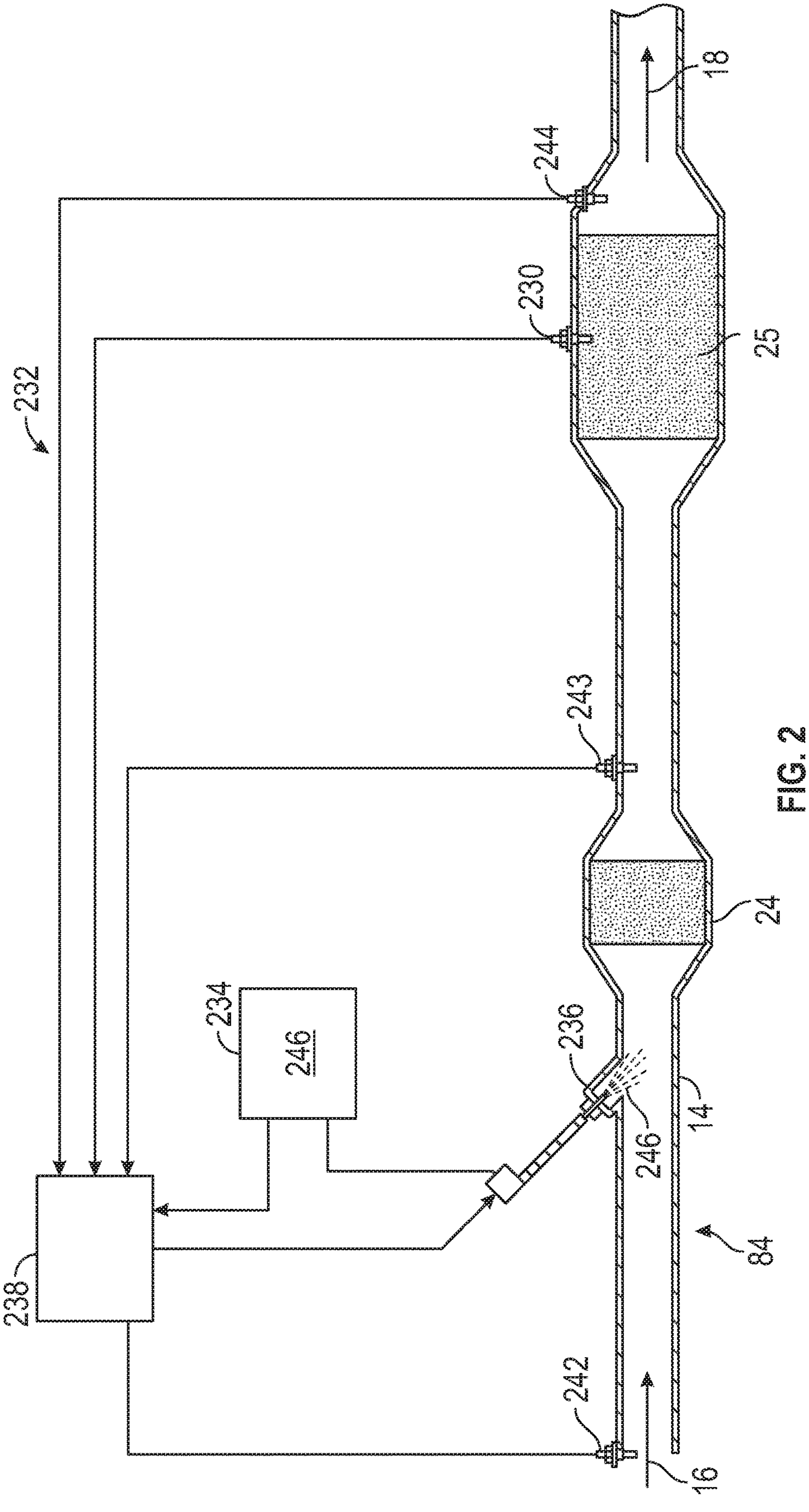

FIG. 2

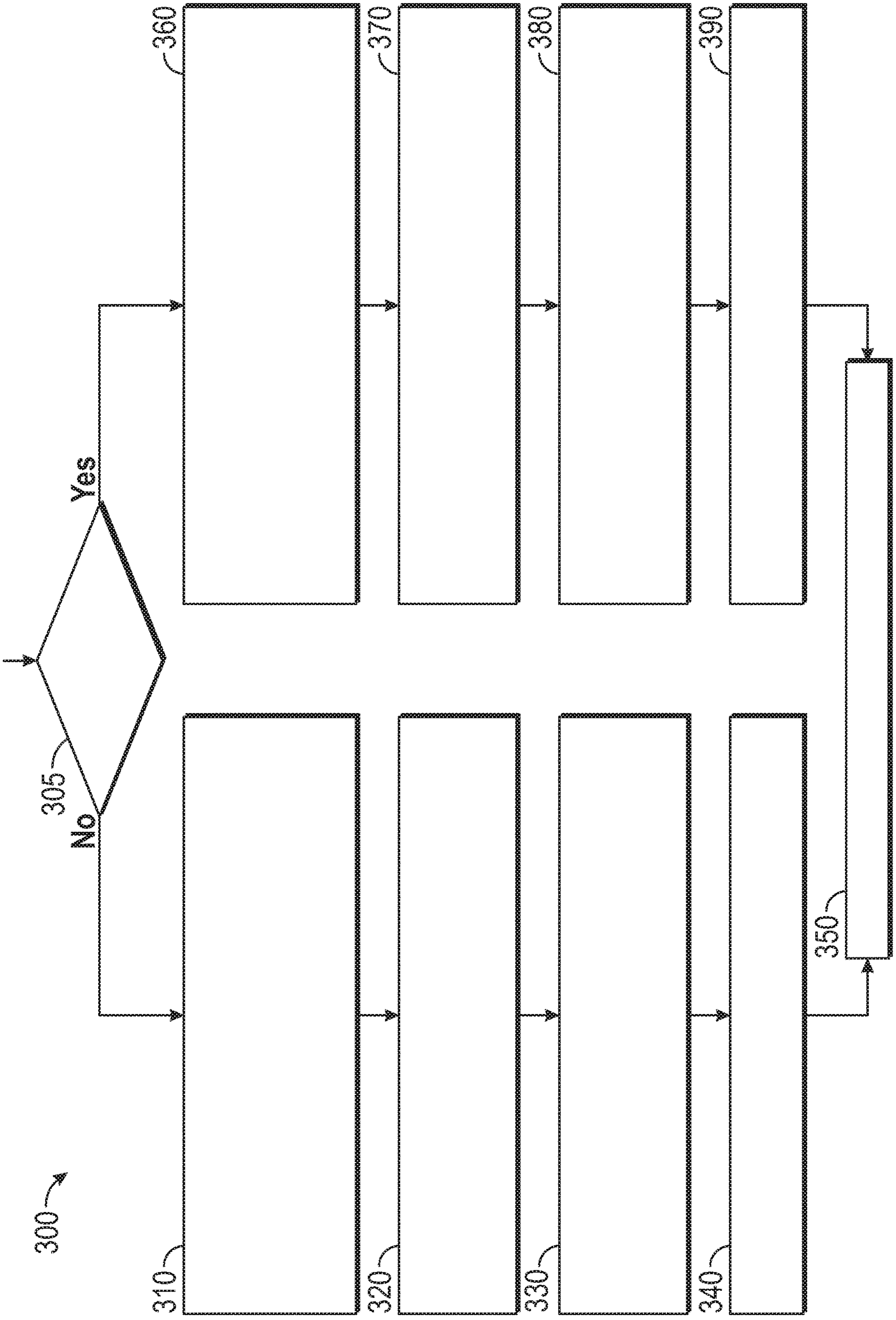

FIG. 3

SELECTIVE CATALYTIC REDUCTION DEVICE CONTROL

INTRODUCTION

[0001] The present disclosure relates to exhaust systems for internal combustion engines, and more particularly to exhaust systems using selective catalytic reduction (SCR) units for emissions control.

[0002] Exhaust gas emitted from an internal combustion engine, particularly a diesel engine, is a heterogeneous mixture that contains gaseous emissions such as carbon monoxide ("CO"), unburned hydrocarbons ("HC") and oxides of nitrogen ("NO_x") as well as condensed phase materials (liquids and solids) that constitute particulate matter ("PM"). Catalyst compositions, typically disposed on catalyst supports or substrates, are provided in an engine exhaust system as part of an aftertreatment system to convert certain, or all of these exhaust constituents into non-regulated exhaust gas components.

[0003] Exhaust gas treatment systems typically include selective catalytic reduction (SCR) devices. An SCR device includes a substrate having an SCR catalyst disposed thereon to reduce the amount of NOx in the exhaust gas. The typical exhaust treatment system also includes a reductant delivery system that injects a reductant such as, for example, ammonia (NH3), urea ($(NH_2)_2$ CO, etc.). The SCR device makes use of NH_3 to reduce the NOx. For example, when the proper amount of NH3 is injected to the SCR device under the proper thermal conditions, the NH3 reacts with the NOx in the presence of the SCR catalyst to reduce the NOx emissions. If the NH3 injection rate is too high, then there is excess of ammonia in the exhaust and, ammonia (NH3) can slip from the SCR. On the other hand, if there is too little ammonia in the exhaust, SCR NOx conversion efficiency will be decreased.

SUMMARY

[0004] According to one or more embodiments an emissions control system for treating exhaust gas from an internal combustion engine in a motor vehicle, includes a reductant injector. The emissions control system also includes a first selective catalytic reduction (SCR) device. The emissions control system also includes a second SCR device. The emissions control system further includes a controller to control the reductant injection into the exhaust gas. The controlling of the reductant injection includes determining an amount of NOx and an amount of NH3 at an outlet of the first SCR device. The controlling of the reductant injection further includes determining an amount of NOx and an amount of NH3 at an outlet of the second SCR device. The controlling of the reductant injection further includes computing an amount of reductant to inject to maintain a first predetermined ratio between the amount of NH3 and the amount of NOx at the outlet of the first SCR device and to maintain a second predetermined ratio between the amount of NH3 and the amount of NOx at the outlet of the second SCR device to ensure the optimal operation of both selective catalytic reduction systems, the first SCR device and the second SCR device. The controlling of the reductant injection further includes sending a command for receipt by the reductant injector to inject the computed amount of reductant.

