(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
30 July 2009 (30.07.2009)

PCT

(10) International Publication Number
WO 2009/094255 A2

(51) International Patent Classification:
F01N 3/00 (2006.01) *F01N 3/28* (2006.01)

(21) International Application Number: PCT/US2009/030738

(22) International Filing Date: 12 January 2009 (12.01.2009)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
12/018,583 23 January 2008 (23.01.2008) US

(71) Applicant *(for all designated States except US)*: **CUMMINS FILTRATION IP INC.** [US/US]; 1400 73rd Avenue NE, Minneapolis, MN 55432 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **QI, Baohua** [CN/US]; 6076 Basswood Drive, Columbus, IN 47201 (US). **MCDANIEL, Mickey, R.** [US/US]; 2420 Waldon Drive, Greenwood, IN 46143 (US). **OGUNLEYE, Hakeem** [NG/US]; 4807 Pine Ridge Drive, Columbus, IN 47201 (US). **XI, Clyde** [CA/US]; 3440 West Car Hill Road, Columbus, IN 47201 (US). **MA, Hongbin** [CN/US]; 2093 Oneida Ct., Columbus, IN 47201 (US).

(74) Agent: **SCHUMANN, Michael, D.**; Hamre, Schumann, Mueller & Larson, P.C., P.O. Box 2902, Minneapolis, MN 55402 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

WO 2009/094255 A2

(54) Title: FEEDBACK CONTROL IN SELECTIVE CATALYTIC REDUCTION

(57) Abstract: An apparatus for introducing a reductant into an exhaust system is described. The apparatus includes a controller that generates a resulting dosing command used as an instruction to release an amount of reductant into the exhaust system. The controller includes a feedback control module that generates a weighing factor. The weighing factor is configured to be applied to a lower limit dosing command and configured to be applied to an upper limit dosing command, where the lower and upper limit dosing commands converted by the weighing factor are used by the controller to generate the resulting dosing command.

FEEDBACK CONTROL IN SELECTIVE CATALYTIC REDUCTION

Priority Information

This application is being filed as a PCT International Patent Application in the name of Cummins Filtration IP, Inc. and claims the benefit of priority of US Patent Application Number 12/108583, filed January 23, 2008 and entitled "FEEDBACK CONTROL IN SELECTIVE CATALYTIC REDUCTION," which is hereby incorporated by reference in its entirety.

Field

A control is disclosed that can optimize performance and dosing economy of a reductant used with selective catalyst reduction (SCR) devices, such as in combustion exhaust streams. Particularly, a feedback control is configured to generate a command for a dosing rate of reductant that at least meets $deNO_x$ targets for a system, while also being limited within a maximum allowed dosing rate determined by the maximum allowed NH_3 slip.

Background

Selective catalyst reduction (SCR) devices are widely known and used, and are particularly used in combustion exhaust streams of diesel engines, as one example.

To meet Environmental Protection Agency (EPA) requirements, SCR devices are used to introduce a reductant which reduces NO_x generated in engine exhaust systems. Along with SCR devices, sensory and feedback control capabilities have been employed to detect the presence of NO_x and to introduce a reductant, based on the NO_x detected by the control. The introduced reductant reacts with the NO_x to facilitate its reduction. Feedback control modules can greatly improve NO_x reduction or "$deNO_x$" performance.

However, due to cross-sensitivity of sensors employed in known feedback control modules, NH_3 (e.g. ammonia) that is present in the system also is read as NO_x by the sensor (known as an "NH_3 slip"). The NH_3 slip is unwanted emissions caused by limited catalyst capability. When the control system generates a certain amount of NH_3 slip, the NO_x sensor reports the NH_3 slip as NO_x due to its dual sensitivity to NH_3. As electrochemical sensors are typically used in such SCR devices in order to keep costs down, rather than optical sensors which are significantly more expensive (e.g. Fourier Transform Infrared Spectroscopy (FTIR) sensors), such cross-sensitivity of the sensor has been known to occur. The incorrect sensing information triggers false positive feedback, causing reductant introduction into the system at higher dosages, which can lead to an unstable system and reductant waste.

Thus, improvements can still be made to SCR devices, particularly those using a feedback control and improvements can still be made to limit overall reductant dosing.

Summary

The following technical disclosure describes an improved dosing control that can help optimize reduction of NO_x in engine exhaust material, while limiting introduction of a reductant into an exhaust system, and while meeting dosing requirements, for example EPA dose requirements. Generally, the dosing control is configured to generate a resulting dosing command through a weighing factor, where the weighing factor is applied to process upper ("limit") and lower (feed-forward) limit dosing commands to generate the resulting dosing command.

In one embodiment, an apparatus for introducing a reductant into an exhaust system includes at least one sensor configured to detect NO_x produced during engine combustion, and includes a controller operatively connected with the sensor. The controller is configured to receive an output of NO_x detected by the sensor. The controller is configured to process the output from the sensor and generate a resulting dosing command having an instruction to introduce a reductant into the exhaust system. The resulting dosing command is generated with a weighing factor and from a lower limit dosing command (feed-forward dosing command), which is determined by emission requirements or targets, and from an upper limit dosing command ("limit" dosing command), which is limited by the maximum allowed NH_3 slips. The weighing factor is configured to be applied to the lower and upper limit dosing commands, such that the weighing factor processes the lower and upper limit dosing commands into end values of the resulting dosing command.

In one embodiment, the controller includes a feedback control module configured to receive the output from the sensor and generate the weighing factor. In yet another embodiment, the feedback control module is configured to only adjust the weighing factor and apply it to the lower and upper limit dosing commands for processing.

In one embodiment, the controller is configured to periodically update the resulting dosing command, where the sensor is configured to periodically detect NO_x produced and the controller periodically generates an updated resulting dosing command.

As one example only, the dosing control described is useful with selective catalytic reduction devices for combustion engine exhaust systems. For instance, at least one sensor is operatively connected to an outlet of a selective catalyst reduction device. A doser is operatively connected to the controller and connected to the selective catalyst reduction device, where the doser is configured to receive the resulting dosing command from the

controller and configured to introduce the reductant into the exhaust system at the outlet of the selective catalyst reduction device. The amount of reductant introduced is based on the resulting dosing command received from the controller.

In another embodiment, a method of controlling introduction of a reductant into an exhaust system includes calculating a lower limit dosing command and calculating an upper limit dosing command. An emission level is calculated based upon a detected NO_x output and is compared to an emission target, where an emission error thereby is generated. Through a feedback controller, a weighing factor is generated based on the emission error. A resulting dosing command is calculated using the lower (feed-forward) and upper ("limit") limit dosing commands together with the weighing factor.

Other features of novelty and various advantages of the disclosure are pointed out in the following detailed description. For a better understanding of such features and their advantages, reference should also be made to the drawings which form a further part hereof, and to the accompanying descriptive matter, in which there are illustrated and described various embodiments of the inventive concepts.

Brief Description of the Drawings

FIG. 1 is a schematic view of one embodiment of a dosing control apparatus being used with one schematic example a system for combustion exhaust stream including an SCR doser driver/doser device.

FIG. 2 is a schematic view for one embodiment of a feedback control module in the dosing control apparatus shown in FIG. 1.

FIG. 3 is a schematic view of one embodiment of a NO_x sensor value compensation component of the feedback control module of FIG. 2.

FIG. 4 is a graph showing a relationship between a NH_3 to NO_x ratio (ANR) in reaction and NO_x conversion efficiency.

FIG. 5 is a schematic view of one embodiment of a procedure for determining a lower limit dosing command for use in generating a resulting dosing command.

FIG. 6 is a schematic view of one embodiment of a procedure for calculating catalyst efficiency in determining an upper limit dosing command for use in generating a resulting dosing command.

FIG. 7 is a graph showing a relationship between NH_3 to NO_x ratio in reaction and each of deNOx efficiency and deNH3 efficiency.

FIGs 8A and 8B are a set of graphs showing a piece-wise linearization in a $deNH_3$ efficiency calculation.

FIG. 9 is a schematic view of one embodiment of a procedure for calculating upper limit dosing command.

FIG 10 illustrates a schematic representation of a general selective catalyst reduction exhaust system as known in the art.

Detailed Description

Generally, a dosing control as described herein includes a configuration to generate a resulting dosing command through a weighing factor, where the weighing factor is applied to upper and lower limit dosing commands to generate end values of the resulting dosing command. The control can provide optimized reduction of NO_x in engine exhaust material, without excessive introduction of a reductant into an exhaust system, and while still meeting needed reductant doses, such given by EPA requirements.

A unique control scheme is presented, where the dosing command generation includes a feed-forward command (i.e. lower limit) generation and a limit command generation (i.e. upper limit), where both commands are processed using the weighing factor. For example, in feed-forward command generation the necessary amount of dosing for meeting emission requirements or targets is generated (i.e. EPA requirements), while in limit command generation the maximum allowed dosing rate is provided, which is limited by the maximum allowed NH_3 slip. The weighing factor is generated for adjusting the resulting dosing command to be within dosing rate values generated in the feed-forward command generation and the limit command generation. Thereby, a tradeoff is made between the best performance (limit command generation) and the best urea dosing economy (feed-forward command generation) by using the weighing factor.

As one example, a NO_x slip value acquired from a NO_x sensor downstream of an SCR device is screened, and a trustable NO_x slip value is evaluated for generating the weighing factor. Such a control helps to avoid system instabilities, since a weighing factor rather than the control system gains is modified, and an adjustment range of the resulting dosing command is limited within the dosing commands generated in the feed-forward command generation and the "limit" command generation while using the weighing factor. Using such a control design, the necessary dosing command is provided (i.e. EPA standards), while $deNO_x$ performance and dosing economy are optimized. It will be appreciated that the control described herein can be easily calibrated to function with multiple SCR configurations and engines.

FIGs 1-9 generally illustrate one non-limiting embodiment of an apparatus for generating a dosing command for introducing a reductant, for example, into a combustion engine exhaust system. As one particular application, the apparatus described herein is useful for introducing a reductant to reduce NO_x exhaust material generated by an exhaust system employing a selective catalyst device. As shown, FIG. 1 is a schematic view of one embodiment of the apparatus as a dosing control. In one embodiment, the dosing control is shown incorporated with a selective catalyst reduction device (Doser Driver/Doser/SCR Plant) 103. The apparatus includes a sensor S (101) that detects NO_x at an outlet of a SCR device, and that outputs the NO_x detection to a dosing controller 100. The controller processes the feedback values from the sensor S (101) and calculates a weighing factor (Feedback Dosing Cmd. Calc.) to be used for generating the resulting dosing command in a dosing command generation module 104 (Dosing Cmd. Generation).

