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CA 2422164 A1 2004/04/02

(21) 2 422 164

# (12) DEMANDE DE BREVET CANADIEN
# CANADIAN PATENT APPLICATION

(13) A1

(22) **Date de dépôt/Filing Date**: 2003/03/14

(41) **Mise à la disp. pub./Open to Public Insp.**: 2004/04/02

(30) **Priorité/Priority**: 2002/10/02 (2406386) CA

(51) **Cl.Int.$^7$/Int.Cl.$^7$** B01D 53/92, B01D 53/96, B01D 53/56, B01D 53/02

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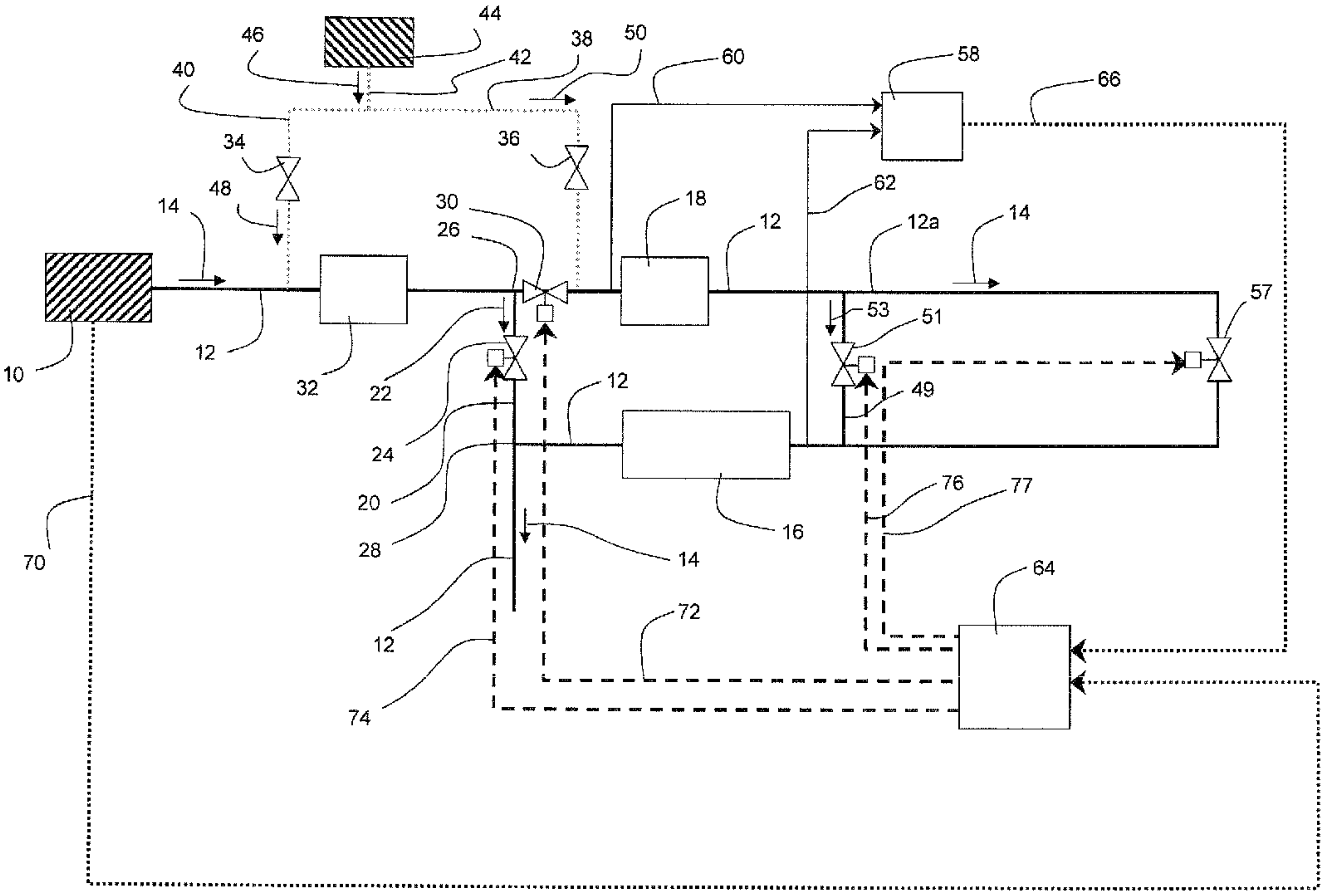
(54) Titre : GESTION PAR DERIVATION DE LA CONTAMINATION PAR LE SOUFRE D'ABSORBEURS DE NOX PEU CHARGES

(54) Title: BYPASS CONTROLLED MANAGEMENT OF SULFUR CONTAMINATION OF LEAN NOX ADSORBERS



(57) **Abrégé/Abstract:**

A method and apparatus for de-sulfating a NOx adsorber is disclosed where the NOx adsorber is used to treat exhaust gases created during the combustion of fuels in general. A desulfation line is used to bypass a portion of the exhaust line. This help to maintain a catalyst close enough to the engine to light off during de- sulfation or regeneration of adsorber, an adsorber far enough away from the engine to allow heat dissipation from the exhaust gas ensuring a cooled exhaust gas during removal of NOx and a catalyst and adsorber proximate to each other during desulfation to ensure high desulfation temperatures.

# Abstract

A method and apparatus for de-sulfating a NOx adsorber is disclosed where the NOx adsorber is used to treat exhaust gases created during the combustion of fuels in general. A de-sulfation line is used to bypass a portion of the exhaust line. This help to maintain a catalyst close enough to the engine to light off during de-sulfation or regeneration of adsorber, an adsorber far enough away from the engine to allow heat dissipation from the exhaust gas ensuring a cooled exhaust gas during removal of NOx and a catalyst and adsorber proximate to each other during de-sulfation to ensure high desulfation temperatures.

# BYPASS CONTROLLED MANAGEMENT OF SULFUR CONTAMINATION OF LEAN $NO_x$ ADSORBERS

## Field of the Invention

This invention relates to a method and apparatus for managing oxides of sulfur that contaminate NOx adsorbers of internal combustion engine aftertreatment systems.

## Background of the Invention

Emissions controls for internal combustion engines are becoming increasingly important in transportation and energy applications. One class of pollutants of concern are oxides of nitrogen (NOx). NOx form during combustion in internal combustion engines.

One effective NOx treatment system is a lean NOx adsorber (LNA). LNA systems need to be periodically regenerated and de-sulfated. That is, over time, a reductant is needed to treat NOx traps to permit further NOx removal to take place.

As discussed in, by way of example, U.S. Patent No. 6,393,834, sulfur poisoning of NOx adsorbers from oxides of sulfur generated in the combustion chamber and found in the exhaust gas (as it can exist in the engine fuel or lubricants) can interfere with the ability of the adsorber to remove NOx. Removal of these oxides of sulfur periodically during operation of the engine helps to provide for a more efficient NOx adsorber.