[0005] In one or more examples, determining the amount of NH3 at the outlet of the first CR device is based on computing a first estimated NH3 storage level for the first SCR device, and is further based on receiving a NOx measurement at an inlet of the first SCR device. In one or more examples, determining the amount of NH3 at the outlet of the second SCR device is based on computing a second estimated NH3 storage level for the second SCR device, and the amount of NH3 at the outlet of the first SCR device. Determining the amount of NH3 at the outlet of the second SCR device is further based on receiving a NOx measurement at the outlet of the first SCR device. In one or more examples, the first SCR device is a SCR filter. In one or more examples, the second SCR device is an underfloor SCR device. In one or more examples, computing the amount of reductant includes estimating the amount of NH3 and the amount of NOx at the outlet of the second SCR device based on an operating model that includes a combination of the first SCR device and the second SCR device.

[0006] According to one or more embodiments, an exhaust system for treating exhaust gas emitted by an internal combustion engine, performs a selective catalytic reduction (SCR) of exhaust gas. The exhaust system includes a first SCR device, and a controller to control reductant injection into the exhaust gas. The controlling of the reductant injection includes determining if the exhaust system includes a second SCR device. In response to the exhaust system including the first SCR device only, the controlling of the reductant injection includes computing an amount of reductant to inject based on a first model of the first SCR device, the first model estimating a first NH3 storage level at the first SCR device. In response to the exhaust system including the second SCR device, the controlling of the reductant injection includes computing the optimal amount of reductant to inject based on a combination of the first model of the first SCR device and a second model of the second SCR device, the combination estimating the first NH3 storage level at the first SCR device and a second NH3 storage level at the second SCR device. The controlling of the reductant injection further includes sending a command to a reductant injector to inject the amount of reductant.

[0007] In one or more examples, the first model uses a first NOx measurement from an inlet of the first SCR device and a second NOx measurement from an outlet of the first SCR device. Further, the second model uses the second NOx measurement from the outlet of the first SCR device and a third NOx measurement from an outlet of the second SCR device. Further yet, in one or more examples, the first model uses a first NH3 estimation from the outlet of the first SCR device and the amount of reductant injected. In one or more examples, the second model uses the first NH3 estimation from an outlet of the first SCR device and a second NH3 estimation from an outlet of the second SCR device. In response to the exhaust system including the second SCR device, computing the optimal amount of reductant includes maintaining a first predetermined trade-off between an amount of NH3 and an amount of NOx at the outlet of the first SCR device and to maintain a second predetermined trade-off between an amount of NH3 and an amount of NOx at the outlet of the second SCR device.