In one embodiment, the sensor S (101) and weighing factor generation are configured in a feedback control module 102 (Feedback Dosing Cmd. Calc.), where a NO_x level output from the selective catalyst device is used to generate the weighing factor for adjusting the resulting dosing command. A dosing command generation module 104 (Dosing Command Generation) uses the weighing factor to process an upper limit dosing command generated in a module 105 ("Limit" Dosing Cmd. Calc.) and a lower limit dosing command provided by a module 107 (Feed Forward Cmd. Calc.). In one embodiment, the upper limit dosing command is generated by using inputs that include the maximum allowed NH_3 slips (Max. Allowed NH_3 Slip) and the NO_x concentration at the selective catalyst reduction device (NO_x Concentration at SCR inlet). In one embodiment, the lower limit dosing command is generated by using inputs that include the maximum allowed NO_x concentration at an outlet of a selective catalyst reduction device (Max. Allowed NO_x Con. At SCR Outlet) and the NO_x concentration at an inlet of the selective catalyst reduction device (NOx Concentration at SCR inlet).

As further shown in FIG. 1, the dosing control may also use additional inputs for generating the resulting dosing command. For example, such inputs may include, but are not limited to, a catalyst NOx conversion efficiency (deNOx efficiency) calculation (module 106, Eff. Calculation) which may be applied as an input in the generation of each of the upper limit and lower limit dosing commands. In one embodiment, the deNOx efficiency calculation is dependent upon various parameters that include, for example, (1) the temperature (Catalyst T) of the selective catalyst reduction device, (2) exhaust flow rate/space velocity (Exh. Flow), and (3) the split ratio of NO2 to NO at SCR inlet (NO_2/NO Split at SCR inlet). Additionally, (4) the NH_3 concentration or dosing level, and (5) overall NO_x level or NO_x concentration at the inlet of the selective catalyst reduction (SCR) device, can also be included in efficiency calculation. Catalyst temperature affects both SCR reaction types and reaction rate, while exhaust flow changes SCR reaction rate by changing exhaust air residence time in catalyst. At a given catalyst temperature and exhaust flow, especially at low temperature, the SCR device is at its highest efficiency when the NO_2/NO ratio is 1:1 (fast-SCR). When NO is dominant, the SCR device typically operates at its standard efficiency (standard-SCR). However, if there is more NO_2 than NO, then the SCR device may become less efficient. Such factors are known to affect deNO_x and deNH_3 efficiency calculations.

By using the weighing factor, the resulting dosing command is calculated based on the upper limit and lower limit dosing commands (described in detail below). The resulting dosing command then is used as an instruction to the SCR device so that a doser and doser driver may introduce a reductant into the exhaust system. In one embodiment, the reductant to be introduced is urea. It will be appreciated to one of skill in the art, however, that other known reductants may be employed if desired or necessary.

As another example of an additional input (FIG. 1), the control may include a value of NH_3 storage compensation (NH3 Storage) module 108. The NH_3 storage compensation value may include inputs such as the temperature of the SCR device (Catalyst T), exhaust flow (Exh. Flow), and the NO_2/NO ratio or the NO_x split at the SCR device inlet.

FIG. 2 is a schematic view of one embodiment of the feedback control module 102 in the dosing control depicted in FIG. 1. Generally, the feedback control module does not directly control the resulting dosing command. Rather, the feedback control module modifies the weighing factor so that the weighing factor can be used to process the upper and lower limit dosing commands in generating the resulting dosing command.

The feedback control module includes a block 201 that provides compensation for the NO_x sensor value (NOx Sensor Value Compensation). In one embodiment, the compensation is to address the effects of cross-sensitivity and pressure. As one example, the following formula (Equation 1) represents the cross-sensitivity to NH_3 and NO_2 concentration:

$$NOx_{Act}^{P} = NOx_{Sen}^{P} - k_{NH3}NH_3 + k_{NO2}NO_2$$

where

NOx_{Act}^{P} represents actual NO_x parts per million (ppm) value at pressure P;

NOx_{Sen}^{P} represents NO_x sensor ppm value at pressure P;

k_{NH3} represents coefficient of NH_3 compensation;

NH_3 represents NH_3 ppm value;

k_{NO2} represents coefficient of NO_2 compensation, and

NO_2 represents NO_2 ppm value.

In certain embodiments, $k_{NH3} = 0.9$ as an example and $k_{NO2} = 0.9$ as an example.

In carrying out compensation of the NO_x sensor value, the feedback control module may also be configured to provide pressure compensation. Cross-sensitivity compensation coefficient values and pressure compensation formula are determined by characteristics of the NO_x sensor.

FIG. 3 shows a schematic configuration for correction of the sensing value from a tailpipe NO_x sensor (i.e. SCR device outlet). The sensing value correction includes a cross-sensitivity compensation (block 303), which is calculated based on NH_3 slip and NO_2 slip estimated in block 301 and 302 respectively, and pressure compensation in block 304 using ambient pressure (P) information.

NH_3 slip is estimated using urea dosing command (NH3 Cmd.) and deNH_3 efficiency (deNH3 Eff.), which is calculated in the upper "limit" dosing command generation.

To estimate NO_2 slip, the SCR reactions are simplified using the following assumptions:

Assumption 1. Only two reactions: fast-SCR reaction and standard-SCR reaction are considered;

Assumption 2. Only NO and NO_2 exist in exhaust NO_x to SCR;

Assumption 3. Fast-SCR reaction has absolute priority in the two SCR reactions (i.e., standard-SCR only happens when there is no fast-SCR).

Based on these assumptions, the NO_2 slip is calculated using the equations:

$$when\, C_{NH3} eff_{deNH3} \le \min(C_{NO}, C_{NO2}) eff_{fast\_SCR} \beta,$$
$$C_{NO2}^{slip} = \min(C_{NO}, C_{NO2}) - C_{NH3} eff_{deNH3} / \beta;$$
$$when\, C_{NH3} eff_{deNH3} > C_{NO2} eff_{fast\_SCR} \beta \; and \; C_{NO2} \le C_{NO},$$
$$C_{NO2}^{slip} = C_{NO2}(1 - eff_{fast\_SCR});$$
$$when\, C_{NH3} eff_{deNH3} > C_{NO} eff_{fast\_SCR} \beta \; and \; C_{NO2} > C_{NO},$$
$$C_{NO2}^{slip} = (C_{NO2} - C_{NO} eff_{fast\_SCR})(1 - eff_{deNO2}), \text{ where}$$
$$eff_{deNO2} = (C_{NH3} eff_{deNH3} / \beta - C_{NO} eff_{fast\_SCR}) / (C_{NO2} - C_{NO}).$$

In the equations, C_{NO2} is NO_2 concentration at the SCR inlet; C_{NO} is NO concentration at the SCR inlet; C_{NH3}, is NH_3 concentration at the SCR inlet (dosing cmd.), and C_{NO2}^{Slip} is

NO_2 slip at tailpipe; eff_{fast_SCR} is NO_x conversion efficiency for fast SCR reaction; eff_{deNH3} is NH_3 conversion efficiency; eff_{deNO2} is NO_2 conversion efficiency, and β is NH_3 to NO_x reaction ratio.

Turning back to FIG. 2, once compensation of the NO_x sensor value has been performed, the feedback control module is configured to provide for screening of the NO_x sensing value in a block 202 (NOx Sensing Value Screening). In some embodiments, certain NO_x sensing values are used in the feedback control module. For example, NOx sensing values at a steady state may be used in the feedback control module, NO_x sensing values within a trustable range may be used in the feedback control module, NO_x sensing values with a valid compensation may be used in the feedback control module, and average NO_x sensing values may be used in the feedback control module.

Accurate screening of the NO_x sensing value is dependent on various conditions. Such conditions which may affect accurate screening of the NO_x sensing value include, for example, NO_x value changing rate and SCR bed temperature. When the SCR bed temperature is too low or too high, such as due to the error and uncertainties in estimating NH_3 slip and NO_2 slip, NO_x value compensation may not be accurate, thereby affecting NO_x sensing value accuracy. Further, where there exists a large difference between SCR inlet temperature and SCR outlet temperature (i.e. a large difference between exhaust gas temperature and bed temperature), uncertainty may be induced in estimating catalyst capability, which may affect the accuracy of the NO_x sensing value.

Other conditions which may affect accurate NO_x sensing values include exhaust flow rate. Where the exhaust flow is too low, urea distribution may be non-uniform, therefore affecting NO_x sensing accuracy. Where the exhaust flow is too high, due to higher uncertainty in the exhaust flow sensor, estimates of NH_3 slip and NO_2 slip could be affected resulting in deterioration of NO_x sensing accuracy.

Still other conditions which may have an affect on NO_x sensing value accuracy include, NO_x concentration, where a NO_x sensing value may only be accurate within a certain NO_x concentration range. Likewise, accurate sensing of NO_x value may depend upon other operation conditions, such as ambient pressure, and the presence of NH_3 slips and NO_2 slips.

Once screening of the NO_x sensing value has been performed, the feedback control module is configured to provide evaluation of the NO_x level. In some embodiments, evaluation of the NO_x level includes evaluation of the tailpipe NO_x level (Block 203, Tailpipe NOx Level Evaluation). One purpose of SCR device control is to limit the NO_x level at the tailpipe within a range, while considering dosing economy, performance, and sensitivity to sensor uncertainties. The feedback control module is configured to perform NO_x level evaluation by calculating the average NO_x level at the tailpipe during a calibratable period of time. As one example, the tailpipe NO_x level limits may include a range such as from 1.6g/kwh to 1.9g/kwh (e.g. for Euro5 standard). It will be appreciated that the feedback control module periodically updates NO_x level value with a calibrated rate.

Once evaluation of the NO_x level has been performed, the feedback control module is configured to perform an error generation in a block 204 (Error Generation). In performing error generation, the feedback control module may set a target NO_x range at the tailpipe as a command for the control system. In one embodiment, the target NO_x range includes an upper value (Tailpipe NO_x_Limit_Hi) and a lower value (Tailpipe NO_x_Limit_Lo).

In one embodiment, the feedback control module compares the above evaluation of the NO_x level or NO_x emission with the target NO_x range values, and generates an error. If NO_x emission is higher than the upper value (i.e. Tailpipe NO_x_Limit_Hi, then the error generated is: Tailpipe NO_x_Limit_Hi - NO_x_emission. Otherwise, if NO_x emission is lower than NO_x_Limit_Lo, then the error generated is NO_x_Limit_Lo - NO_x_emission. However, if NO_x emission is within NO_x_Limit_Hi and NO_x_Limit_Lo, then the error is 0. (i.e. target value is within range).

In one embodiment, the feedback control module includes a proportional integral derivative (PID) controller in a controller block (FDBK Controller (P)) 205. It will be appreciated that the feedback control module is not necessary limited to a proportional-integral-derivative controller, and may be any suitable control feedback loop mechanism used in industrial control systems. Generally, the feedback control module is configured to correct an error between a measured process variable and a desired set point by calculating and then outputting a correction action that can adjust the process accordingly.