One method of removing oxides of sulfur from a NOx adsorber is to drive these sulfur contaminants off. For the purposes of this application the de-sulfation temperature is that relatively high temperature at which sulfur is effectively released from the adsorber. The NOx adsorber reactive capacity decreases quickly at temperatures significantly below the de-sulfation temperature of the catalyst. Therefore, in order to periodically drive off oxides of sulfur, that is de-sulfate the adsorber, the aftertreatment system should employ a method and system architecture that allows the exhaust gas to be heated to the de-sulfation temperature quickly and physically near the adsorber while allowing for the NOx adsorber to work well during normal operation.

In line oxidation of a reductant can provide the necessary heat to de-sulfate the adsorber, however such systems need to consider a NOx adsorber distant enough from the engine to ensure that the exhaust gas temperature during NOx adsorption is cool enough to allow for efficient adsorption and, at the same time, provide a catalyst, used to promote oxidation of the exhaust gas, close enough to the engine to light the catalyst off at all exhaust gas temperatures yet still be proximate enough to the adsorber to provide rich exhaust gas at the de-sulfation temperature.

This invention provides a means and apparatus of de-sulfating a NOx adsorber while addressing the problems noted above.

## Summary of the Invention

One aspect of the invention provides a de-sulfation line that shortcuts the route between the adsorber and an oxidation catalyst disposed in the exhaust line.

An aftertreatment system is disclosed for treating Nox found in exhaust gas produced during combustion of a fuel within a combustion chamber of an operating internal combustion engine. The system comprises:

a. an exhaust line for directing the exhaust gas from the engine;
b. a NOx adsorber disposed in the exhaust line,
c. a first catalyst disposed in the exhaust line upstream of the NOx adsorber, the catalyst capable of oxidizing a reductant;
d. a reductant line for delivering a reductant from a reductant store to the exhaust line upstream of the catalyst;
e. a reductant flow control disposed in the reductant line for controlling flow of the reductant into the exhaust line;
f. a de-sulfation line for directing the exhaust gas from the catalyst to the adsorber, the de-sulfation line providing a shorter path between the catalyst and the adsorber than that provided by the exhaust line; and

g. a de-sulfation flow control for controlling flow of exhaust gas through the de-sulfation line.

The system can be practiced with the reductant being hydrogen, and in a preferred example the reductant is a hydrocarbon. The first catalyst, with the hydrocarbon, is capable of reducing the lambda of exhaust gas to a value below one.

In one embodiment of the system, the first catalyst can be a reformer in series with an oxidation catalyst upstream of the reformer. In another embodiment, the catalyst can be partial oxidation catalyst. In a preferred embodiment, a close coupled catalyst is disposed in the exhaust line upstream of first catalyst and downstream of the reductant line.

The aftertreatment system can further comprise a second reductant line and a second reductant flow control. The second reductant line can be used to introduce the reductant from the reductant store to the exhaust line downstream of the close coupled catalyst and upstream of the first catalyst.

The aftertreatment system can further comprise an injector for injecting the reductant into the exhaust line.

The de-sulfation flow control can be a valve, and for improved modulation of flow through the by-pass line this valve is preferably a variable control valve.

The aftertreatment system can further comprise a by-pass line and a by-pass flow control disposed in the by-pass line to control the flow of the exhaust gas through the by-pass line. This by-pass line connects a first point in the exhaust gas line upstream of the NOx adsorber to a second point in the exhaust gas line downstream from the adsorber. The by-pass flow control controls the flow of the exhaust gas through the by-pass line. In a preferred example, the by-pass flow control is a valve.

A method is also provided of operating an internal combustion engine equipped with an aftertreatment system for removing NOx from exhaust gas generated by combustion of a fuel in at least one combustion chamber of the engine. The method comprises directing all of the exhaust gas through an exhaust line to a lean NOx adsorber disposed in the exhaust line during normal operation of the engine, periodically de-sulfating the lean NOx adsorber by a de-sulfation cycle temporally defined by a de-sulfation cycle start time and a de-sulfation cycle end time, and controlling conditions within the adsorber by:

(a) determining a target de-sulfation temperature,

(b) where the temperature of the exhaust at the NOx adsorber is below the target de-sulfation temperature, heating the exhaust gas upstream of the NOx adsorber,

(c) reducing the exhaust gas with a reductant upstream of the NOx adsorber, reducing the lambda of the exhaust gas to less than one, and

(d) directing the reduced exhaust gas to the adsorber and directing at least some of the reduced exhaust gas to bypass a portion of the exhaust line.

The method can be practiced with the reductant being hydrogen. The method can also be practiced with the reductant being a hydrocarbon, and a preferred example of a hydrocarbon is methane.. The method can further comprise determining the exhaust gas temperature by reference to at least one of engine speed, engine load, engine intake manifold temperature, intake air mass flow, the fuel flow into the engine or the intake manifold pressure into the engine.

The method may further comprise determining exhaust gas temperature by reference to a temperature sensor provided in the exhaust line. The temperature sensor can also determine the temperature of exhaust gas entering into the NOx adsorber.

In a preferred method, the reduced exhaust gas is a de-sulfation flow and a de-sulfation line provides a means for some of the de-sulfation flow to by-pass a portion of the exhaust line. The method can further comprise determining a target de-sulfation flow through the de-sulfation line, and controlling the flow through the de-sulfation line to be substantially equal to the target de-sulfation flow.

Target de-sulfation flow can be determined by reference to at least one of the engine speed, the engine load, the engine intake manifold temperature, the intake air mass flow, the fuel flow into the engine, the intake manifold pressure of the engine, and exhaust gas flow out of the engine.

A further embodiment of the method comprises reducing flow of said exhaust gas through the NOx adsorber by bypassing a portion of the exhaust gas around the NOx adsorber during the desulfation cycle. In another embodiment of the method of the de-sulfation start time is determined by reference to NOx concentrations within the exhaust gas downstream of the NOx adsorber. The de-sulfation start time can be triggered to occur when the NOx concentration exceeds a pre-determined threshold after a regeneration cycle of the NOx adsorber has been completed. The de-sulfation end time can also be pre-determined based on the de-sulfation start time.

Further aspects of the invention and features of specific embodiments of the invention are described below.

## Brief Description of the Drawings

In drawings which illustrate non-limiting embodiments of the invention:

Figure 1 shows a schematic of an aftertreatment system according to one embodiment of the invention.

Figure 2 shows a graph demonstrating flow of exhaust gas and temperature over the range of engine operating conditions with adsorption, regeneration and de-sulfation zones.