[0008] According to one or more embodiments a computer-implemented method for controlling reductant injection into an emissions control system that includes a first selective catalytic reduction (SCR) device includes determining if the emissions control system includes a second SCR device. In response to the exhaust system including the first SCR device only, the controlling of the reductant injection includes computing an amount of reductant to inject based on a first model of the first SCR device, the first model estimating a first NH3 storage level at the first SCR device. In response to the exhaust system including the second SCR device, the controlling of the reductant injection includes computing the optimal amount of reductant to inject based on a combination of the first model of the first SCR device and a second model of the second SCR device, the combination estimating the first NH3 storage level at the first SCR device and a second NH3 storage level at the second SCR device. The controlling of the reductant injection further includes sending a command to a reductant injector to inject the amount of reductant.

[0009] In one or more examples, the first model uses a first NOx measurement from an inlet of the first SCR device and a second NOx measurement from an outlet of the first SCR device. Further, the second model uses the second NOx measurement from the outlet of the first SCR device and a third NOx measurement from an outlet of the second SCR device. Further yet, in one or more examples, the first model uses a first NH3 estimation from the outlet of the first SCR device and the amount of reductant injected. In one or more examples, the second model uses the first NH3 estimation from an outlet of the first SCR device and a second NH3 estimation from an outlet of the second SCR device. In response to the exhaust system including the second SCR device, computing the optimal amount of reductant includes maintaining a first predetermined trade-off between an amount of NH3 and an amount of NOx at the outlet of the first SCR device and to maintain a second predetermined trade-off between an amount of NH3 and an amount of NOx at the outlet of the second SCR device.

[0010] The above features and advantages, and other features and advantages of the disclosure are readily apparent from the following detailed description when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Other features, advantages and details appear, by way of example only, in the following detailed description, the detailed description referring to the drawings in which:

[0012] FIG. **1** is a generalized illustration of an engine and an associated exhaust aftertreatment system that is configured to treat the exhaust flow produced by the engine;

[0013] FIG. **2** depicts a block diagram of the reductant injection control system according to one or more embodiments; and

[0014] FIG. **3** depicts a flowchart of an example method for determining an amount of reductant to inject into the exhaust system according to one or more embodiments.

DETAILED DESCRIPTION

[0015] The following description is merely exemplary in nature and is not intended to limit the present disclosure, its application or uses. It should be understood that throughout the drawings, corresponding reference numerals indicate like or corresponding parts and features. As used herein, the term module refers to processing circuitry that may include an application specific integrated circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group) and memory module that executes one or more software or firmware programs, a combinational logic circuit, and/or other suitable components that provide the described functionality.

[0016] In general, referring to the configuration shown in FIG. **1**, a schematic diagram depicts an embodiment of an internal combustion engine **12**, a control system **84**, and an exhaust gas treatment system **10**, in accordance with the one or more embodiments. In the description herein, the engine **12** is described as a diesel engine, however, the engine **12** may be a gasoline engine in one or more examples. The exemplary diesel engine **12** and control system **84** comprises a four-cycle internal combustion diesel engine **12** and electronic engine control module (ECM) **238** that may be configured to accomplish the emission control of exhaust gas flow **16** at tailpipe **19**, in accordance with control methods and strategies described herein. The engine may include a known compression-ignition engine having an operating regime that is primarily lean of stoichiometry. Alternatively, diesel engine **12** may include an engine configured to employ any one of a number of engine configurations and associated engine control strategies, and which also includes those having an operational regime (or regimes) that is lean of stoichiometry, e.g., homogeneous-charge compression-ignition engines.

[0017] Diesel engine **12** may be any diesel engine configuration or application, including various vehicular applications (e.g., automotive, marine and the like), as well as various non-vehicular applications (e.g., pumps, generators and the like). During operation, diesel engine **12** generates an exhaust gas feedstream or flow represented by arrows **16** containing regulated and unregulated emission constituents, generally including constituent gases and particulate matter. Exhaust gas treatment system **10** acts to convert regulated constituents, such as, for example, various hydrocarbons (HC), carbon monoxide (CO), nitrides of oxygen (NOx) and particulate matter (PM), to unregulated constituents, such as, for example, nitrogen (N2) and water (H2O).

[0018] The exhaust gas treatment system **10** contains piping, joints, and other suitable flow passage and connection features that, together, define a contained passage configured to receive the exhaust flow **16** from the engine **12** and discharge a treated exhaust flow **16** from a tailpipe **19**. The exhaust gas treatment system **10** includes, as shown, a selective catalytic reduction device (SCR) **24** and an underfloor ammonia-SCR device (uSCR) **25**. The exhaust gas treatment system **10** may further include a Diesel Oxidation Catalyst device (DOC) **22**. Downstream from the DOC **22**, the two SCR devices are connected in series (serial positioning)—the SCR **24** and the uSCR **25** respectively.

[0019] The SCR **24** and the uSCR **25** operate cooperatively to decrease NOx emissions, present in the exhaust gas **16** at engine out, to acceptable concentration levels. In general terms, the gaseous emissions originally contained in the exhaust gas **16**, are treated to limit the quantity of regulated constituents delivered to the atmosphere. A urea injector **236** is positioned upstream of the SCR **24** to inject an amount of urea solution (e.g., AdBlue, DEF) into the exhaust flow **16**.

[0020] The diesel engine **12** is fluidly coupled to an outlet manifold **15** that collects the combustion exhaust products discharged from each cylinder in the engine **12** and consolidates them into the exhaust flow **16** that is delivered to the exhaust gas treatment system **10**.

[0021] The DOC **22** is mounted to the exhaust manifold with an inlet that fluidly communicates directly with the exhaust manifold to receive the exhaust flow **16**. The exhaust flow **16** exits the DOC **22** and flows downstream towards the SCR **24**, for a first selective catalytic reduction and subsequently to the uSCR **25** for a second selective catalytic reduction.

[0022] The DOC **22** may include a combination of platinum (Pt), palladium (Pd), and rhodium (Rh) dispersed as fine particles on a high-surface area base metal oxide such as γ-alumina (γ-Al_2O_3) or a cerium/zirconium oxide (CeO_2—ZrO_2). In one or more examples, the base metal oxide is also present in the SCR **24** anywhere from about 70 g/L to about 150 g/L of available flow volume over the SCR **24**. In further examples, the Pt/Pd/Rh loading on the base metal oxide ranges from about 1 to about 7 g/L of available flow volume over the SCR **24**.

[0023] In one or more examples, the SCR **24** includes one or more components that utilize a reductant **246** and a catalyst to transform NO and NO_2 in the exhaust gas **16**.