The PID controller is used to calculate a control signal, which is the weighing factor value, from the error values. The PID converts error values to control values (weighing factor values). By way of example only, if a weighing factor change of 0.2 (unitless) is desired, when an error of 0.5 g/kwh is present, a gain of 0.4 would be needed to do the calculation. In other examples, if there is a desire to accumulate the error for adjustment, an integrator may be used.

The result value generated in the controller block 205 is then further processed in a block 206 (Weighing Factor Generation). In the block 206, the system determines if the value generated in feedback control can be used as the weighing factor. In case of, e.g., sensor errors, or no update for a long time, when feedback values are not trustable, the system uses values generated using other means, e.g., using lookup tables, rather than that generated by the feedback controller. The weighing factor is generated using the feedback control module described above and the dosing control applies the weighing factor to the lower (feed-forward) and upper ("limit") limit dosing commands in generating the resulting dosing command.

As above, dosing control is configured to periodically update the resulting dosing command through the feedback control module. In another embodiment, the dosing control may be configured to include at least one look-up table as an input for generating the weighing factor if necessary, such as when the sensor fails or when the resulting dosing command is not updated for a period of time by the feedback control module. Some exemplary look-up tables may include but are not limited to an input of engine speed and an input of total fueling.

Among its benefits, the feedback control module is a "safe" control, since the resulting dosing command may only be adjusted within a range as allowed by emission requirements. Feedback control can be used to suitably adjust the resulting dosing command for uncertainties in SCR inlet NOx estimations and variations in system parameters due to ambient changes and catalyst aging. Different from previous feedback control designs, the feedback control herein does not control reductant dosing by directly using sensed NO_x, rather sensed NO_x are processed to estimate emission level. The processed values are used to generate a weighing factor, which may be later updated or modified for periodically adjusting the resulting dosing command. That is, the feedback control module of the dosing control may modify dosing indirectly as needed, where the input for generating the command uses information gained from the exhaust output.

Turning to generation of the lower and upper limit dosing commands, FIGs 4-9 show exemplary configurations that the dosing control may employ for generating the lower (feed-forward) and upper ("limit) limit dosing commands. In one embodiment, the lower limit dosing command is a calculation based on, for example, known emission requirements or targets for the exhaust system, and the upper limit dosing command is a calculation based on the maximum allowed ammonia slips.

FIG. 4 shows a relationship between a NH_3 to NO_x ratio in reaction and NO_x conversion efficiency. FIG. 5 shows a schematic view of one embodiment of a procedure for generating the lower limit dosing command. In one embodiment, the dosing control calculates the lower limit dosing command, which is referred as the needed dosing command or feed-forward dosing command (FF dosing command in FIG. 5). Generally, the feed-forward dosing command is calculated as the reference at which the system is able to meet the minimum required reductant dose (i.e. EPA requirements). For example, the feed-forward dosing command is based on temperature, exhaust flow, other engine operating conditions as known in the art, such as engine speed.

FIG. 4 shows a graph of a relationship between a NH_3 to NO_x ratio in reaction and NO_x conversion efficiency. In one embodiment for calculating the feed forward dosing command, the dosing control is configured to consider the following equations:

(Equation 2)

$$\eta = (C_{NH3} / C_{NOx})\alpha / \beta$$

where

β represents NH_3 to NO_x ratio in reaction (β changes with NO_2/NO ratio);

C_{NOx} represents NO_x concentration at the SCR device inlet;

C_{NH3} represents NH_3 concentration at the SCR device inlet (the lower limit dosing command is calculated using C_{NH3})

α represents deNO_x efficiency when ANR equals β (ANR: Ammonia to NO_x Ratio); and

η represents deNO_x efficiency.

When the $NH_3/NO_x \leq \beta$, the following Equation 3 also may be considered by the dosing control.

(Equation 3)

$$C_{NOx}\eta = C_{NOx} - C_{Slip}^{NOx}$$

where

$C_{NOx}\eta$ represents NO_x reacted in catalyst;

C_{NOx} represents NO_x at the SCR device inlet; and

$C_{Slip}{}^{NOx}$ represents NO_x slip (emission) at the SCR device outlet.

However, where $NH_3/NO_x > \beta$, then the catalyst is not capable, as the feed forward command equals limit command, which is further described below with respect to FIG. 5.

According to equations (2) and (3), the NH_3 concentration C_{NH3} is:

(Equation 4)

$$C_{NH3} = \beta(C_{NOx} - C_{slip}^{NOx}) / \alpha$$

Turning back to FIG. 5, a procedure for the dosing control to generate the lower (feed-forward) limit dosing command is illustrated. A determination on whether the (NO_x_in – NO_x_target)/NO_x_in > Max_deNO_xeff (α) is made. ("NO_x_in" is the NO_x flow rate at the

SCR inlet, while "NO_x_target" is the target NO_x flow rate determined by emission requirements.) If yes (Y), then the catalyst is not capable ($NH_3/NO_x > \beta$), and the feed forward command equals the limit command. If no (N), then Equation 4 is used to calculate the lower limit or feed forward dosing command.

FIG. 6 shows one example of such a procedure for a catalyst efficiency calculation for use in calculating the upper limit dosing command. In FIG. 6, Ta is defined as a low temperature limit for dosing (T_min). The limit Ta is a function of space velocity (Sv), which is calculated based on exhaust flow rate and catalyst size (Sv = Exhaust Volumetric Flow Rate/Catalyst Volume), and NO_2 to NO ratio: Ta= f_a (Sv, NO_2/NO). The NO_x conversion efficiency at ANR of β and temperature of Ta is Ea, and Ea is also a function of space velocity and NO_2 to NO ratio: Ea= g_a (Sv, NO_2/NO). The lightoff temperature in FIG. 6 is Tb. Tb is a function of space velocity and NO_2 to NO ratio: Tb= f_b (Sv, NO_2/NO). The NO_x conversion efficiency at ANR of β and temperature of Ta is Eb, and similar as Ea, Eb = g_b (Sv, NO_2/NO). A determination is made on whether $T \geq Ta$, where T is the catalyst temperature. If no (N), then the catalyst efficiency calculation ends. If yes (Y), then a determination is made whether $T \geq Tb$. If no (N), then a linear equation Eff. = (T-Ta)(Eb-Ea)/(Tb-Ta) is used to perform the efficiency calculation.

When catalyst temperature is too high, due to the oxidation of NH_3 back to NO_x, the deNO_x conversion efficiency will decrease. T1 is defined as the temperature at which deNO_x efficiency starts to decrease and T2 represents the high temperature limit for dosing, and as that for Ta and Tb, T1= f_1 (Sv, NO_2/NO), T2= f_2 (Sv, NO_2/NO). The deNOx efficiency at ANR of β and temperature T1 is E1, E1= g_1 (Sv, NO_2/NO). The deNOx efficiency at ANR of β and temperature T2 is E2, E2= g_2 (Sv, NO_2/NO). As further shown in FIG. 6, if the temperature T is in between T1 and Tb, then an equation Eff. = $1 - \exp(-K*T^{1.5}/Sv)$ is used to perform the efficiency calculation, where K is a coefficient determined by Sv and NO_2/NO: K= h_k (Sv, NO_2/NO). A linear equation, Eff. = (T-T1)(E2-E1)/(T2-T1), is used for calculating efficiency for catalyst temperature higher than T1 and lower than T2. If catalyst temperature higher than T2, dosing is disabled.

It will be appreciated that the efficiency calculation may be an input of either or both the lower (feed-forward) and upper ("limit") limit dosing commands. The efficiency calculation as an input for the feed-forward dosing command is not shown, however, one of skill in the art would be able to determine an efficiency calculation as an input for calculating the feed-forward dosing command using known methods. Based on the deNO_x efficiency at ANR of β, both deNO_x efficiency and deNH_3 efficiency can be obtained. FIG. 4 shows the relationship between ANR and $deNO_x$ efficiency, while FIG. 7 is a graph showing a relationship between NH_3 to NO_x ratio in reaction and both of deNOx efficiency (I) and $deNH_3$ efficiency (II). As one exemplary calculation, Equation 5 below may be employed for determining $deNH_3$ efficiency is:

(Equation 5)

$deNH_3$_efficiency = $deNO_x$_efficiency (η)* β/ANR

Turning specifically to the upper ("limit") limit dosing command, the dosing control design calculates the upper limit dosing command, which is also called the "limit" dosing command. Generally, the "limit" dosing command is calculated as the reference at which a maximum reductant dosage is allowed for the system.

As shown in the equations for calculating $deNO_x$ and $deNH_3$ efficiencies, an ANR value is needed for the calculation. However, in "limit" dosing command generation, the NH_3 concentration in the ANR (dosing level) is a term that is determined by using $deNO_x$ or $deNH_3$ efficiency. Consequently, a "loop" exists in the calculation process resulting in an equation that needs to be solved for obtaining the "limit" dosing command.

To avoid solving non-linear equations in SCR control, a piece-wise linearization method can be used. FIGs 8A and 8B show a set of graphs showing the piece-wise linearization in $deNH_3$ efficiency calculation respectively using ANR and NAR. In FIG. 8A, β, β_1, and β_2 are break points; e_α, $e_{\alpha 1}$, and $e_{\alpha 2}$ are, respectively, the $deNH_3$ efficiency at β, β_1, and β_2. In FIG. 8B, NAR is NO_x to Ammonia Ratio: NAR = 1/ANR; γ, γ_1, and γ_2 are break points corresponding to β, β_1, and β_2: ($\gamma = 1/\beta$, $\gamma_1 = 1/\beta_1$, $\gamma_2 = 1/\beta_2$). Using NAR for linearization avoids solving second-order equations in calculating "limit" dosing command and can provide a more accurate catalyst efficiency calculation.

Referring to FIG. 9, the dosing control design may employ the following equations in generating the "limit" dosing command and incorporating $deNH_3$ efficiency as the basis for determining catalyst efficiency.

For example, when NAR$\leq \gamma$ (i.e., ANR $\geq \beta$), the $deNO_x$ efficiency is approximately constant at α. The "limit" dosing command can be calculated using Equation 6:

$$C_{NH3} = C_{Slip}^{NH3} + \alpha\beta C_{NH3},$$

where C_{slip}^{NH3} is the NH_3 slip at SCR outlet.