## Detailed Description

A method of de-sulfating a NOx adsorber is disclosed where the NOx adsorber is used to treat exhaust gases created during combustion in an engine's combustion chamber. A reductant, preferably methane, is introduced into the exhaust line wherein the reductant is oxidized reducing the exhaust gas and elevating the temperature of the exhaust gas to a temperature above the de-sulfation temperature. The heated exhaust gas at the de-sulfation temperature is then routed through a bypass line directly to the NOx adsorber in order to ensure retention of exhaust gas heat necessary for de-sulfation.

Figure 1 is a schematic showing a preferred embodiment of the subject aftertreatment system. Exhaust line 12 carries exhaust gases flowing in the direction of arrow 14 from an engine block 10 to a NOx aftertreatment system. In the aftertreatment system, exhaust line 12 carries exhaust gases to NOx adsorber 16 through exhaust line 12 as indicated by arrow 14. Exhaust line 12 includes section 12a bounded by a de-sulfation line 49. Gases exiting adsorber 16 are delivered to an outlet through exhaust line 12. Catalyst 18 is disposed in exhaust line 12 upstream of adsorber 16.

A by-pass line 20 is capable of carrying a portion of the exhaust gases around adsorber 16 as may be desirable while absorber 16 is being regenerated or de-sulfated. The exhaust gas may be directed through by-pass line 20 as indicated by arrow 22 by opening by-pass valve 24. By-pass valve 24 may be disposed anywhere along by-pass line 20. In the embodiment shown, by-pass line 20 branches off from exhaust line 12 at junction 26 and rejoins exhaust line 12 at junction 28 downstream from NOx adsorber 16.

Valves 24 and 30 are provided to help control the flow of exhaust gas through exhaust line 12 during regeneration and de-sulfation.

Close coupled catalyst 32 is provided in exhaust line 12 physically proximate to engine block 10. A hydrocarbon, preferably methane, may be introduced just prior to catalyst 18 and / or catalyst 32. Hydrocarbon valves 34 and 36 are disposed in respective main line 38 and close-coupled line 40, each of which branches off of store line 42. Store line 42 is connected to store 44 from which methane is allowed to flow as indicated by arrow 46. Flow direction 48 and 50 along lines 38 and 40 are also provided.

De-sulfation line 49 bypasses section 12a of exhaust line 12 running between catalyst 18 and adsorber 16. Valves 51 and 57 are disposed in de-sulfation line 49 and section 12a, respectively. Arrow 53 indicates flow direction in de-sulfation line 49 as shown.

Temperature sensor 58 is used to measure temperatures before catalyst 18 and adsorber 16 as shown by the respective intersection points of sensor feed lines 60 and 62 with exhaust line 12. Finally, sensor 58 feeds information to controller 64 through feed line 66. Feed line 70 provides engine data to controller 64. Controller

64 drives valves 24, 30, 51 and 57 through feed lines 72, 74, 76 and 77, respectively.

Figure 2 provides a graph of flow of the exhaust gas plotted against temperature. The area within line 800 defines a range for example properties of exhaust gas exiting out of engine block 10 over operating conditions of the engine. The area within line 802 defines a range of target properties for the exhaust gas directed into catalyst 18 during regeneration. The area within line 804 defines a range of target properties for the exhaust gas through NOx adsorber 16 during normal operation (adsorption). The area within line 806 defines a range of target properties for the exhaust gas through NOx adsorber 16 during de-sulfation. Point A is a typical midpoint operating condition for the engine.

Using the NOx aftertreatment system of Figure 1, a preferred method of de-sulfating a NOx adsorber is described below. Exhaust gas is generated by combustion events within one or more combustion chambers disposed upstream of exhaust line 12 in engine block 10. Exhaust gas results from the combustion of fuel such as natural gas or a mixed fuel that includes natural gas or methane. The fuel is, in general, either directly injected into the combustion chamber or pre-mixed with a quantity of air to create a fumigated charge. In each case, spark ignition, hot surface ignition or compression ignition is utilized to initiate the combustion process within the combustion chamber.

During normal operation of the engine, valves 24 and 51 are closed and exhaust gas flows along exhaust line 12 including line 12a helping to ensure that the temperature of the exhaust gas flowing through adsorber 16 is low enough to satisfy the NOx adsorption sought during normal operation. The exhaust gas passes through NOx adsorber 16 which removes NOx. The extended route between block 10 and adsorber 16 helps to provide for a relatively cool exhaust gas during adsorption. By way of example, during normal operation, NOx adsorber under lean operating conditions, that is with an excess of oxygen available in the exhaust gas, will drive NOx to $(NO_3)_2$ by way of:

$$NO + \tfrac{1}{2} O_2 \ (Pt) \rightarrow NO_2 \qquad (1)$$
$$XO + 2\ NO_2 + \tfrac{1}{2} O_2 \rightarrow X(NO_3)_2 \qquad (2)$$

where X is in a washcoat (this is described further below). Eventually NOx adsorber 16 will become less effective at removing NOx as $X(NO_3)_2$ uses up adsorbing sites in adsorber 16. As such, periodic regeneration is required to remove NOx. Controller 64 determines when NOx adsorber 16 needs regenerating. In general, a regeneration strategy can periodically be employed that targets regeneration flow of exhaust gas through the adsorber. Catalyst 18 provides the necessary environment to ensure regeneration. That is, methane provided to catalyst 18 during regeneration is oxidized and reformed to provide an exhaust gas environment that has a low oxygen potential and includes effective reductants for regeneration such as CO and hydrogen.

A regeneration cycle targeted at regeneration of adsorber 16, however, will fail to de-sulfate adsorber 16. That is, within adsorber 16, $X(SO_x)$ also uses up adsorbing sites that would otherwise be available to remove NOx. Therefore, in order to maintain the efficiency of adsorber 16, in addition to a regeneration cycle, a de-sulfation cycle is also required periodically. A similar chemical environment is required for de-sulfation as is required for regeneration, namely, an environment with a low oxygen potential across adsorber 16 during de-sulfation. In addition, the temperature of the exhaust gas needs to be held at the de-sulfation temperature, a temperature which is higher than the temperature required for regeneration. As such, when a de-sulfation cycle is needed, de-sulfation line 49 is opened to shorten the distance traveled by the exhaust gas by bypassing section 12a of line 12, helping to ensure that the heat from the exhaust gas is not dissipated significantly as the exhaust gas flows from catalyst 18 to adsorber 16.

The de-sulfation process can be commenced through an open loop control, based on selected parameters from the engine map, or closed loop control, based, in part, on the exhaust gas exhaust gas temperature and the reactive capacity of catalyst 18 at the given exhaust gas temperature. By way of example, one open loop control would use a calibration of the treatment system over a range of engine operating conditions to estimate the time required for adsorber 16 to be de-sulfated in light of catalyst 18 chosen.