[0024] The SCR catalyst composition for the SCR **24** and the uSCR **25** is generally a porous and high surface area material, which can operate efficiently to convert NO_x constituents in the exhaust gas **16** in the presence of a reductant **246**, such as ammonia. For example, the catalyst composition can contain a zeolite impregnated with one or more base metal components such as iron (Fe), cobalt (Co), copper (Cu), vanadium (V), sodium (Na), barium (Ba), titanium (Ti), tungsten (W), and combinations thereof. In a particular embodiment, the catalyst composition can contain a zeolite impregnated with one or more of copper, iron, or vanadium. In some embodiments the zeolite can be a β-type zeolite, a Y-type zeolite, a ZM5 zeolite, or any other crystalline zeolite structure such as a Chabazite or a USY (ultra-stable Y-type) zeolite. In a particular embodiment, the zeolite comprises Chabazite. In a particular embodiment, the zeolite comprises SSZ. Suitable SCR catalyst compositions can have high thermal structural stability, particularly when used in tandem with known particulate filter (PF) devices or when incorporated into SCR devices, which are regenerated via high temperature exhaust soot burning techniques.

[0025] The SCR catalyst composition for the SCR **24** and the uSCR **25** can optionally further include one or more base metal oxides as promoters to further decrease the SO_3 formation and to extend catalyst life. The one or more base metal oxides can include WO_3, Al_2O_3, and MoO_3, in some embodiments. In one embodiment, WO_3, Al_2O_3, and MoO_3 can be used in combination with V_2O_5.

[0026] The uSCR **25** is positioned downstream from the SCR **24** in the under-floor position. In one or more examples, the distance between the SCR **24** and the uSCR **25** ranges from about 3 ft. to about 10 ft. The inlet of the uSCR **25** fluidly communicates with the outlet of the SCR **24** to receive the exhaust flow **16**. The outlet of the uSCR **25** communicates the exhaust flow **16** downstream towards the tailpipe opening **19** that emits the exhaust flow to atmosphere.

[0027] The uSCR **25** may include fine particles of (1) a base metal ion-substituted zeolite and/or a base metal ion-substituted silicoaluminophosphate and (2) an oxygen storage material. Zeolites and silicoaluminophosphates are open-framework, microporous, and ammonia absorbent polymorphic molecular sieve materials that are preferably ion-substituted with Cu or Fe. The base metal ion-substituted particles are present in the uSCR **25**, in total, anywhere from about 120 g/L to about 180 g/L of available flow volume over the uSCR **25**, in one or more examples. The oxygen storage material is a metal oxide or a mixed metal oxide that exhibits oxygen storage and release capacity. In one or more examples, the oxygen storage material is present in the uSCR catalyst **25** anywhere from about 5 g/L to about 50 g/L of available flow volume over the uSCR **25**. Any suitable distribution of the particulate materials may be employed. The fine particles of the base metal ion-substituted zeolite/silicoaluminophosphate and the oxygen storage material may, for example, be uniformly mixed within a single washcoat layer or, alternatively, relegated to separate and discrete contacting washcoat layers or zones. The oxygen storage material may also be concentrated near the inlet or the outlet of the uSCR **25** or in some other non-uniform distribution.

[0028] The base metal ion-substituted zeolites that may be used to prepare the uSCR **25** include a Cu or Fe substituted β-type zeolite, Y-type zeolite, ZSM-5 zeolite, Chabazite zeolite, or USY (ultra-stable Y-type) zeolite. Further, the base metal ion-substituted silicoaluminophosphates (SAPO) that may be used to prepare the uSCR **25** include a Cu or Fe substituted SAPO-5, SAPO-34, or SAPO-44. Some specific metal oxides or mixed metal oxides that may be included in the uSCR **25** as the oxygen storage material are cerium-containing and praseodymium-containing metal oxides or mixed metal oxides such as CeO_2, Pr_6O_{11}, CeO_2—ZrO_2, CuO—CeO_2, FeO_x—CeO_2 ($1.0 \leq X \leq 1.5$), MnO_x—CeO_2 ($1.0 \leq X \leq 3.5$), and Pr_6O_{11}—CeO_2. Each of these materials, without being bound by theory, are believed to have crystal lattice structures that can accommodate non-stoichiometric unit cell quantities of oxygen (both higher and lower) without decomposing. This property equates to an ability to reversibly store and release oxygen in response to the partial pressure of oxygen in the exhaust flow **16** and/or equilibrium shifts that accompany the localized consumption of oxygen during NOx reduction.

[0029] When the diesel engine **12** is operating, the exhaust gas treatment system **10** removes the various regulated emissions from the exhaust flow **16** while limiting the amount of ammonia that slips into the exhaust flow **16**. The exhaust flow **16** passes, first, through the close-coupled SCR **24** and, second, through the under-floor uSCR **25**. The combined catalytic activity of the SCR **24** and the uSCR **25** are able to continuously treat the exhaust flow **16** across a robust variety of engine operating conditions. The initial NOx reduction process takes place at SCR **24** where the NOx exiting DOC **22** reacts with NH3 stored in the SCR **24**. Any NOx that escapes past the SCR **24** is reduced at the uSCR **25** with the NH3 stored in the uSCR **25** further reducing levels of NOx concentration in the treated exhaust flow **16**. The NH3 stored in SCR **24** and uSCR **25** comes from the urea injector **236**, while the NH3 stored by uSCR **25** comes from SCRF **24**, when the NH3 is captured by the uSCR **25**. The exhaust gas treatment system **10** further includes a reductant injector system **84** that controls an amount of reductant injected directly into the SCR **24** and indirectly into the uSCR **25**.

[0030] The air/fuel mixture supplied to the engine **12** is constantly adjusted by an electronic fuel injection system (not shown) to achieve a predetermined air to fuel mass ratio, for instance air to fuel ratio may range from 15 to 50, or 15 to 80 on other diesel engine applications. The combustion of the air/fuel mixture in the cylinders of the engine **12** provides the exhaust flow **16** with a relatively large amount of nitrogen (e.g. >70 vol. %.), a small amount of oxygen, and unwanted gaseous emissions comprised of carbon monoxide, HC's, and NOx. The amount of oxygen present is generally less than about 2.0 vol. %. The amount of carbon monoxide, HC's and NOx present is typically about 0.8 vol. % or less, about 800 ppm or less, and about 1500 ppm or less, respectively. The NO_x constituency of the exhaust flow **16** generally includes a large molar proportion of NO (greater than 90 mol %). It should be noted that above values are examples and that in one or more embodiments, the values may be different than those listed above. It is understood that the above values are exemplary and that in one or more examples, the engine **12** can operate with the above measurements being different than those described herein.

[0031] The instantaneous air to fuel mass ratio of the air/fuel mixture, however, may oscillate between 15 to 80 according to the engine calibrations and operating conditions. These oscillations cause the chemical composition of the exhaust flow **16** to vary within particular limits.