When NAR > γ, and more specifically, when γ <NAR$\leq \gamma_1$, the $deNH_3$ efficiency is θ in the following Equation 7:

(Equation 7) $\theta = k_1(NAR) + b_1$

where in Equation 7, the coefficient k_1 and parameter b_1 are calculated, respectively, using Equation 8 and Equation 9:

(Equation 8) $k_1 = (e_a - e_{a1})/(\gamma - \gamma_1)$

(Equation 9) $b_1 = e_{a1} - k_1\gamma_1$;

and when $\gamma_1 < NAR \leq \gamma_2$, the $deNH_3$ efficiency is θ in the following Equation 10:

(Equation 10) $\theta = k_2(NAR) + b_2$

where in Equation 10, the coefficient k_2 and parameter b_2 are calculated, respectively, using equation 11 and equation 12:

(Equation 11) $k_2 = (e_{a1} - e_{a2})/(\gamma_1 - \gamma_2)$

(Equation 12) $b_2 = e_{a2} - k_2\gamma_2$;

when $NAR > \gamma_2$, the $deNH_3$ efficiency is θ in the following Equation 13:

(Equation 13) $\theta = e_{a2}$.

The limit dosing command can be calculated using the following Equation 14:

(Equation 14) $C_{NH3} = C_{Slip}^{NH3} + \theta C_{NH3}$

Above, k1, k2, b1, and b2 are results calculated by using equations 7-12. For example, k1 and k2 functionally are slopes in linear fitting equations for $deNH_3$ efficiency, and b1 and b2 functionally are bias values: $deNH_3$ efficiency = k * (NOx/NH3) + b.

With further reference to FIG. 9, a schematic view of one example of a procedure for calculating the "limit" dosing command is shown. As discussed, the dosing control generates the "limit" dosing command (see FIG. 1) through a series of calculations and value determinations. In one embodiment, e_a, e_{a1}, and e_{a2} are calculated. Then, the dosing commands are calculated as C_{i1}, C_{i2}, C_{i3}, and C_{i4} where

C_{i1} is the NH_3 dosing level C_{NH3} calculated according to Equation 6;

C_{i2} is the NH_3 dosing level C_{NH3} calculated according to Equations 7, 8, 9, and 14;

C_{i3} is the NH_3 dosing level C_{NH3} calculated according to Equations 10, 11, 12 and 14, and C_{i4} is the NH_3 dosing level C_{NH3} calculated according to Equations 13 and 14.

After the dosing commands are calculated, the following determination steps are performed to choose a valid value from C_{i1}, C_{i2}, C_{i3}, and C_{i4}. A determination is made as to whether C_{NOx}/C_{i1} (NAR) is less than or equal to gamma (γ). If yes (Y), then C_{i1} is valid and the value of C_{i1} is used for generating the "limit" dosing command C_i. If no (N), then a determination is made as to whether C_{NOx}/C_{i2} is higher than gamma (γ), but lower than or equal to gamma 1 (γ_1). If in this determination the result is yes (Y), then the value of C_{i2} is used for calculating the upper "limit" dosing command C_i. If in this determination, the result is no (N), then a determination is made as to whether C_{NOx}/C_{i3} is higher than gamma 1 (γ_1), but lower than or equal to gamma 2 (γ_2). If in this determination, the result is yes (Y), then the value of C_{i3} is selected. If no (N), then a determination is made as to whether C_{NOx}/C_{i4} is higher than gamma 2 (γ_2). If in this determination, the result is yes (Y), then the value of C_{i4} is selected. If the result is no (N), then result value C_i for "limit" dosing command generation is the minimum of C_{i1}, C_{i2}, C_{i3}, and C_{i4}.

As described, the upper limit dosing command is generated using linear calculations in at least one ANR regions. Further, in following the linear calculations, a result examination process, which examines if the assumptions for the linear calculations are valid, is used for selecting the valid linear calculation result as the upper limit dosing command.

It will be appreciated that when NAR> γ, or ANR $\leq \beta$ (normal dosing range), the deNH_3 efficiency is not sensitive to ANR or NAR change (FIG. 7 and FIG. 8). As a result, the "limit" dosing command is not sensitive to uncertainties in NO_x sensing value at SCR inlet. A tradeoff thus exists between dosing economy ("limit" dosing command is higher than "feed-forward" dosing command) and system robustness to uncertainties in SCR inlet NO_x estimate ("limit control is less sensitive to uncertainties in SCR inlet NO_x estimate).

Referring back to the weighing factor, once the lower and upper limit dosing commands have been generated, the weighing factor is applied to the lower (feed-forward) limit dosing command and the upper ("limit") limit dosing command in generating the resulting dosing command. In one embodiment, the weighing factor may be applied to the upper limit dosing command in a product of the upper limit dosing command (limit cmd) and the weighing factor (factor), the value of which is within 0 to 1, according to the formula:

limit cmd * factor.

For the lower limit dosing command, the weighing factor may be applied to the lower limit dosing command in a product of the lower limit dosing command (feed-forward cmd) and the difference of 1 and the weighing factor (1-factor), according to the formula:

feed-forward cmd * (1-factor).

The resulting dosing command is the sum of these two values:

Resulting dosing command = feed-forward cmd * (1-factor) + limit cmd * factor.

Since the feed-forward dosing command is always equal or lower than the "limit" command, the above equation sets the resulting dosing command within the range determined by the lower (feed-forward) and upper ("limit") commands. Thus, the resulting dosing command (or actual dosing instruction) to the doser is a specific dosing rate value within the lower and upper limits, and drawn from the range determined by the lower and upper limit commands which appears inside the controller.

Turning to FIG 10, a schematic representation of a general selective catalyst reduction device as known in the art is shown, but incorporated with a dosing control in accordance with the inventive concepts described. In one embodiment of such a device, exhaust air generated in an engine (not shown in the figure) flow through a SCR catalyst 30 for reducing NOx emission. A NO_x sensor 20 (or NO_x estimate, a.k.a. virtual sensor) is at the upstream of the SCR catalyst 30 for detecting NO_x level at SCR inlet (NO_{x}_in). And a temperature sensor 25 is used to measure exhaust air temperature at SCR inlet (T_in). At the down stream of the SCR catalyst 30, a NO_x sensor 45 is installed for sensing tailpipe NO_x slip that is used in the feedback control. Another temperature sensor 40 at the downstream of the SCR catalyst 30 is used together with the SCR inlet temperature sensor 25 for better estimation of the SCR catalyst temperature. All sensors (temperature sensors 25 and 40 and NOx sensors 20 and 45) are connected to an Engine Control Module (ECM), which has the dosing controller running inside. Based on the sensing information, the ECM generates a resulting dosing command and sends the instruction to an injection system 15 that injects a reductant (i.e. urea) from a tank 10 into the SCR catalyst 30.

As described, the dosing control is used for introducing a reductant to reduce NO_x exhaust material, such as that generated by an exhaust system employing a selective catalyst device. In one embodiment of the dosing control, a NO_x sensor is disposed downstream of an SCR device (such as the NO_x sensor 45). The sensor is operatively connected to a controller. It will be appreciated that the controller may be run in a central processing unit (such as the ECM 35) configured to carry out the control functions described, and may be configured to be activated manually or automatically as one of skill in the art could accomplish. As described, the controller receives the output of the sensors, and generates a weighing factor accordingly to be used in processing lower (feed-forward) limit and upper ("limit") limit dosing commands. As one example, the SCR outlet NO_x sensor and weighing factor generation are configured in a feedback control module of the dosing control, where a NO_x level output from the selective catalyst device is used to produce the weighing factor to be used for adjusting the resulting dosing command. The resulting dosing command is then used as an instruction to the SCR device, where the controller delivers the instruction to an injection system such as a doser and a doser driver, so that the doser and doser driver may introduce a reductant into the exhaust system.

In one embodiment, the reductant to be introduced is urea. It will be appreciated, however, that other reductants may be employed if desired or necessary. It further will be appreciated that the dosing control described may be easily calibrated to function with multiple SCR configurations and engines.

As above, NH_3 slips are unwanted emissions. This is because too much NH_3 slip creates an undesirable smell (e.g. at more than 25ppm), as a by-product of SCR reactions. Further, reductant overdosing causes dosing inefficiency and possible false positive feedback due to cross-sensitivity of NO_x sensors. As a result, a maximum dosing command could become saturated (too much reductant is released). However, the dosing control as described herein is configured, such that the upper limit dosing command of the resulting dosing command is dependent upon a maximum allowed ammonia NH_3 slips (i.e. the limit command) so as to avoid such undesired consequences. For example, the NH_3 slip may be maintained to about 25ppm or less.

Among its benefits, the feedback control module is a "safe" control, since the resulting dosing command may only be adjusted within a range as allowed by emission requirements and further limited by the weighing factor. Feedback control can be used to suitably adjust the resulting dosing command for uncertainties in SCR inlet NO_x estimations and for variations in system parameters due to ambient changes and catalyst aging. Different from previous feedback control designs, the feedback control herein does not control reductant dosing by directly using sensed NO_x, rather sensed NO_x are processed to estimate emission level. The processed values are used to generate a weighing factor, which may be later updated or modified for periodic adjusting of the resulting dosing command. That is, the feedback control module of the dosing control may modify dosing indirectly as needed, where the input for generating the command uses information gained from the exhaust output. The feedback control herein further uses a linear method without requiring an iterative process for solving equations, as shown for example in calculating the upper ("limit") dosing commands.

The inventive concepts disclosed herein may be embodied in other forms without departing from the spirit or novel characteristics thereof. The embodiments disclosed in this application are to be considered in all respects as illustrative and not limiting. The scope of the invention is indicated by the appended claims rather than by the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are intended to be embraced therein.

We Claim:

1. An apparatus for generating a dosing command for introducing a reductant into an exhaust system comprising:

at least one sensor configured to detect NO_x produced during engine combustion; and

a controller operatively connected with the sensor, the controller configured to receive an output of NO_x detected by the sensor, the controller configured to process the output from the sensor and generate a resulting dosing command having an instruction to introduce a reductant into the exhaust system, the resulting dosing command including a lower limit dosing command, an upper limit dosing command, and a weighing factor, the weighing factor configured to be applied to the lower and upper limit dosing commands in a calculation to provide the resulting dosing command, such that the resulting dosing command is a value within end values of the lower and upper limit dosing commands.

2. The apparatus of claim 1, wherein the sensor is operatively connected to an outlet of the exhaust system.

3. The apparatus of claim 1, wherein the controller comprises a feedback control module is configured to receive the output from the sensor and generate the weighing factor.

4. The apparatus of claim 3, wherein the feedback control module is configured to only adjust the weighing factor and apply the weighing factor to the lower and upper limit dosing commands.

5. The apparatus of claim 3, wherein the feedback control module is a type of proportional-integral-derivative controller.

6. The apparatus of claim 1, wherein the controller is configured to periodically update the resulting dosing command.

7. The apparatus of claim 1, wherein the controller further comprising at least one look-up table as an input for generating the weighing factor when the sensor fails or when the resulting dosing command is not updated for a period of time.

8. The apparatus of claim 7, wherein the look-up table comprising an engine speed input and a total fueling input.

9. The apparatus of claim 1, wherein the weighing factor, a value of which varies between 0 and 1, applied to the upper limit dosing command comprising a product of the upper limit dosing command (limit cmd) and the weighing factor (factor), according to the formula:

limit cmd * factor, and

the weighing factor applied to the lower limit dosing command comprising a product of the lower limit dosing command (feedforward cmd) and the difference of 1 and the weighing factor (1-factor), according to the formula:

feed-forward cmd * (1-factor).