That is, the controller would monitor such variables as the engine load and speed, and then determine from a look-up table, the time needed for de-sulfation. The system can be calibrated such that the engine operating conditions, which are indicative of sulfur content in the exhaust gas, are used to estimate when de-sulfation for the adsorber is desirable. This is somewhat dependent on an assumed range of sulfur content in the engine fuel, which can vary depending on such factors as the source of that fuel. Open loop control can be driven by such conditions as torque, speed, intake manifold temperature, intake manifold pressure, as well as other conditions known to those skilled in the technology.

A closed loop control for determining when to commence a de-sulfation cycle can also be used. By way of example, one such control can monitor NOx levels within exhaust line 12 downstream of adsorber 16 over the course of many regeneration cycles. When the capacity of the adsorber falls below a predetermined level, then the controller can commence a de-sulfation cycle. By way of example, the capacity of the adsorber can be measured by the time between regeneration cycles, and when the length of time between regeneration cycles falls below a predetermined level, then the controller will determine that it is time to commence a de-sulfation cycle.

During a de-sulfation cycle, the exhaust gas must be provided to the adsorber as a rich exhaust gas (oxygen depleted environment) and with a temperature suitable for de-sulfation. The controller can control exhaust gas flow and the introduction of methane to provide a de-sulfation strategy that will help to limit the use of hydrocarbons, such as methane. Provision to ensure a rich environment throughout the adsorber during de-sulfation should be made as sulfur oxides may be further reduced in the rich exhaust gas environment.

During a de-sulfation cycle, a preferred set of reaction conditions across catalyst 18 comprises:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (3)$$

$$CH_4 + \tfrac{1}{2}O_2 \rightarrow CO + 2H_2 \qquad (4)$$

The resulting rich and hot exhaust gas environment is used for de-sulfation as follows:

$$X(SO_x) \rightarrow SO_x \qquad (7)$$

where X is in a washcoat.

Lambda, a measure of the oxygen potential in the exhaust gas or whether the gas is rich or lean, needs to be low (quantitatively, a value below one) to promote reaction 7. For the purposes of this application, lambda is a measure of the oxygen potential of the exhaust gas. As a point of reference, a lambda value above 1 denotes a high oxygen potential and a lambda value below 1 denotes a low oxygen potential as it relates to reaction 7. A rich exhaust gas environment is an environment with a lambda value below 1 while a lean exhaust gas environment is an environment with a lambda value above 1.

For the purposes of this application, the flow of exhaust gas through the NOx adsorber during de-sulfation will be referred to as the de-sulfation flow.

Once commenced, controller 64 determines a de-sulfation strategy based, generally, on the exhaust gas flow, the exhaust gas temperature, a desired exhaust gas flow chosen considering the reactive capacity of catalyst 18 at a given exhaust gas temperature, and lambda of the exhaust gas from the engine. The de-sulfation strategy for a given de-sulfation cycle can be done by an open loop or closed loop strategy. The de-sulfation strategy can be controlled by the quantity and rate of the methane introduced into the exhaust gas from store 44, and by the amount of by-pass flow dictated by valves 24 and 30. The goal is to efficiently provide an exhaust gas environment wherein lambda is below one and the temperature of the exhaust gas is high enough to promote reaction 7. This can be realized if reductants are provided to the exhaust gas to drive lambda of the exhaust gas below 1 and to heat the exhaust gas to the de-sulfation temperature. The de-sulfation flow is directed through de-sulfation line 49 so that it retains more heat compared to the case where the exhaust gas is routed through section 12a of line 12. At commencement of the de-sulfation cycle, controller 64 causes valve 51 to open and valve 57 to close. The de-sulfation flow bypasses section 12a to some extent depending on the control strategy chosen and the valve position chosen for valve 57 in section 12a. Note that oxidation through the adsorber with other reductants such as hydrogen, methane or other hydrocarbons can also provide the necessary rich exhaust gas environment.

Bypass line 20 is helpful to ensure efficient regeneration and de-sulfation, however, for the purposes of this application it is not necessary. The system is capable of providing full exhaust flow through the NOx adsorber during de-sulfation.

In an open loop strategy, the controller is preferably calibrated to direct flow of exhaust gas through the adsorber and methane into the exhaust gas based on the engine speed and load just prior to and during de-sulfation. Engine intake manifold temperature, intake air mass flow, fuel flow or intake manifold pressure can also be used as indicators of exhaust gas properties that are useful for controlling the de-sulfation cycle. A constant de-sulfation cycle time can also be used. This can be appropriate as the de-sulfation time is relatively long as compared to such variables as the catalyst light off time and cycle variations related to varying exhaust gas flow. An open loop strategy employs an engine calibration that considers one or more engine operating conditions, each of which is indicative of at least one of exhaust gas temperature, flow and lambda value. The controller is calibrated to direct a desired flow of exhaust gas through the NOx adsorber based on the characteristics of catalyst 18 and adsorber 16. A look-up table can be used to determine whether the exhaust gas flow exceeds the desired de-sulfation flow and, if so, directs excess exhaust gas around adsorber 16 via by-pass line 20. This is referred to as the by-pass flow if exhaust gas is by-passed during de-sulfation. The desired by-pass flow is achieved by adjusting valves 24 and 30 to match the target de-sulfation flow though adsorber 16.

The look-up table can also be used to provide a desired flow rate across de-sulfation line 49. As mentioned above, valve 51 is opened at the commencement of a de-sulfation cycle to direct a significant portion of the de-sulfation flow through de-sulfation line 49. Valve 57 disposed in section 12a can provide additional control over the flow through de-sulfation line 49 during de-sulfation. Valves suitable for the purpose described for valves 51 and 57 are well known. For example, each valve could be a simple two position valve, a multi-position valve, or a variable position control valve, with the choice of valve type being dictated by cost and the desired degree of control. Also, one of valves 51 or 57 could be eliminated, reducing control, but simplifying controls and reducing costs and maintenance by removing a moving component. In each case, the controller can adjust de-sulfation flow by splitting the flow through section 12a and de-sulfation line 49.

With reference to the embodiment provided in the fig. 1, valves 51 and 57 can be employed to control flow through section 12a and de-sulfation line 49. By closing valve 57 and opening valve 51 all of the de-sulfation flow passes through de-sulfation line 49. However, with this illustrated embodiment, greater variability can also be achieved by splitting the de-sulfation flow between de-sulfation line 49 and section 12a. If valve 51 is eliminated, an operable system can still be designed, but de-sulfation flow and normal exhaust gas flow control would need to consider that a portion of the de-sulfation flow would be directed from catalyst 18 to adsorber 16 through de-sulfation line 49 during all operating modes. By continuously splitting the exhaust flow in this manner, the exhaust gas temperature would be elevated temperature at adsorber 16 and could require another means for managing temperature to keep the exhaust gas below a target temperature during normal operation. Alternatively, without valve 57, there will always be a quantity of de-sulfation flow forced through section 12a, andthe controller would need to consider this. In all cases, temperature sensor 58 can be used to feed data to controller 64 that can be used by controller 64 to control the efficiency of the de-sulfation cycle.