[0032] The SCR **24** receives the exhaust flow **16** mixed with the NH3 **246** injected by the urea injector **236**, and stores the NH3. The NO_x gas present in the exhaust gas **16** reacts with the stored NH3. In so doing, the SCR **24** reduces the NO_x contained in the exhaust gas **16** to N_2 and H_2O. In some operative conditions the SCR **24** may slip NH3. This feeds the NH3 to the uSCR **25**, to drive a supplemental catalytic NO_x reduction reaction when NO_x escapes from the first SCR **24**. The NH3 stored in SCR **24** and uSCR **25** comes from the urea injector **236**; the NH3 stored by uSCR **25** coming from SCRF outlet, when the NH3 slips or escapes from SCR **24**.

[0033] The uSCR **25** receives the exhaust flow **16** from the SCR **24**. The uSCR **25** contributes to a further reduction of the NO_x in the exhaust flow **16** by continuously storing the NH3 ammonia slipped from the SCR **24** and making it react with the NO_x downstream of the SCR **24**. The interaction of the two reduction systems SCR **24** and uSCR **25** leads to a substantial reduction of NOx emissions if a suitable amount of reductant **246** (urea NH3) has been injected by the urea injector **236**. Any number of events may slightly diminish the NO_x conversion efficiency of the SCR **24** and permit NO_x to reach the uSCR **25** by way of the exhaust flow **16**. The NO_x that passes through (i.e. slips) the SCR **24** is reduced by the ammonia stored at the uSCR **25**. The ability of the uSCR **25** to accommodate variances in the chemical composition of the exhaust flow **16** and out-of-phase concentration spikes in NO_x and ammonia helps limit the escape of these two substances to atmosphere.

[0034] The oxygen storage material included in the uSCR **25** provides a reserve oxygen supply that enhances the catalytic reduction reaction between ammonia and NO_x. The oxygen storage material absorbs oxygen from the low-oxygen content exhaust flow **16** when NO_x is not present. The accumulated oxygen is then extracted to supplement the sparingly available oxygen in the exhaust flow **16**. This influx of reserve oxygen achieves NO_x reduction efficiency gains in several ways. First, the extra oxygen improves the overall reaction kinetics of the NO_x reduction reactions (both NO and NO_2) since oxygen scarcity can have a rate-limiting effect. Second, the extra oxygen promotes the oxidation of NO to NO_2. This oxidation reaction decreases the NO to NO_2 molar ratio of the NO_x in the uSCR **25**. Such an adjustment is desirable since the overall reduction of NO_x generally proceeds more efficiently when the NO/NO_2 molar ratio is decreased from that originally produced by the engine **12** to, preferably, about 1.0 (equimolar).

[0035] FIG. **2** depicts a block diagram of the reductant injection control system **84** according to one or more embodiments. It should be noted that FIG. **2** depicts a simplified view of the exhaust system and does not depict one or more components, such as the DOC **22**. It should be further noted that in one or more embodiments the reductant injection control system **84** may include additional components than those depicted, and that the depicted block diagram is to describe the technical solutions herein. The SCR **24** and the uSCR **25** receive a reductant **246**, such as at variable dosing rates. Reductant **246** can be supplied from a reductant supply source **234**. In one or more examples, the reductant **246** is injected into exhaust gas conduit **14** at a location upstream of the SCR **24** using a urea injector **236**. The reductant **246** can be in the form of a gas, a liquid, or an aqueous solution, such as an aqueous urea solution. In one or more examples, the reductant **246** can be mixed with air in the injector **236** to aid in the dispersion of the injected spray. The SCR **24** and the uSCR **25** utilize the reductant **246** to reduce the NOx in exhaust **16**.

[0036] The reductant injection control system **84** further includes the control module **238** operably connected, via a number of sensors, to monitor the engine **12**, FIG. **1**, and the SCR devices **24** and **25**. As used herein, the term module refers to an application specific integrated circuit (ASIC), an electronic circuit, a processor (shared, dedicated, or group) and memory that executes one or more software or firmware programs, a combinational logic circuit, and/or other suitable components that provide the described functionality. For example, the control module **238** can execute a SCR chemical model, as described below. The control module **238** can be operably connected to the engine **12**, the SCR **24**, the urea injector **236**, the uSCR **25**, and/or one or more sensors.

[0037] The sensors can include a first NO_x sensor **242**, a second NO_x sensor **243**, and a third NOx sensor **244**, each of which are in fluid communication with the exhaust gas conduit **14**. The NO_x sensors **242**, **243**, **244** detect a NO_x level proximate their location within exhaust gas conduit, and generate a NOx signal, which corresponds to the NOx level. A NOx level can comprise a concentration, a mass flow rate, or a volumetric flow rate, in some embodiments. A NOx signal generated by a NOx sensor can be interpreted by the control module **238**, for example. The control module **238** can additionally be in communication with one or more temperature sensors, such as temperature sensor **32**, FIG. **1**. In one or more examples, the first NOx sensor **242** may be disposed downstream of the engine **12**, at DOC inlet or at DOC outlet, to measure the NOx concentration upstream of SCR **24** so as to detect NOx level at the inlet of the SCR **24**. In the last case, since a NOx sensor is cross-sensitive to ammonia NH3, the NOx sensor **242** is disposed before the urea injector **236**; the second NOx sensor **243** is disposed downstream of the SCR **24** and upstream of the uSCR **25** to detect NOx level at the inlet of the uSCRF **25** (or the outlet of the SCR **24**); and the third NOx sensor **244** is disposed downstream of the uSCR **25** to detect NOx level at the outlet of the uSCR **25**. In one or more examples, the first NOx sensor **242** is located upstream of the DOC **22**, the second NOx sensor **243** is at the outlet of SCR **24**, and the third NOx sensor **244** is at the outlet of uSCR **25**. It should be noted that the positions of the sensors depicted in FIG. **2** are illustrative, and that in one or more embodiments, the sensors may be in different positions than those depicted. Further, in one or more embodiments, a different number of sensors may be used than those depicted herein.

[0038] The reductant **246** can be any compound capable of decomposing or reacting in the presence of exhaust gas **16** and/or heat to form ammonia. When the urea is injected into the hot exhaust gas **16**, the water evaporates and the urea thermally decomposes into NH_3 and CO_2. The NH_3 molecules then are stored in SCR **24** or uSCR **25** components to perform the NOx reduction.