10. The apparatus of claim 1, wherein the lower limit dosing command comprising a calculation based on known emission requirements, and the upper limit dosing command comprising a calculation based on a maximum allowed ammonia slips.

11. The apparatus of claim 10, wherein the maximum allowed ammonia slips is about 25ppm or less.

12. The apparatus of claim 1, wherein the upper limit dosing command is generated based on linear calculations in at least one ammonia to NO_x region.

13. The apparatus of claim 12, wherein the upper limit dosing command is generated based on a result examination process configured to examine whether the linear calculations are valid, and configured to select the valid linear calculation result as the upper limit dosing command.

14. A method of generating a dosing command to introduce a reductant into an exhaust system comprising:

calculating a lower limit dosing command, the lower limit dosing command comprising a calculation based on a maximum allowed NO_x emission for the exhaust system;

calculating an upper limit dosing command, the upper limit dosing command comprising a calculation based on a maximum allowed ammonia slip;

generating a weighing factor, the weighing factor comprising a calculation based on a detected NO_x output;

processing the lower limit and upper limit dosing commands using the weighing factor; and

generating a resulting dosing command based on a calculation of the processed lower limit and upper limit dosing commands, the resulting dosing command being a value within end values of the lower and upper limit dosing commands.

15. The method of claim 14, wherein generating the weighing factor comprising receiving an output from a sensor using a feedback control module, calculating the weighing factor using the output from the sensor, and delivering the weighing factor to a main controller to process the lower limit and upper limit dosing commands using the weighing factor.

16. The method of claim 14, wherein generating the resulting dosing command comprises periodically updating the resulting dosing command.

17. The method of claim 14, wherein generating the resulting dosing command comprises using at least one look-up table as an input for generating the weighing factor when the sensor fails or when the resulting dosing command is not updated for a period of time.

18. The method of claim 17, wherein the look-up table comprising an engine speed input and a total fueling input.

19. The method of claim 14, wherein the lower limit dosing command comprising a calculation based on known emission requirements, and the upper limit dosing command comprising a calculation based on a maximum allowed ammonia slips.

20. The method of claim 19, wherein the maximum allowed ammonia slips is about 25ppm or less.

21. The method of claim 14, wherein calculating the upper limit dosing command further comprises linearly calculating equations in at least one ammonia to NO_x region.

22. The method of claim 21, wherein linearly calculating further comprises examining the validity of assumptions for the linear calculations, and selecting a valid linear calculation result as the upper limit dosing command.

23. A selective catalyst reduction exhaust system comprising:

a selective catalyst reduction device including an inlet and an outlet;

at least one sensor operatively connected to the outlet of the selective catalyst reduction device, the sensor configured to detect NO_x produced during engine combustion;

a controller operatively connected with the sensor, the controller configured to receive an output of NO_x detected by the sensor, the controller configured to process the output from the sensor and generate a resulting dosing command having an instruction to introduce a reductant into the exhaust system, the resulting dosing command including a lower limit dosing command, an upper limit dosing command, and a weighing factor, the weighing factor configured to be applied to the lower and upper limit dosing commands, the weighing factor configured to convert the lower and upper limit dosing commands to end values of the resulting dosing command; and

a doser operatively connected to the controller and connected to the selective catalyst reduction device, the doser configured to receive the resulting dosing command and configured to introduce the reductant into the exhaust system at the inlet of the selective catalyst reduction device and based on the resulting dosing command.

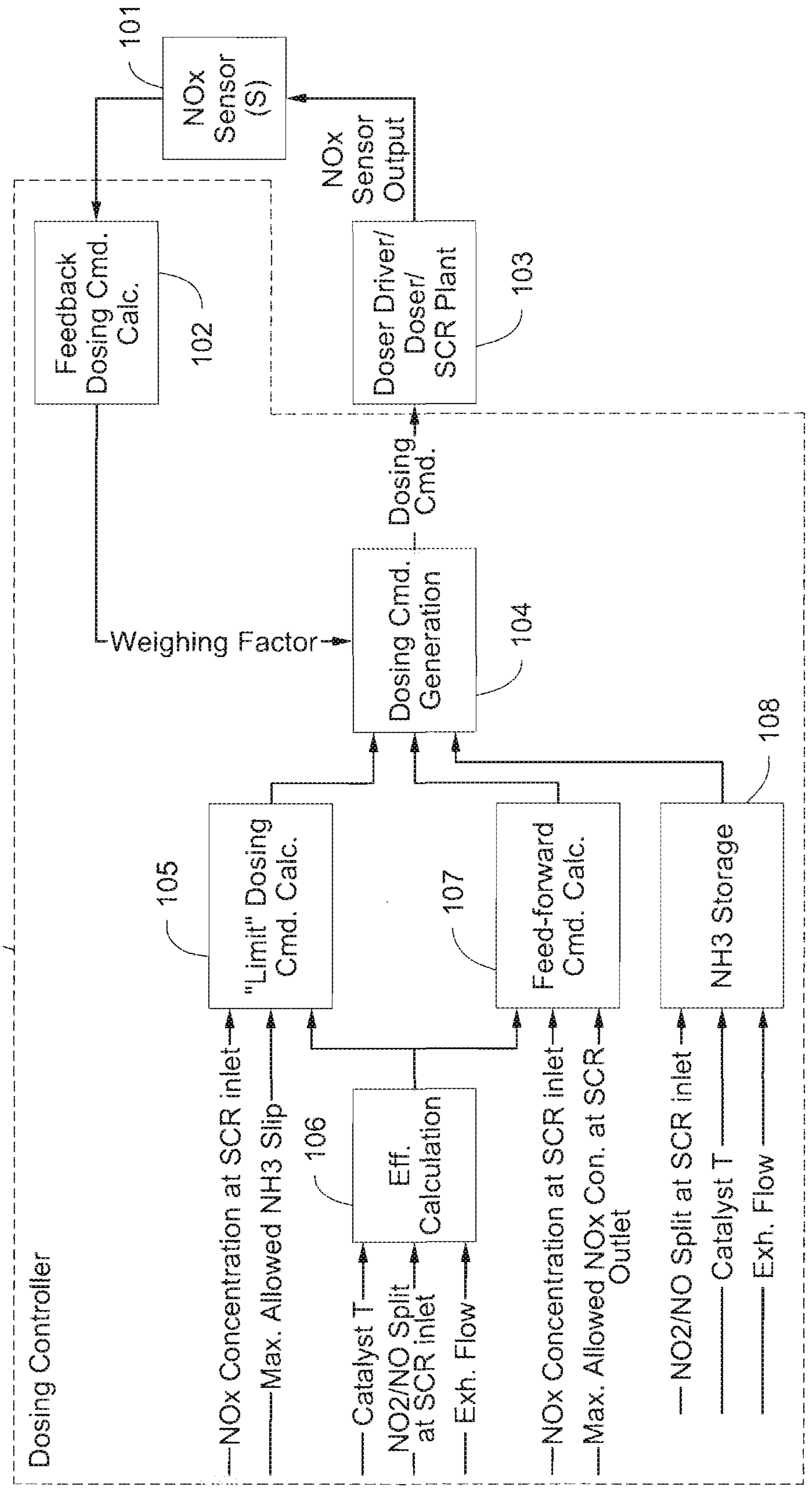

Dosing Controller
100
NOx Sensor (S)
101
NOx Sensor Output
Feedback Dosing Cmd. Calc.
102
Doser Driver/ Doser/ SCR Plant
103
Dosing Cmd.
Weighing Factor
Dosing Cmd. Generation
104
"Limit" Dosing Cmd. Calc.
105
Eff. Calculation
106
Feed-forward Cmd. Calc.
107
NH3 Storage
108
NOx Concentration at SCR inlet
Max. Allowed NH3 Slip
Catalyst T
NO2/NO Split at SCR inlet
Exh. Flow
NOx Concentration at SCR inlet
Max. Allowed NOx Con. at SCR Outlet
NO2/NO Split at SCR inlet
Catalyst T
Exh. Flow