The look-up table for this open loop control can also provide a target methane concentration upstream of catalyst 18. The engine operating conditions provide information about the exhaust gas temperature, flow and lambda of the exhaust gas from block 10. The temperature of the exhaust gas can be used to determine the amount of methane required in order to meet the target temperature range for the exhaust gas during de-sulfation. This target temperature range should be held below a temperature that might damage the catalyst and above a temperature suitable for efficient reformation of methane and de-sulfation of NOx adsorber 16. Moreover, the lambda of the exhaust gas, estimated from the engine operating conditions, determines the amount of methane required to generate a sufficiently rich exhaust gas environment to support efficient de-sulfation.

A closed loop strategy could also be used wherein the temperature would be measured prior to catalyst 18 by sensor 58 through line 60 and prior to adsorber 16 through line 62. The load and speed of the engine could be used by the controller to determine the exhaust gas flow based on look-up tables or a flow meter within the exhaust line could also be used for complete closed loop control. The look-up table along with sensor information can be used to determine the flow of methane to be introduced into exhaust line 12 and how much flow of exhaust gas, if any, to direct through valve 24 and line 20 during de-sulfation to maintain a target de-sulfation flow and de-sulfation temperature. When exhaust gas flow is too high for catalyst 18 to allow complete oxidation of methane or too high to de-sulfate efficiently, some flow is directed into by-pass line 20 until the desired flow is met. If temperature prior to adsorber 16 is too high or too low, the methane quantity can be adjusted to achieve the desired de-sulfation temperature. This can also be done monitoring the temperature into catalyst 18.

As with the open loop system above, de-sulfation flow through de-sulfation line 49 can be determined by a calibration provided to the controller that would include an engine map corresponding to a flow split through de-sulfation line 49 and section 12a. This is dependant on the control available to the controller resulting from the availability and type of valves in section 12a and/or de-sulfation line 49. Also, an open loop control could be used that would consider the temperature of the de-sulfation flow prior to of adsorber 16 and direct that de-sulfation flow through de-sulfation line 49 and section 12a to target the desired temperature required to ensure efficient de-sulfation of adsorber 16. The temperature can also be used to control valve 36 to vary methane flow or quantity providing a hotter exhaust gas into adsorber 16.

An optional close-coupled catalyst 32 is also available to increase exhaust gas temperatures when desired. The proximity of catalyst 32 to engine block 10, helps ensure that exhaust gas is never too cool to oxidize methane within the exhaust gas environment. Therefore, when the controller detects an exhaust gas temperature below a threshold amount, valve 34 will provide methane upstream of catalyst 32, heating and oxidizing the exhaust gas well upstream of adsorber 16.

As noted above, a closed loop strategy may be preferred depending on cost and application considerations. The open loop strategy discussed above utilizes a calibration of the system that provides a target methane injection rate and quantity over a de-sulfation cycle that is based on the engine operating parameters such as load and speed, and could eliminate dynamic monitoring and the added complexity in hardware and software for the system. However, the trade-off is that such a strategy is more likely to de-sulfate adsorber 16 incompletely or to de-sulfate with a higher methane penalty.

To simplify the system, an alternative to using variable flow control valves for valves 24, 30, 51 and 57 is to use 2 position valves (or for that matter other multiple position valves). Here, the controller can elect from one of a plurality of possible settings to control flow through lines 12, 20 and 49. Valve 30 can be fully open or partially open. Valves 24, 51 and 57 can be closed or open. Therefore, controller 70 can select a position for each valve according to the engine operating parameters in order to match exhaust flow through line 12 to a pre-determined target value. That is, at low speed and load, valve 30 and 51 are open fully and valves 24 and 57 are closed. At higher loads and speeds, valves 24, 30 and 51 are fully opened and valve 57 can be closed. At still higher speeds and loads, valve 30 is partially open and valves 24 and 51 are opened while valve 57 can be opened or closed.

As would be understood by a person skilled in the technology, valves, 51 and 57, and for that matter, valves 24 and 30, can be any flow control mechanism and need not be limited to valves.

Other valve configurations can be used as well. More flexibility for the controller to manage flow through lines 12, 20 and 49 during de-sulfation helps the controller to meet a target pre-determined de-sulfation flow for each operating condition. One trade-off is that such flexibility can result in a more expensive system that requires more expensive valves and more complicated software to control those valves.

Referring to fig. 2, flow and temperature over the range of engine operating conditions are provided. Area 800 shows typical exhaust gas flow and temperature conditions expelled from engine block 10. Area 802 provides a desired operating range for temperature and flow of exhaust gas through catalyst 18 during regeneration. Area 804 provides an acceptable exhaust gas flow and temperature range through NOx adsorber during normal engine operation. Area 806 provides an acceptable gas flow and temperature operating range during de-sulfation. Therefore, considering point A, a typical flow and temperature of exhaust gas out of engine block 10, flexibility is required in the system to provide for the three operating modes in order to efficiently treat NOx emissions. During normal engine operation, the temperature of exhaust gas at point A needs to be reduced. The long route provided through line 12 and section 12a to adsorber 16 allows the exhaust gas to dissipate heat before arriving at the adsorber driving the temperature down and within area 804. During regeneration, at point A the flow needs to be reduced and a high temperature needs to be retained. Therefore, flow through bypass line 20 is controlled by valves 24 and 30 allow the regeneration flow through the catalyst and NOx adsorber to be reduced from the exhaust gas flow exiting from engine block 10. As well, the proximity of catalyst 18 helps reduce dissipation of heat from block 10 thereby maintaining temperature within area 802. Area 802 is dependent on the reactive capacity of catalyst 18. Finally, during a de-sulfation cycle, point A needs to be heated to pull it within area 806. Directing the de-sulfation flow through de-sulfation line 49, controlled through values 51 and 57, along with catalyst 18 provide the necessary heating while limiting dissipation of exhaust gas heat to ensure efficient de-sulfation. The aftertreatment system benefits from being able to manage all exhaust gas properties that might be provided to exhaust line 12 and delivered to adsorber 16.

During the de-sulfation cycle where bypass line 20 is used, the NOx levels out of line 12 may increase substantially, as the engine is continuing to operate without NOx treatment of the exhaust gas routed through by-pass line 20. Once de-sulfation is complete, however, NOx quickly falls as all exhaust gas is routed through recently de-sulfated adsorber 16. Therefore, as well as a desire to reduce fuel consumption (consumption of methane), short de-sulfation times also limit the amount of NOx emitted during de-sulfation through by-pass line 20. The longer the period of time needed for de-sulfation, the more cumulative exhaust gas flows through by-pass line 20.