[0039] Equations (1)-(5) provide exemplary chemical reactions for NO_x reduction involving ammonia.

$$6NO+4NH_3\rightarrow 5N_2+6H_2O \tag{1}$$

$$4NO+4NH_3+O_2\rightarrow 4N_2+6H_2O \tag{2}$$

$$6NO_2+8NH_3\rightarrow 7N_2+12H_2O \tag{3}$$

$$2NO_2+4NH_3+O_2\rightarrow 3N_2+6H_2O \tag{4}$$

$$NO+NO_2+2NH_3\rightarrow 2N_2+3H_2O \tag{5}$$

[0040] It should be appreciated that Equations (1)-(5) are merely illustrative, and are not meant to confine the SCR **24** and the uSCR **25** to a particular NOx reduction mechanism or mechanisms, nor preclude the operation of other mechanisms. The SCR **24** and the uSCR **25** can be configured to perform any one of the above NOx reduction reactions, combinations of the above NOx reduction reactions, and other NO_x reduction reactions.

[0041] The reductant **246** can be diluted with water in various implementations. In implementations where the reductant **246** is diluted with water, heat (e.g., from the exhaust) evaporates the water, and ammonia is supplied to the SCR **24** and the uSCR **25**. Non-ammonia reductants can be used as a full or partial alternative to ammonia as desired. Reaction (6) below provides an exemplary general chemical reaction of ammonia production via evaporation and urea decomposition.

$$(NH_2)_2CO+H_2O\rightarrow 2NH_3+CO_2 \tag{6}$$

[0042] It should be appreciated that Equation (6) is merely illustrative, and is not meant to confine the urea or other reductant **246** decomposition to a particular single mechanism, nor preclude the operation of other mechanisms.

[0043] Modeling and optimizing the operation of the two components, SCR **24** and uSCR **25**, is a technical challenge addressed by the technical solutions described herein. In addition, the technical solutions described herein facilitate controlling the operation of both, the SCR **24** and the uSCR **25**, and the resulting NOx from the exhaust gas treatment system **10**, with only one reductant (urea) injector **236** located upstream of SCR **24**. The technical solutions accordingly facilitate a systematic and modular control approach to manage, in a flexible way, both the SCR **24**, and the uSCR **25** architectures with a single controller module **238**. The technical solutions described herein facilitate such flexibility by using a Model Predictive Control (MPC) approach that considers the uSCR **25** and optimizes overall performance of the exhaust gas treatment system **10**, while acting only on the single unique urea injector **236**.

[0044] The controller module **238** extends the MPC beyond just the SCR **24** to optimally determine the urea injection (constrained by the presence of only one single urea injector), while optimizing the trade-off between NOx and NH3 chemical species both at the SCR **24** and uSCR **25** outlets.

[0045] FIG. **3** depicts a flowchart of an example method for determining an amount of reductant **246** to inject into the exhaust gas treatment system **10** according to one or more embodiments. The method **300** is implemented by the controller module **238**. In one or more examples, the controller module **238** executes one or more computer executable instructions that are stored on a computer readable storage device to implement the method. Alternatively, or in addition, the implementation includes the controller module **238** operating according to one or more application specific integrated circuits or field programmable gate array configurations.

[0046] The method **300** includes determining if the uSCR **25** is present and is to be supplied reductant by the reductant injection, at **305**. The determination may be made based on a predetermined flag that is indicative if the uSCR **25** is included in the exhaust gas treatment system **10**. If the uSCR **25** is not to be controlled, the method **300** includes reading a first set of input signals, at **310**. The first set of input signals includes, measurement signals from the first NOx sensor **242** and the second NOx sensor **243**. The first set of input signals can further include temperature measurement of the SCR **24**, and a gas mass flow rate, denoted by F, in the SCR **24**.

[0047] The method further includes estimating an NH3 and NOx output of the SCR **24**, at **320**. The estimation includes using an SCR state observer model of the operation of the SCR **24**. The SCR state observer may include a model based prediction and correction stage. The estimation includes computing an estimated NH3 storage level of the SCR **24**, and further computing an estimate of NOx and an estimate of NH3 at the outlet of the SCR **24**. The SCR state estimation uses an SCR physics model given as follows:

$$\begin{cases} x(k+1) = x(k) + T_s\left(\begin{array}{c} \dfrac{1}{M_{NH3}}(u(k) - y_2(k)) - \dfrac{1}{M_{NOx}} \\ (C_{Nox,in}(k) - y_1(k)) - a_1(k)x(k) \end{array}\right) \\ y_1(k) = \dfrac{F(k)C_{NOx,in}(k)}{F(k) + a_2(k)x(k)} \\ y_2(k) = \dfrac{F(k)(u(k) + a_4(k)x(k))}{F(k) + a_5 - a_3x(k)} \end{cases} \tag{7}$$

[0048] Here, x(k) is an estimated NH3 storage level at the SCR **24** at time interval k, T_s is the sampling or scheduling time at which the aftertreatment control module is iterated in control module **238**, u(k) is the amount of reductant injected, y_1 is the concentration of NO_x at the second NO_x sensor **243**, and y_2 is the concentration of NH_3 at the outlet of the SCR **24**. Further, the estimation uses the concentration of NO_x ($C_{NOx,in}$) at the SCR inlet from the first NOx sensors **242**. F(k) represents the exhaust flow measurement (it may be an estimate) in the SCR **24** at the k-th time instant. Further, the estimation uses multiple pre-calibrated temperature dependent reaction functions a_1-a_5. In the above equation M_{NOx} and M_{NH3} represent the molar mass of NOx and the molar mass of NH3, respectively.

[0049] Referring to the flowchart of FIG. **3** again, the method **300** includes optimizing the amount of reductant (u(k)) that is injected by the reductant injector **236**, into the exhaust gas **16**, at **330**. The controller computes the amount of reductant u(k) to be injected into the exhaust gas, to optimally operate the reduction systems SCR **24** in order to maintain the NOx and NH3 emissions at the outlet of the SCR **24** as low as possible:

$$u(k) = \underset{u}{f}\left(NH3_{in\text{-}k}, \Delta NH3_{in\text{-}k}, NH3_k, NOx_k, wi\right) \tag{8}$$

[0050] Here, wi terms represent weight calibrations, with w_u being a weight calibration for the amount of urea to be injected NH_{3in}, w_{du} being a weight calibration for ensuring a low variation of the injection pattern of reductant. Further, $w_{NOx,SCRF}$ and $W_{NH3,SCRF}$ are weight calibrations based on a tradeoff between NOx and NH_3 at the outlet of the SCR **24**. The control module **238** determines the optimal amount of reductant **246** to be injected so as to minimize a cost function that expresses the system performance, for example a combination of NOx and NH3 concentrations at SCR **24** outlets, NOx reduction efficiency, urea injection efforts, among other factors, at **340** and **350**.