Fig. 1

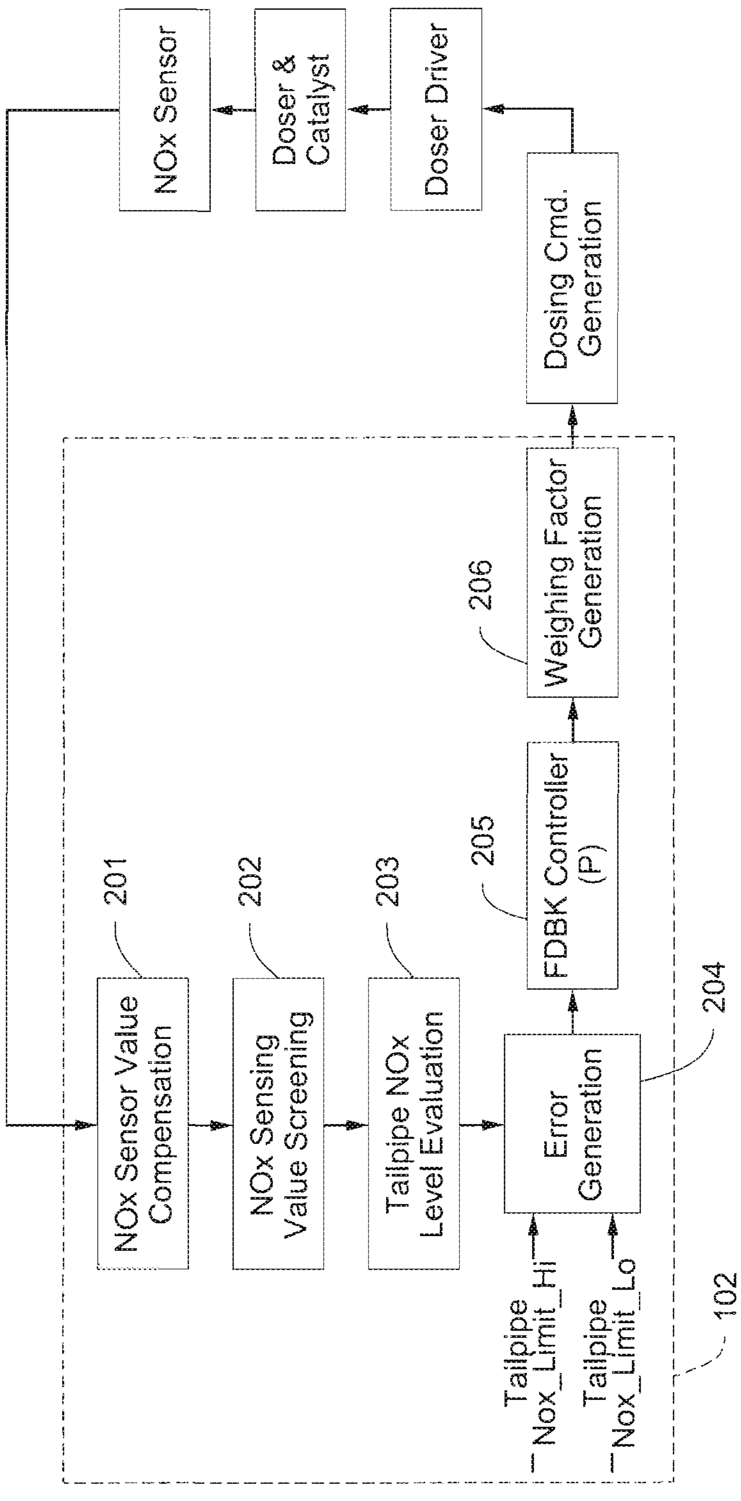
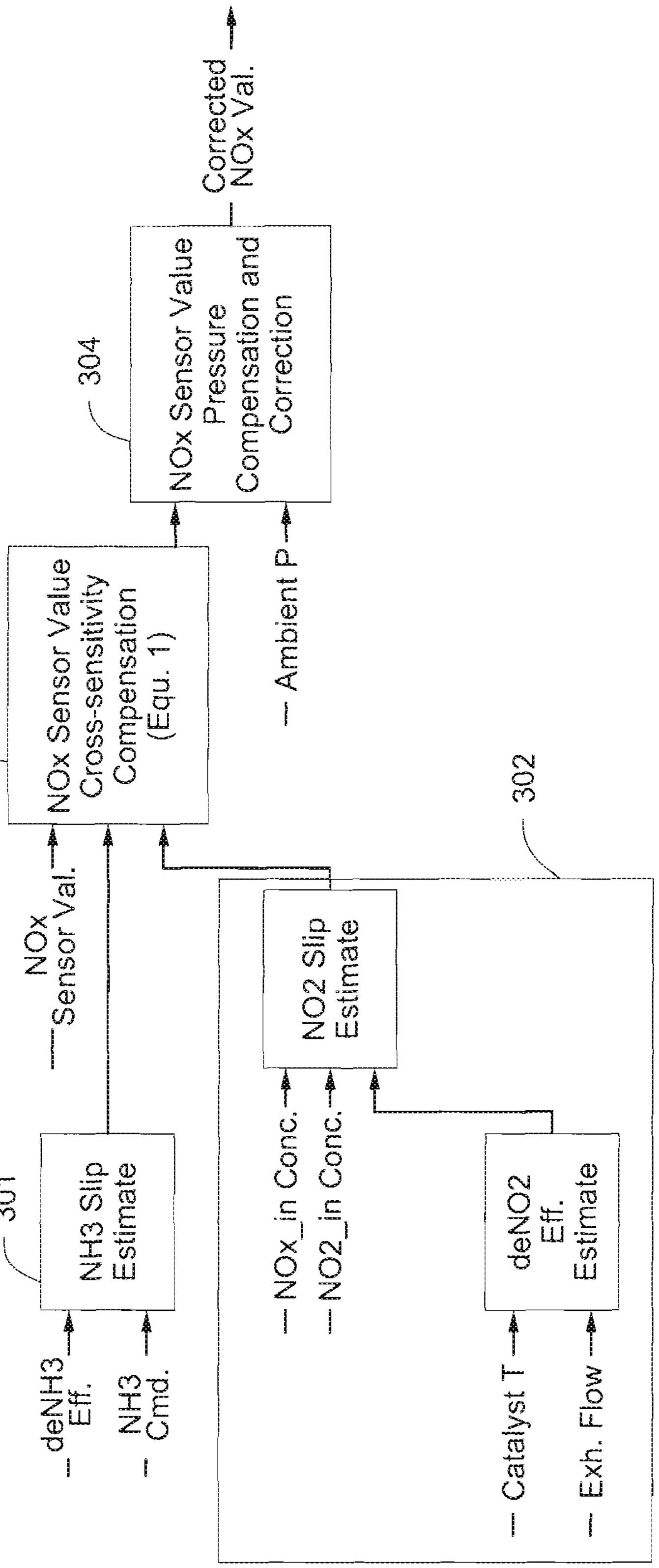

NOx Sensor
Doser & Catalyst
Doser Driver
Dosing Cmd. Generation
206
Weighing Factor Generation
205
FDBK Controller (P)
201
NOx Sensor Value Compensation
202
NOx Sensing Value Screening
203
Tailpipe NOx Level Evaluation
204
Error Generation
Tailpipe Nox_Limit_Hi
Tailpipe Nox_Limit_Lo
102

Fig. 2



Corrected NOx Val.
304
NOx Sensor Value Pressure Compensation and Correction
Ambient P
303
NOx Sensor Value Cross-sensitivity Compensation (Equ. 1)
NOx Sensor Val.
302
NO2 Slip Estimate
NOx_in Conc.
NO2_in Conc.
deNO2 Eff. Estimate
Catalyst T
Exh. Flow
301
NH3 Slip Estimate
deNH3 Eff.
NH3 Cmd.

Fig. 3

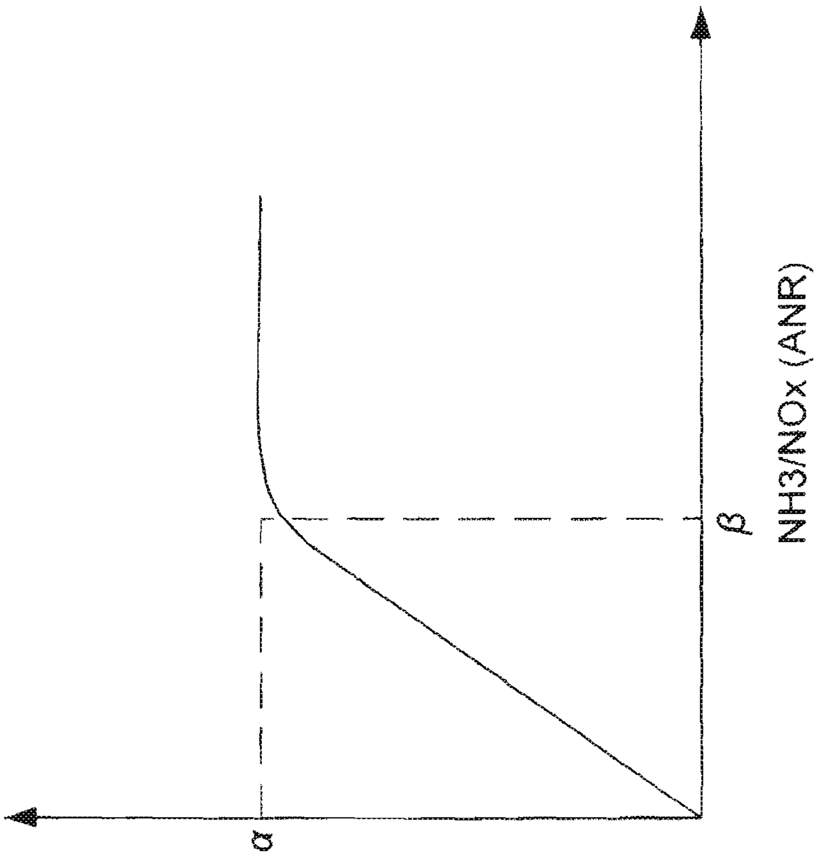
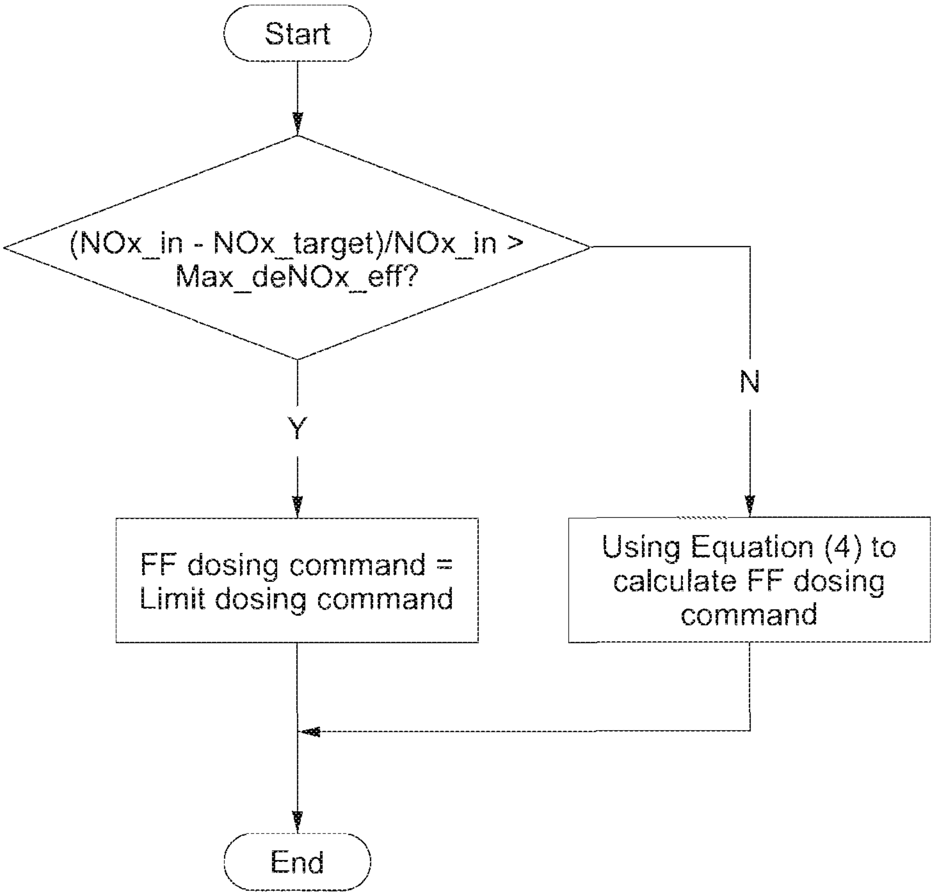


Fig. 4

Fig. 5



Start
(NOx_in - NOx_target)/NOx_in > Max_deNOx_eff?
Y
N
FF dosing command = Limit dosing command
Using Equation (4) to calculate FF dosing command
End