Catalyst 18 is generically describe as a bed that promotes reactions 3 and 4 to provide a desired exhaust gas with a lambda below one at or above the de-sulfation temperature. As this catalyst needs to heat exhaust gas quickly to a very high temperature, it also needs to be selected from materials able to withstand the temperature needed for the exhaust gas and be capable of heating exhaust gas to those temperatures quickly. Catalyst 18 can be a partial oxidation catalyst that partially oxidizes methane and reforms methane, see reaction 4. Catalyst 18 can also be a back-to-back oxidation catalyst and reformer sharing a common boundary surface. This catalyst would first oxidize methane until the oxygen potential was reduced sufficiently. These two catalysts, the oxidation catalyst and reformer, can also be disposed in line 12 in series and need not share a common boundary surface. Also, a combination reformer and oxidation catalyst could be used that integrates the reformer and oxidation catalyst together in a mixed catalyst. Each option provides trade-offs between cost and efficiency considerations that weigh in a decision as to which catalyst to use depending on the aftertreatment system sought.

As noted briefly above, referring again to fig. 1, an additional catalyst, close-coupled catalyst 32, is shown positioned near engine block 10. Some systems need such a catalyst disposed close to the engine to ensure that the exhaust gas is hot enough to support oxidation of methane.

That is, there are some aftertreatment system designs that would benefit from employing a close-coupled catalyst near the engine block so that the exhaust gas temperature under low load and / or speed or idle conditions can be prevented from falling below a threshold limit at which stable oxidation of methane in catalyst 18 would be compromised. The close-coupled catalyst would generally be physically smaller than catalyst 18 and therefore more easily accommodated near the engine. It could not replace catalyst 18 as a larger catalyst allows the system to take advantage of higher exhaust gas flows to provide a quick de-sulfation cycle. Therefore, under such conditions, there are advantages in having close-coupled catalyst 32 near engine block 10 with line 40 feeding methane upstream of such catalyst. This catalyst would then oxidize the methane provided from store 44 to heat the exhaust gas to a temperature suitable to allow catalyst 18 to light off satisfactorily.

As noted above, the de-sulfation cycle is dependant on the exhaust gas temperature. It is important that the exhaust gas introduced into catalyst 18 have a temperature above a minimum temperature to ensure that the catalyst is "lit-off" initially. One strategy for ensuring a higher exhaust gas temperature and controlling the de-sulfation process from the combustion chamber is to choose a combustion strategy or combustion timing that ensures either relatively late heat release, as might be the case with spark ignited engines. Also, a delayed or second direct injection of fuel into the combustion chamber late in the power stroke when de-sulfation is required will help to heat the exhaust gas from block 10. This can also reduce NOx levels with associated benefits during de-sulfation as a quantity of exhaust gas can be directed through the by-pass line without NOx treatment. A reduced NOx level has benefits here. Other strategies are well known to persons skilled in this technology.

As natural gas is, overwhelmingly, methane with a few additional heavier hydrocarbons, $C_2$ and $C_3$ hydrocarbons in general, the methane store 36 can be the fuel storage tanks if the engine is fueled by natural gas. That is, methane store 36 can be a natural gas source such as the engine fuel tanks.

Also, valves 34 and 36 can be injectors that would directly inject methane into exhaust line 12. Injectors would provide greater control over the timing and quantity of methane and, therefore, greater control over the duration of the de-sulfation cycle.

A metal substrate for carrying the catalyst is generally preferred, rather than, for example, a ceramic substrate, if the metal substrate improves thermal response to catalyst 18. As noted above, the quicker the thermal response the quicker the de-sulfation process can be completed, thereby reducing the amount of untreated exhaust gas allowed to flow through by-pass line 20.

An oxidation catalyst can be a component of catalyst 18, and can be any oxidization catalyst suitable for oxidizing the exhaust gas to reduce the oxygen content. By way of example, a suitable oxidation catalyst can promote the following reactions:

$$CxHy + (x+y/4)\ O_2\ (Pt) \rightarrow xCO_2 + y/2\ H_2O$$
$$CxHy + (x+y/4)\ O_2\ (Pd) \rightarrow xCO_2 + y/2\ H_2O$$
$$CxHy + (x/2)\ O_2\ (Pd) \rightarrow xCO + y/2\ H_2$$
$$CO + ½\ O_2 \rightarrow CO_2$$

By way of example only, for the operating conditions known for this application, a suitable washcoat formulation comprises $Al_2O_3$. Other suitable washcoat formulations can also be used, as would be understood by a person skilled in this technology.

A reformer can be a component of catalyst 18, and reformers suitable for this application are well known. The reformer is preferably suitable to convert methane with water to CO and $H_2$. By way of example, the reformer can be a precious metal-based catalyst with washcoat materials including $Al_2O_3$.

NOx adsorber 16 typically adsorbs and stores of NOx in the catalyst washcoat while operating under lean conditions and $NO_2$ can be released and reduced to $N_2$ under rich operating conditions when a de-sulfation mixture, that includes hydrogen and rich exhaust gas, is passed through the adsorber. As noted above, the following shows typical operation of the NOx adsorber under lean conditions:

$$NO + ½\ O_2\ (Pt) \rightarrow NO_2$$
$$XO + 2\ NO_2 + ½\ O_2 \rightarrow X(NO_3)_2$$

and under rich conditions:

$$X(NO_3)_2 \rightarrow XO + 2NO + 3/2\ O_2$$
$$X(NO_3)_2 \rightarrow XO + 2NO_2 + ½\ O_2$$

$NO + CO\ (Rh) \rightarrow \frac{1}{2} N_2 + CO_2$
$2NO_2 + 4H_2 \rightarrow N_2 + 4H_2O$

where X is provided in the washcoat and is typically an alkali (eg., K, Na, Li, Ce), an alkaline earth (eg., Ba, Ca, Sr, Mg) or a rare earth (eg., La, Yt).

A further advantage can be realized if a fuel is used that combines methane and hydrogen as two major components. By way of example, natural gas with 10 to 50% hydrogen might be appropriate as an engine fuel and appropriate for de-sulfation. Such a fuel could then be utilized in the embodiments discussed wherein the hydrogen introduced with the fuel prior to the oxidation catalyst could help to light off those catalysts and help to provide an exhaust gas environment with a lambda less than 1. Further, by providing a quantity of hydrogen into the exhaust stream, the burden on catalyst 18 is reduced. Less reforming is required for de-sulfation due to the presence of hydrogen in the injected fuel.

The method taught above for bypassing exhaust gas can also be used if hydrogen is injected into the exhaust gas. Here, the de-sulfation strategy is driven by a target de-sulfation flow through the NOx adsorber that would efficiently de-sulfate while limiting the associated fuel penalty and release of untreated NOx and NOx slip during de-sulfation. This is that much more beneficial if the engine is fueled by hydrogen, with the fuel providing a ready source of reductant, but this method would be useful, as well, if an external reformer can be used.

Whenever flow is referred to in this disclosure, it is the mass or molar flow rate of the gas in question.