[0051] Referring to the flowchart of FIG. **3** again if it is determined that the uSCR **25** is to be controlled (i.e. the uSCR **25** is part of the exhaust gas treatment system **10**; at **305**) the method **300** includes receiving a second input set, at **360**; else, only the SCRF **24** is used, at **340**. The second input set includes the NOx sensor readings from the first NOx sensor **242**, the second NOx sensor **243**, and the third NOx sensor **244**, the third reading being from the uSCR outlet. The second input set further includes the SCR **24** temperature and an uSCR **25** temperature measured by the one or more temperature sensors at the respective devices. Further, the second input set includes the gas mass flow rates through the SCR **24** and through the uSCR **25**.

[0052] Further, the method includes a model based observer to estimate one or more values for the SCR **24** and the uSCR **25**, at **370**. The estimation includes computing an NH3 storage level at the SCR **24** and at the uSCR **25**. Further, the estimation includes computing NOx and NH3 at the SCR outlet and at the uSCR outlet. The estimations can be based on the following physic-based equation for the uSCR:

$$x_{uSCR}(k+1) = x_{uSCR}(k) + T_s\left(\frac{1}{M_{NH3}}(C_{NH3,in,uSCR}(k) - y_{2,uSCR}(k)) - \frac{1}{M_{NOx}}(C_{NOx,in,uSCR}(k) - y_{1,uSCR}(k)) - a_{1,uSCR}(k)x_{uSCR}(k)\right) \tag{9}$$

$$y_{1,uSCR}(k) = \frac{F_{uSCR}(k)C_{NOx,in,uSCR}(k)}{F_{uSCR}(k) + a_{2,uSCR}x_{uSCR}(k)} \tag{10}$$

$$y_{2,uSCR}(k) = \frac{F_{uSCR}(k)(C_{NH3,in,uSCR}(k) + a_{4,uSCR}(k)x_{uSCR}(k))}{F_{uSCR}(k) + a_{5,uSCR} - a_{3,uSCR}x_{uSCR}(k)} \tag{11}$$

[0053] Here, the $C_{NH3,in,uSCR}$ (k) is the y_2(k) from equation (7) and $C_{NOx,in,uSCR}$(k) is the y_1(k) from the equation (7). $y_{1,uSCR}$(k) and $y_{2,uSCR}$(k) represent the concentration of NOx and NH3 concentration at the uSCR outlet, respectively.

[0054] The method **300** further includes optimizing the amount of reductant (u(k)) that is injected by the reductant injector **236**, at **380**. The optimization includes linearizing a combination of the SCR model and the uSCR model from the equations (7) and (9). The linearized model of the combination of the SCR **24** and the uSCR **25** can be expressed as follows:

$$x(k+1) = A(p(k))x(k) + B_u(p(k))u(k)$$

$$y(k) = C(p(k))x(k),$$

where:

$$x(k) = \begin{bmatrix} \Theta \cdot \theta(k) \\ u(k-1) \\ \Theta_{UF} \cdot \theta_{uSCR}(k) \end{bmatrix}$$

$$u(k) = C_{NH3,in}(k)$$

$$A(p(k)) = \begin{bmatrix} A_{11}(p(k)) & 0 & 0 \\ 0 & 0 & 0 \\ A_{21}(p(k)) & 0 & A_{22}(p(k)) \end{bmatrix}$$

$$B_u(p(k)) = \begin{bmatrix} B_1(p(k)) \\ 1 \\ B_2(p(k)) \end{bmatrix};$$

$$C(p(k)) = \begin{bmatrix} C_1(p(k)) & 0 & 0 \\ C_2(p(k)) & D_2(p(k)) & 0 \\ C_3(p(k)) & 0 & 0 \\ C_m(p(k)) & D_m(p(k)) & 0 \\ C_{12\_1}(p(k)) & 0 & C_{12\_2}(p(k)) \\ C_{22\_1}(p(k)) & D_{22}(p(k)) & C_{22\_2}(p(k)) \\ 0 & 0 & C_{32\_2}(p(k)) \\ C_{m2\_1}(p(k)) & D_{m2}(p(k)) & C_{m2\_2}(p(k)) \end{bmatrix}; \text{ and}$$

$$y(k) = \begin{bmatrix} y_1(k) \\ y_2(k) \\ y_3(k) \\ y_4(k) \\ y_{1,uSCR}(k) \\ y_{2,uSCR}(k) \\ y_{3,uSCR}(k) \\ y_{4,uSCR}(k) \end{bmatrix}.$$

[0055] Here, Θ is the NH3 storage capacity of the SCR **24**, θ(k) is the NH_3 storage level at the SCR **24** at time k, Θ_{UF} is the NH_3 storage capacity of the uSCR **25**, θ_{uSCR}(k) is the NH_3 storage level at the uSCR **25** at time k.

[0056] The method **300** includes optimizing the amount of reductant (u(k)) that is injected into the exhaust gas **16** by the reductant injector **236**, at **390**. The optimization includes solving at real time a numerical optimization problem to determine the optimal amount of urea to be injected so as to minimize a cost function that expresses the system performance. For example, the cost function can include a combination of NOx and NH3 concentrations at SCR outlet and/or uSCR outlet, NOx reduction efficiency, urea injection efforts, and other such parameters described herein.

$$u(k) = \underset{NH3_{in}}{\arg\min}\ f(NH3_{in}, NH3_k, NOx_k, NOx_{UF,k}, NH3_{UF,k}, w_i, \in, \rho_{\in}) \tag{12}$$

[0057] Here, in addition to the terms from equation (8), the w terms include, $w_{NOx,uSCR}$ and $W_{NH3,uSCR}$, which are weight calibrations for NOx measurement at the outlet of the uSCR **25** and an estimated for NH_3 at the outlet of the uSCR **25**, respectively. The controller module **238** accordingly is responsible for computing an optimal amount of reductant to inject to maintain a first predetermined ratio between the amount of NH3 and the amount of NOx at the outlet of SCR **24** and to maintain a second predetermined ratio between the amount of NH3 and the amount of NOx at the outlet of the uSCR **25**.

[0058] The optimization can be solved by using linear and nonlinear programming techniques to determine the amount of reductant **246** to be injected by computing the minimal u(k) per equation (12). The method **300** hence, includes determining the optimal level of reductant **246** to be injected into the exhaust gas treatment system **10**, at **350**. In one or more examples, the optimal level of the reductant **246** is the minimum u(k) that is computed by optimizing the expressions in equation (12) (or in case without the uSCR the equation (8)).

[0059] The controller module **238** instructs the injector **236** to inject the corresponding amount of reductant **246** according to the computed u(k) value. The injector **236** injects the commanded amount of reductant **246** into the exhaust gas treatment system **10** in response.