Fig. 6

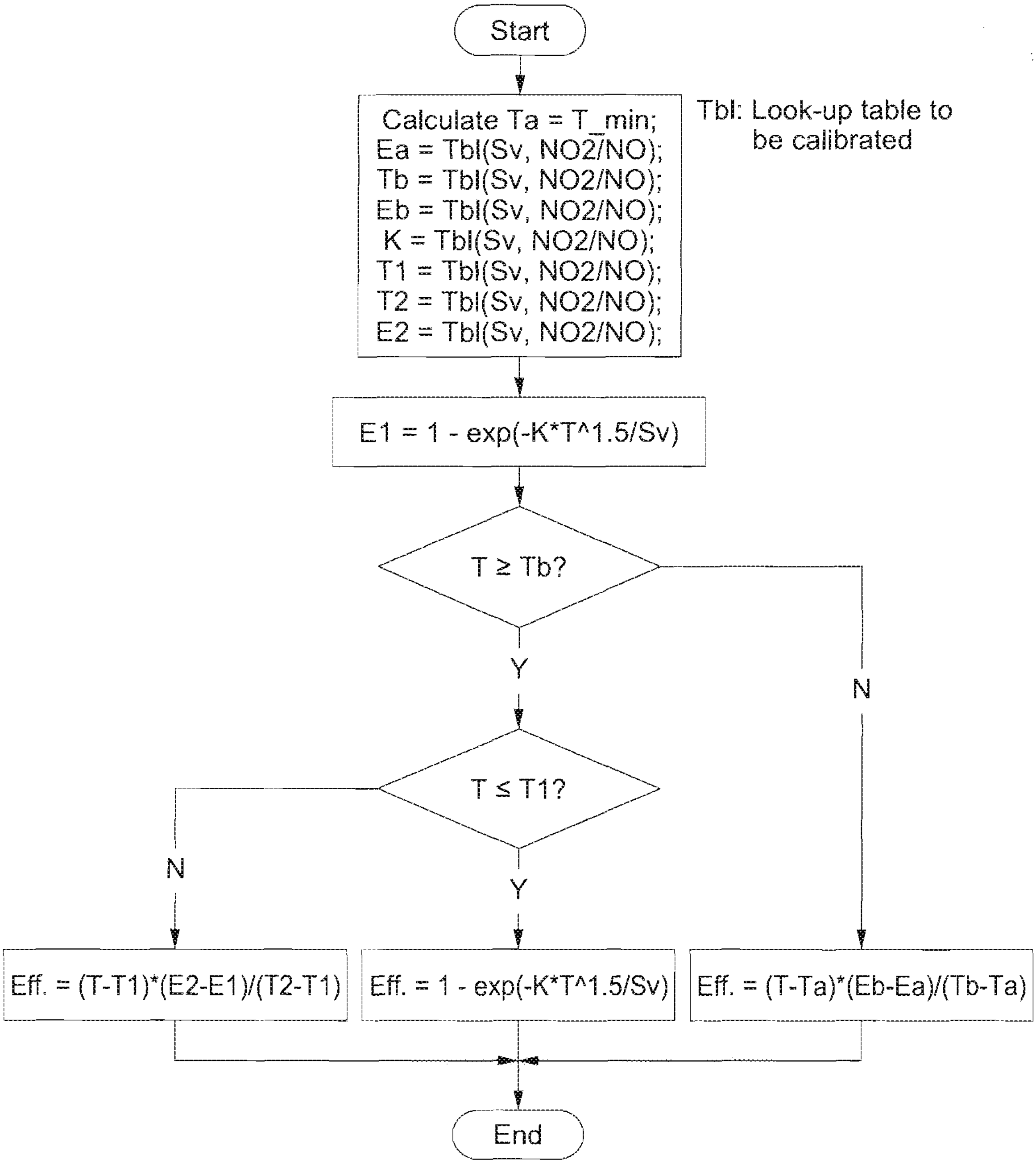

Start
Calculate Ta = T_min;
Ea = Tbl(Sv, NO2/NO);
Tb = Tbl(Sv, NO2/NO);
Eb = Tbl(Sv, NO2/NO);
K = Tbl(Sv, NO2/NO);
T1 = Tbl(Sv, NO2/NO);
T2 = Tbl(Sv, NO2/NO);
E2 = Tbl(Sv, NO2/NO);
Tbl: Look-up table to be calibrated
E1 = 1 - exp(-K*T^1.5/Sv)
T ≥ Tb?
Y
N
T ≤ T1?
N
Y
Eff. = (T-T1)*(E2-E1)/(T2-T1)
Eff. = 1 - exp(-K*T^1.5/Sv)
Eff. = (T-Ta)*(Eb-Ea)/(Tb-Ta)
End

Fig. 7

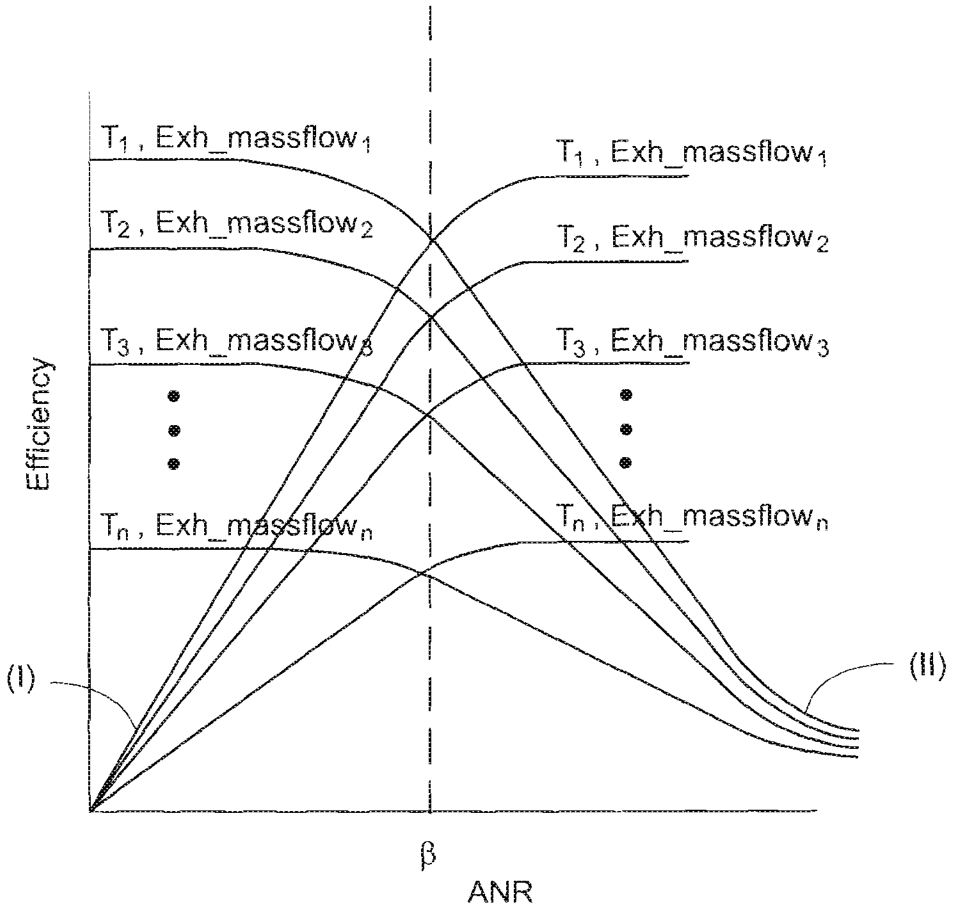
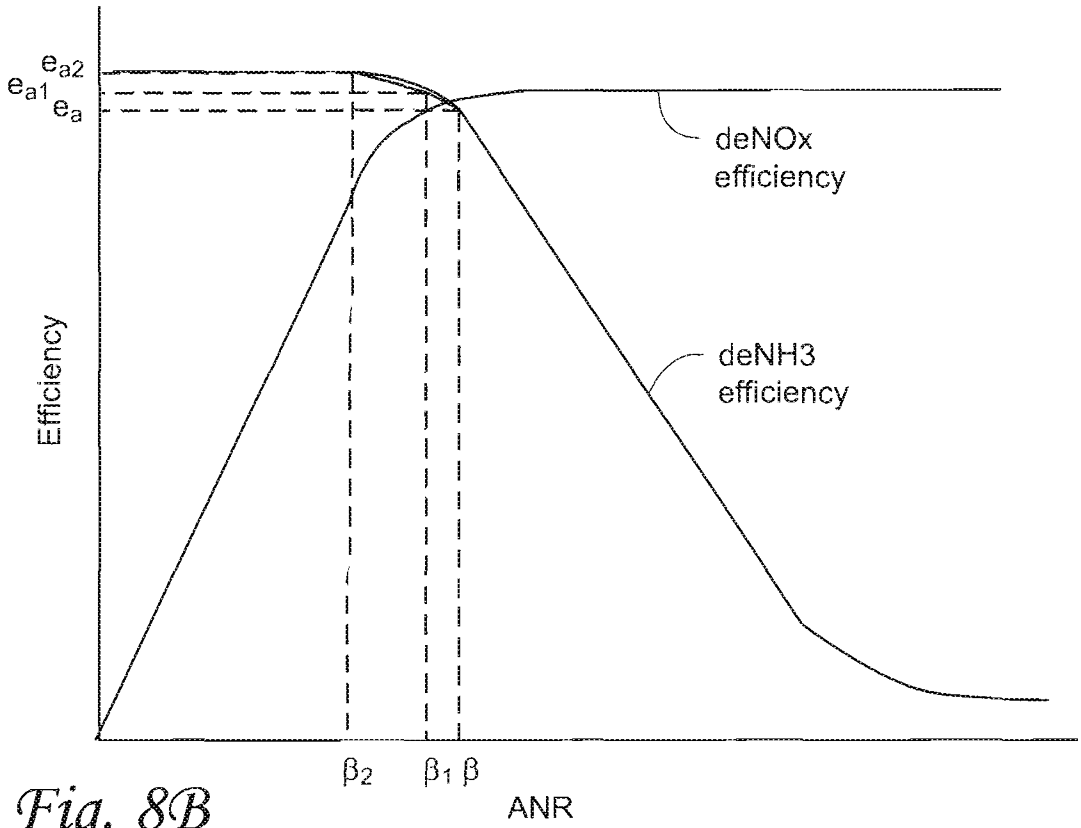
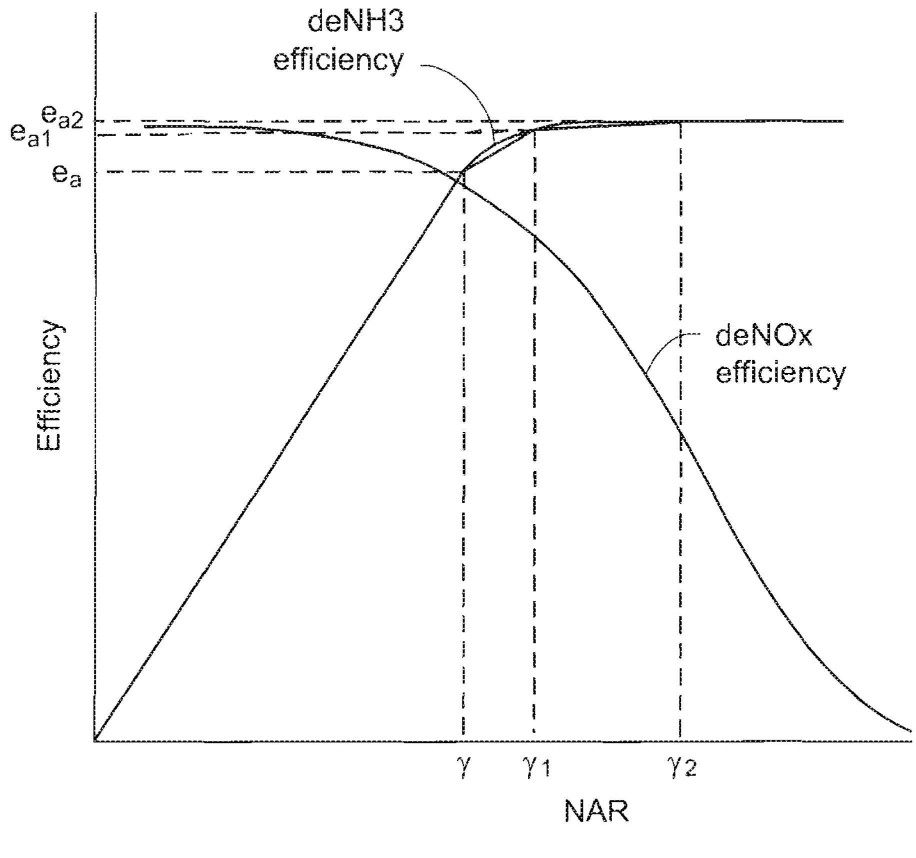