Exhaust gas recirculation (EGR) can also be utilized to help reduce NOx emissions during de-sulfation when a by-pass line is opened. Increased EGR rates during de-sulfation can reduce NOx generated in the combustion chamber resulting in less NOx flowing through by-pass line 20 and into the atmosphere. Further, increases in EGR can also be used to reduce the concentration in oxygen in the exhaust gas during de-sulfation, reducing, in turn the burden on the oxidation catalyst to reduce oxygen during a de-sulfation cycle as well as reduce the amount of methane needed to burn off oxygen.

While particular elements, embodiments and applications of the present invention have been shown and described, it will be understood, of course, that the invention is not limited thereto since modifications may be made by those skilled in the art without departing from the scope of the present disclosure, particularly in light of the foregoing teachings.

**What is claimed is:**

2. An aftertreatment system for treating NOx found in exhaust gas produced during combustion of a fuel within a combustion chamber of an operating internal combustion engine, said aftertreatment system comprising:

    a. an exhaust line for directing said exhaust gas from said engine,
    b. a NOx adsorber disposed in said exhaust line,
    c. a first catalyst disposed in said exhaust line upstream of said NOx adsorber, said catalyst capable of oxidizing a reductant,
    d. a reductant line for delivering a reductant from a reductant store to said exhaust line upstream of said catalyst,
    e. a reductant flow control disposed in said reductant line for controlling flow of said reductant into said exhaust line,
    f. a de-sulfation line for directing said exhaust gas from said catalyst to said adsorber, said de-sulfation line providing a shorter path between said catalyst and said adsorber than that provided by said exhaust line, and

g. a de-sulfation flow control for controlling flow of exhaust gas through said de-sulfation line.

3. The aftertreatment system of claim 1 wherein said reductant is hydrogen.

4. The aftertreatment system of claim 1 wherein said reductant is a hydrocarbon, said catalyst capable of reducing said exhaust gas with said hydrocarbon to a lambda value below one.

5. The aftertreatment system of claim 1 wherein said catalyst is a partial oxidation catalyst.

6. The aftertreatment system of claim 1 further comprising a close coupled catalyst disposed in said exhaust line upstream of said catalyst and downstream of said reductant line

7. The aftertreatment system of claim 5 further comprising a second reductant line and a second reductant flow control, said second reductant line for delivering said reductant from said reductant store to said exhaust line downstream of said of said close coupled catalyst and upstream of said first catalyst.

8. The aftertreatment system of claim 1 wherein said reductant flow control is an injector.

9. The aftertreatment system of claim 1 wherein said de-sulfation flow control is a valve.

10. The aftertreatment system of claim 8 wherein said valve is a variable control valve.

11. The aftertreatment system of claim 1 further comprising a by-pass line and a by-pass flow control disposed in said by-pass line, said by-pass line connecting a first point in said exhaust gas line upstream of said adsorber to a second point in said exhaust line downstream from said adsorber, said by-pass flow control for controlling the flow of said exhaust gas through said by-pass line.

12. The aftertreatment system of claim 10 wherein said by-pass flow control is a valve.

13.

14. A method of operating an internal combustion engine equipped with an aftertreatment system for removing NOx from exhaust gas generated by combustion of a fuel in at least one combustion chamber of said engine, said method comprising:

during normal operation of said engine, directing all of said exhaust gas through an exhaust line to a lean NOx adsorber disposed in said exhaust line;

periodically de-sulfating said lean NOx adsorber by a de-sulfation cycle temporally defined by a de-sulfation cycle start time and a de-sulfation cycle end time, and controlling conditions within said adsorber during said de-sulfation cycle by:

a. determining a target de-sulfation temperature,
b. when the temperature of said exhaust at said NOx adsorber is below said target de-sulfation temperature, heating said exhaust gas upstream of said NOx adsorber,
c. reducing said exhaust gas with a reductant upstream of said NOx adsorber, reducing the lambda of said exhaust gas to less than one, and
d. directing said reduced exhaust gas to said adsorber and directing at least some of said reduced exhaust gas to bypass a portion of said exhaust line.

15. The method of claim 12 wherein said reductant is hydrogen.

16. The method of claim 12 wherein said reductant is a hydrocarbon.

17. The method of claim 14 wherein said hydrocarbon comprises methane.

18. The method of claim 12 further comprising determining said exhaust gas temperature by reference to at least one of:
the speed of said engine,
the load of said engine,
the intake manifold temperature of said engine,
the intake air mass flow,
the fuel flow into said engine,

the intake manifold pressure of said engine.

19. The method of claim 12 further comprising determining said exhaust gas temperature by reference to a temperature sensor provided in said exhaust line.

20. The method of claim 17 wherein said temperature sensor determines the temperature of said exhaust gas entering into said NOx adsorber.

21. The method of claim 12 wherein said reduced exhaust gas is a de-sulfation flow and a de-sulfation line provides a means for some of said de-sulfation flow to bypass portion of said exhaust line, said method further comprising:

a. determining a target de-sulfation flow through said de-sulfation line,

b. controlling flow through said de-sulfation line to be substantially equal to said target de-sulfation flow.

22. The method of claim 19 wherein said target de-sulfation flow is determined by reference to at least one of:

the speed of said engine,
the load of said engine,
the intake manifold temperature of said engine,
the intake air mass flow,
the fuel flow into said engine,
the intake manifold pressure of said engine, and
exhaust gas flow out of said engine,

23. The method of claim 12 further comprising reducing flow of said exhaust gas through said NOx adsorber by bypassing a portion of said exhaust gas around said NOx adsorber during said de-sulfation cycle.

24. The method of claim 12 wherein said de-sulfation start time is determined by reference to NOx concentrations within said exhaust gas downstream of said NOx adsorber, wherein said de-sulfation start time is triggered to occur when said NOx concentration exceeds a pre-determined threshold after a regeneration cycle of said NOx adsorber has been completed.