[0060] The technical solutions described herein facilitate improvements to emissions control systems used with internal combustion engines, such as those used in vehicles. For example, the technical solutions provide a control strategy that optimizes the overall performance of the exhaust gas treatment system composed of an SCR **24** and a uSCR **25** to maintain tailpipe NOx emissions within a predetermined range, and by using only a single reductant (urea) injector **236**, at **340**. Further, the technical solutions facilitate the controller module **238** to operate based on a calibration value that indicates whether the controller module **238** computes an amount of reductant for only the SCR **24** or a combination of both the SCR **24** and the uSCR **25**. The system automatically handles the selected configuration without any manual intervention.

[0061] The technical solutions described herein accordingly optimize the performance of the entire exhaust gas treatment system **10** including the two SCR devices, the SCR **24** and the uSCR **25**, using a single reductant injector **236**. The single reductant injector is controlled to inject a computed amount of reductant that may directly be injected at a first SCR device, such as the SCR **24** and indirectly at the second SCR device, such as the uSCR **25**. The reductant amount is computed using a physics-based model and the amount of reductant is computed in real time by solving a numerical programming problem in the ECM processor. Accordingly, the technical solutions described herein provide a systematic and modular control approach to manage, in a flexible way, both, SCR and/or SCR+uSCR architectures with a single optimal controller and injector system.

[0062] While the above disclosure has been described with reference to exemplary embodiments, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from its scope. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the disclosure without departing from the essential scope thereof. Therefore, it is intended that the present disclosure not be limited to the particular embodiments disclosed, but will include all embodiments falling within the scope thereof.

What is claimed is:

1. An emissions control system for treating exhaust gas from an internal combustion engine in a motor vehicle, the emissions control system comprising:

a reductant injector;

a first selective catalytic reduction (SCR) device;

a second SCR device; and

a model-based controller that is configured to control the reductant injection into the exhaust gas, the controlling of the reductant injection comprising:

determining an amount of NOx and an amount of NH3 at an outlet of the first SCR device;

determining an amount of NOx and an amount of NH3 at an outlet of the second SCR device;

computing an amount of reductant to inject to maintain a first predetermined ratio between the amount of NH3 and the amount of NOx at the outlet of the first SCR device and to maintain a second predetermined ratio between the amount of NH3 and the amount of NOx at the outlet of the second SCR device to ensure the optimal operation of both selective catalytic reduction systems, the first SCR device and the second SCR device; and

sending a command for receipt by the reductant injector to inject the computed amount of reductant.

2. The emissions control system of claim **1**, wherein determining the amount of NH3 at the outlet of the first SCR device is based on computing a first estimated NH3 storage level for the first SCR device, and is further based on receiving a NOx measurement at an inlet of the first SCR device.

3. The emissions control system of claim **2**, wherein determining the amount of NH3 at the outlet of the second SCR device is based on computing a second estimated NH3 storage level for the second SCR device, and the amount of NH3 at the outlet of the first SCR device.

4. The emissions control system of claim **3**, wherein determining the amount of NH3 at the outlet of the second SCR device is further based on receiving a NOx measurement at the outlet of the first SCR device of the first SCR device.

5. The emissions control system of claim **1**, wherein the first SCR device is a SCR filter.

6. The emissions control system of claim **5**, wherein the second SCR device is an underfloor SCR device.

7. The emissions control system of claim **1**, wherein computing the amount of reductant comprises estimating the amount of NH3 and the amount of NOx at the outlet of the second SCR device based on a state observer that includes a combination of physical models for the first SCR device and the second SCR device.

8. An exhaust system for treating exhaust gas emitted by an internal combustion engine, configured to perform a selective catalytic reduction (SCR) of exhaust gas, the exhaust system comprising:

at least a first SCR device;

a controller configured to control injection of a reductant into the exhaust gas, the controlling of the reductant injection comprising:

determining if the exhaust system includes a second SCR device;

in response to the exhaust system including the first SCR device only, computing an amount of reductant to inject based on a first model of the first SCR device, the first model estimating a first NH3 storage level at the first SCR device;

in response to the exhaust system including the second SCR device, computing the optimal amount of reductant to inject based on a combination of the first model of the first SCR device and a second model of the second SCR device, the combination estimating the first NH3 storage level at the first SCR device and a second NH3 storage level at the second SCR device; and

sending a command to a reductant injector to inject the amount of reductant.

9. The exhaust system of claim **8**, wherein the first model uses a first NOx measurement from an inlet of the first SCR device and a second NOx measurement from an outlet of the first SCR device.

10. The exhaust system of claim **9**, wherein the second model uses the second NOx measurement from the outlet of the first SCR device and a third NOx measurement from an outlet of the second SCR device.

11. The exhaust system of claim **9**, wherein the first model uses a first NH3 estimation from the outlet of the first SCR device and the amount of reductant injected.

12. The exhaust system of claim **11**, wherein the second model uses the first NH3 estimation from an outlet of the first SCR device and a second NH3 estimation from an outlet of the second SCR device.

13. The exhaust system of claim **12**, wherein, in response to the exhaust system including the second SCR device, computing the optimal amount of reductant comprises maintaining a first predetermined trade-off between an amount of NH3 and an amount of NOx at the outlet of the first SCR device and to maintain a second predetermined trade-off between an amount of NH3 and an amount of NOx at the outlet of the second SCR device.

14. The exhaust system of claim **12**, wherein the second SCR device is an underfloor SCR device.

15. A computer-implemented method for controlling reductant injection into an emissions control system that comprises a first selective catalytic reduction (SCR) device, the method comprising:

determining if the emissions control system includes a second SCR device;

in response to the emissions control system including the first SCR device only, computing an optimal amount of reductant to inject based on a first model of the first SCR device, the first model estimating a first NH3 storage level at the first SCR device;

in response to the emissions control system including the second SCR device, computing the optimal amount of reductant to inject based on a combination of the first model of the first SCR device and a second model of the second SCR device, the combination estimating the first NH3 storage level at the first SCR device and a second NH3 storage level at the second SCR device; and

sending a command to a reductant injector to inject the amount of reductant.

16. The method of claim **15**, wherein the first model uses a first NOx measurement from an inlet of the first SCR device and a second NOx measurement from an outlet of the first SCR device.

17. The method of claim **16**, wherein the second model uses the second NOx measurement from the outlet of the first SCR device and a third NOx measurement from an outlet of the second SCR device.

18. The method of claim **15**, wherein the first model uses a first NH3 estimation from an outlet of the first SCR device and the amount of reductant injected.

19. The method of claim **15**, wherein, in response to the emissions control system including the second SCR device, computing the optimal amount of reductant comprises maintaining a first predetermined ratio between an amount of NH3 and an amount of NOx at a first outlet of the first SCR device and to maintain a second predetermined ratio between an amount of NH3 and an amount of NOx at an outlet of the second SCR device.

20. The method of claim **15**, wherein the second SCR device is an underfloor SCR device.

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