T1 , Exh_massflow1
T2 , Exh_massflow2
T3 , Exh_massflow3
Tn , Exh_massflown
T1 , Exh_massflow1
T2 , Exh_massflow2
T3 , Exh_massflow3
Tn , Exh_massflown
Efficiency
(I)
(II)
β
ANR

Fig. 8A



e_{a2}
e_{a1}
e_a
deNOx
efficiency
deNH3
efficiency
Efficiency
β_2
β_1
β
ANR

Fig. 8B



deNH3
efficiency
e_{a2}
e_{a1}
e_a
deNOx
efficiency
Efficiency
γ
γ_1
γ_2
NAR

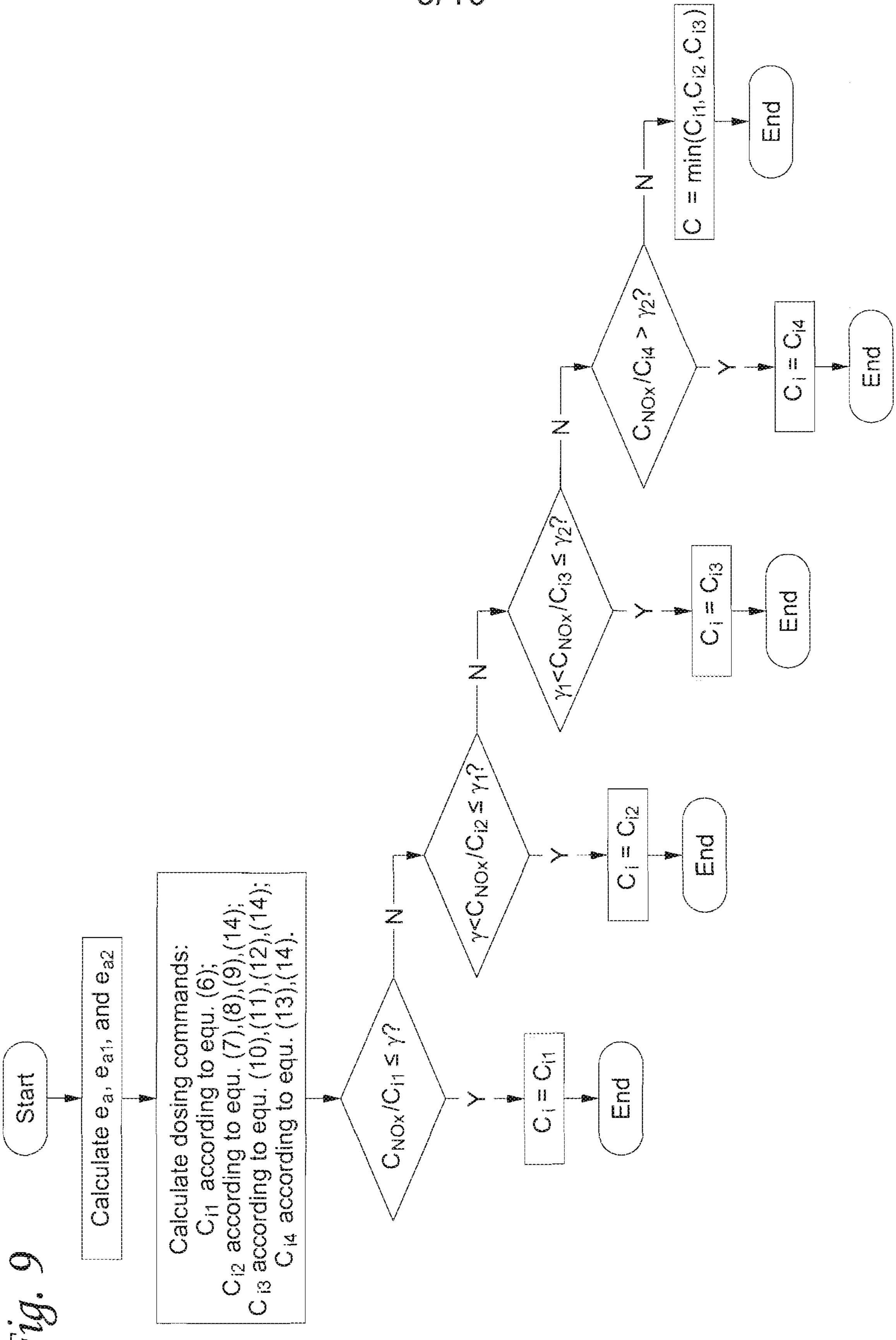

Start
Calculate e_a, e_{a1}, and e_{a2}
Calculate dosing commands:
C_{i1} according to equ. (6);
C_{i2} according to equ. (7),(8),(9),(14);
C_{i3} according to equ. (10),(11),(12),(14);
C_{i4} according to equ. (13),(14).
$C_{NOx}/C_{i1} \le \gamma$?
Y
$C_i = C_{i1}$
End
N
$\gamma < C_{NOx}/C_{i2} \le \gamma_1$?
Y
$C_i = C_{i2}$
End
N
$\gamma_1 < C_{NOx}/C_{i3} \le \gamma_2$?
Y
$C_i = C_{i3}$
End
N
$C_{NOx}/C_{i4} > \gamma_2$?
Y
$C_i = C_{i4}$
End
N
$C = \min(C_{i1}, C_{i2}, C_{i3})$
End

Fig. 9

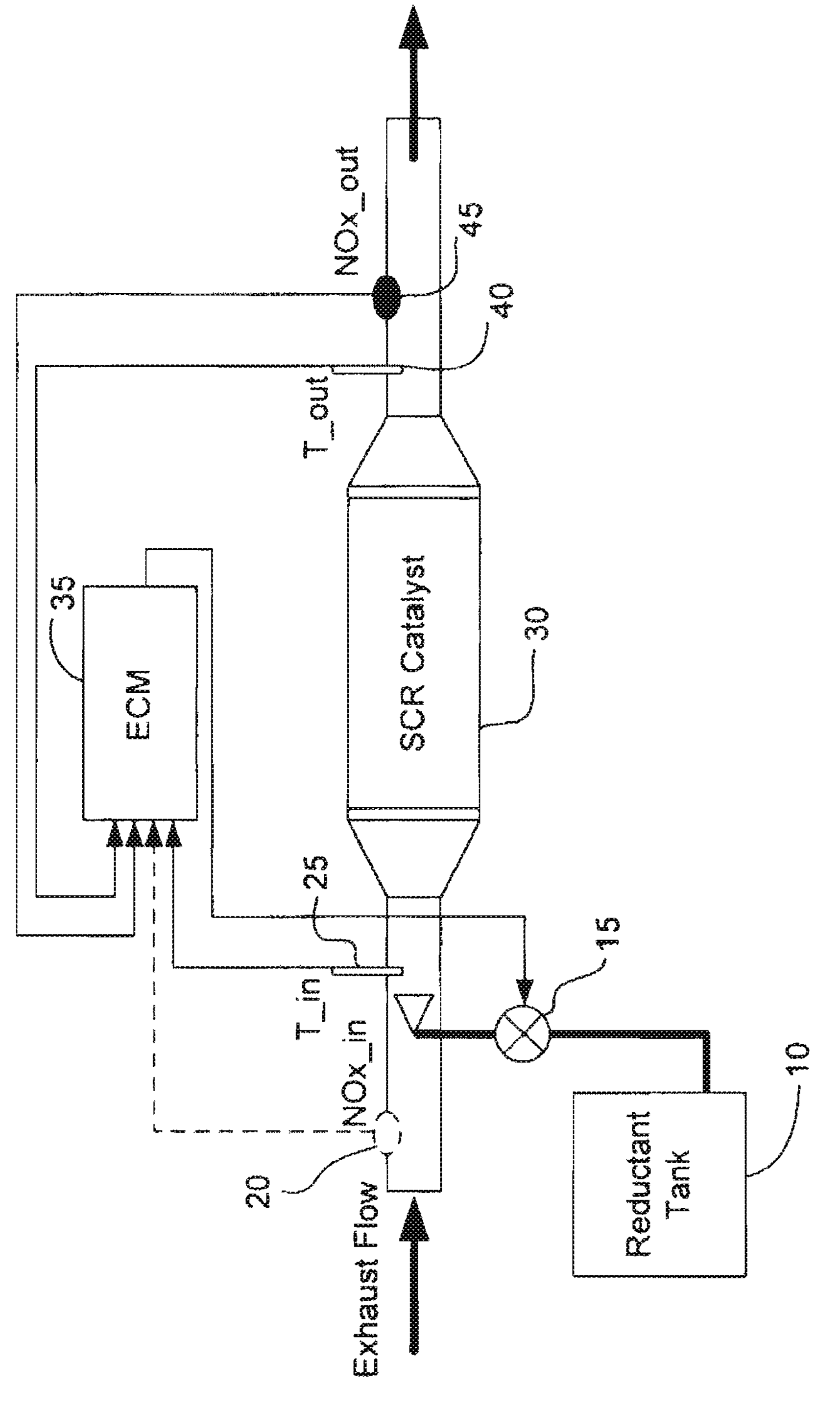

NOx_out
45
40
T_out
35
ECM
SCR Catalyst
30
25
15
T_in
NOx_in
10
20
Exhaust Flow
Reductant Tank

Fig. 10