25. The method of claim 12 wherein said de-sulfation end time is pre-determined based on said de-sulfation start time

26. The method of any one of claims 12 through 23 wherein said reductant is also used as a fuel for said engine.

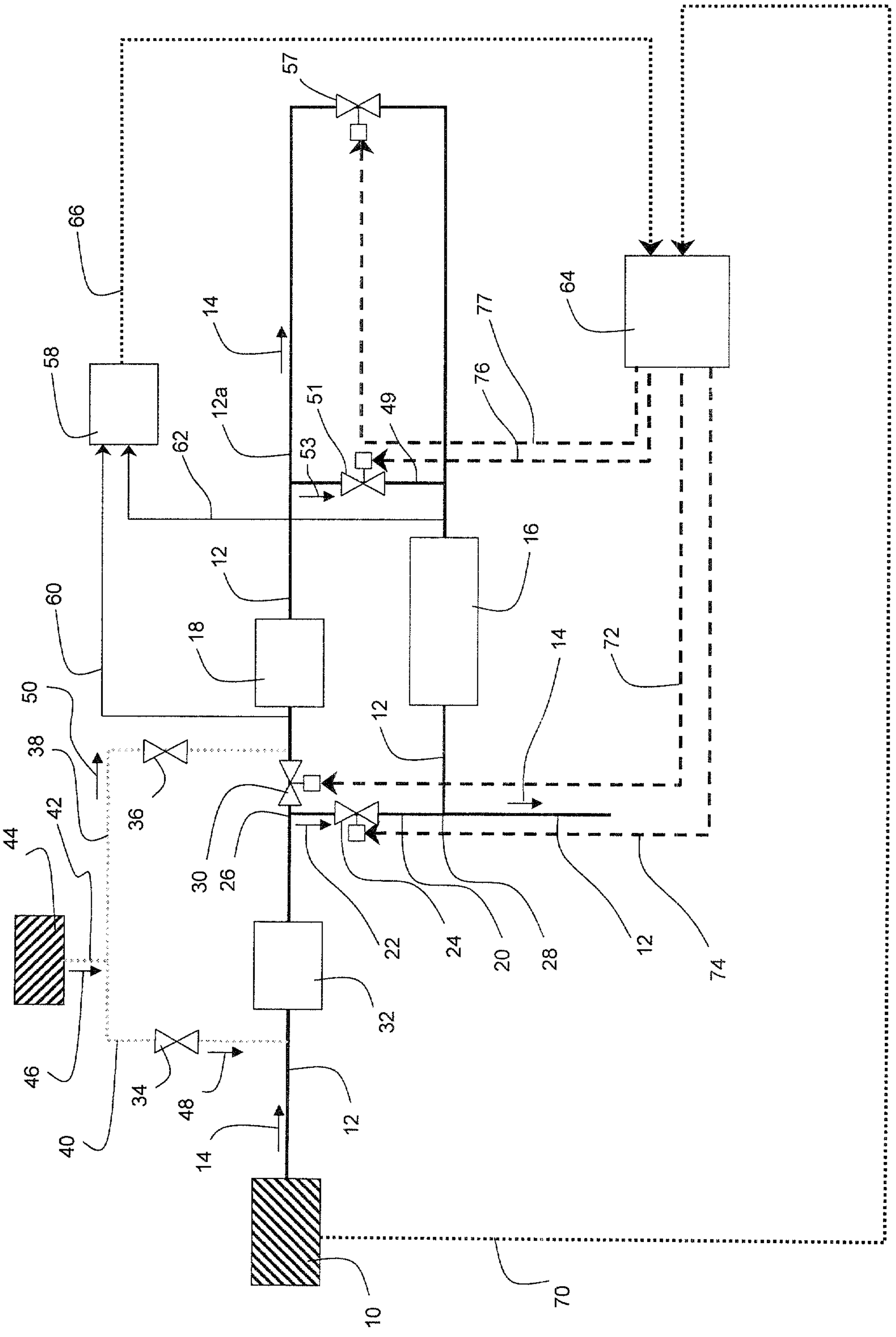

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FIG. 1

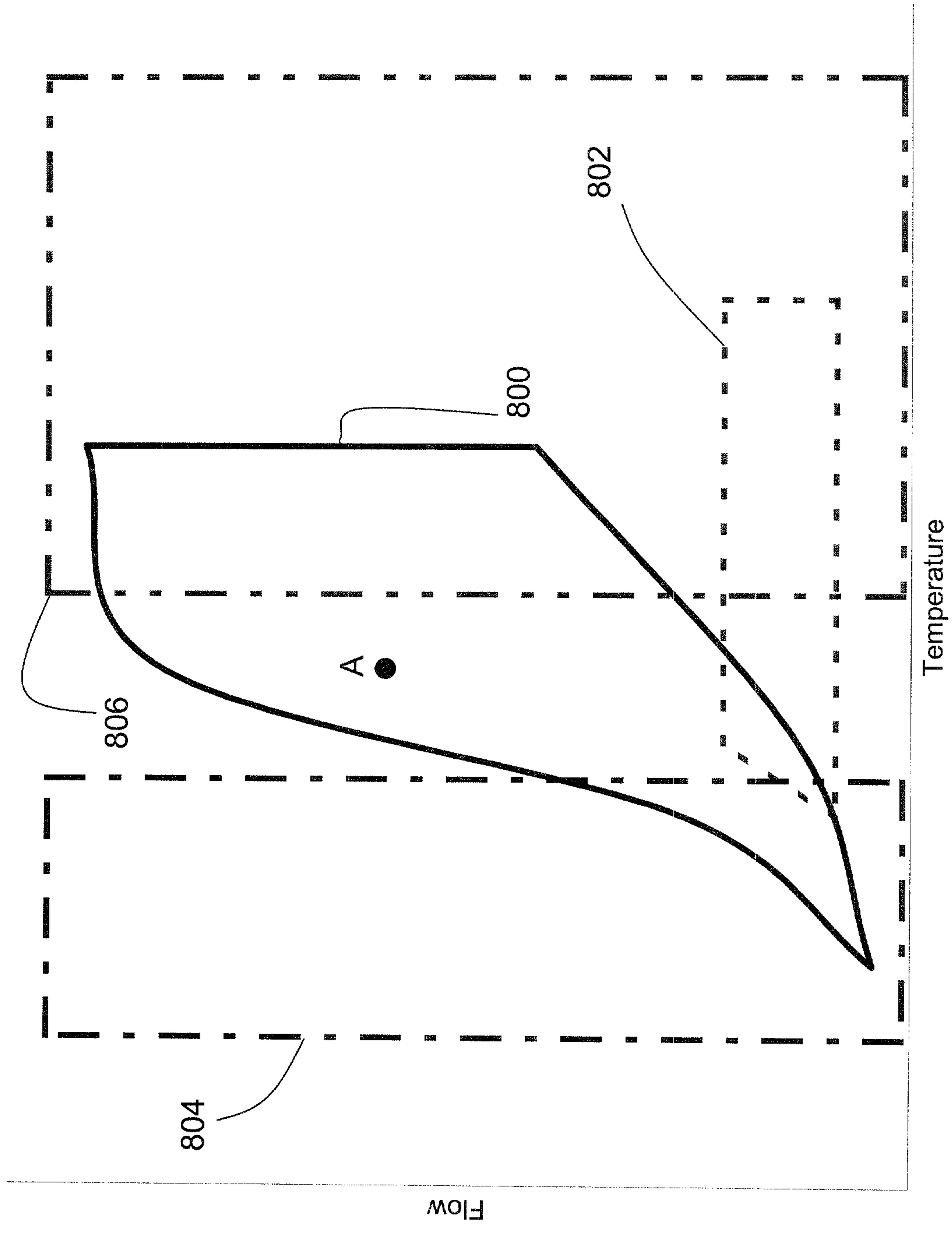
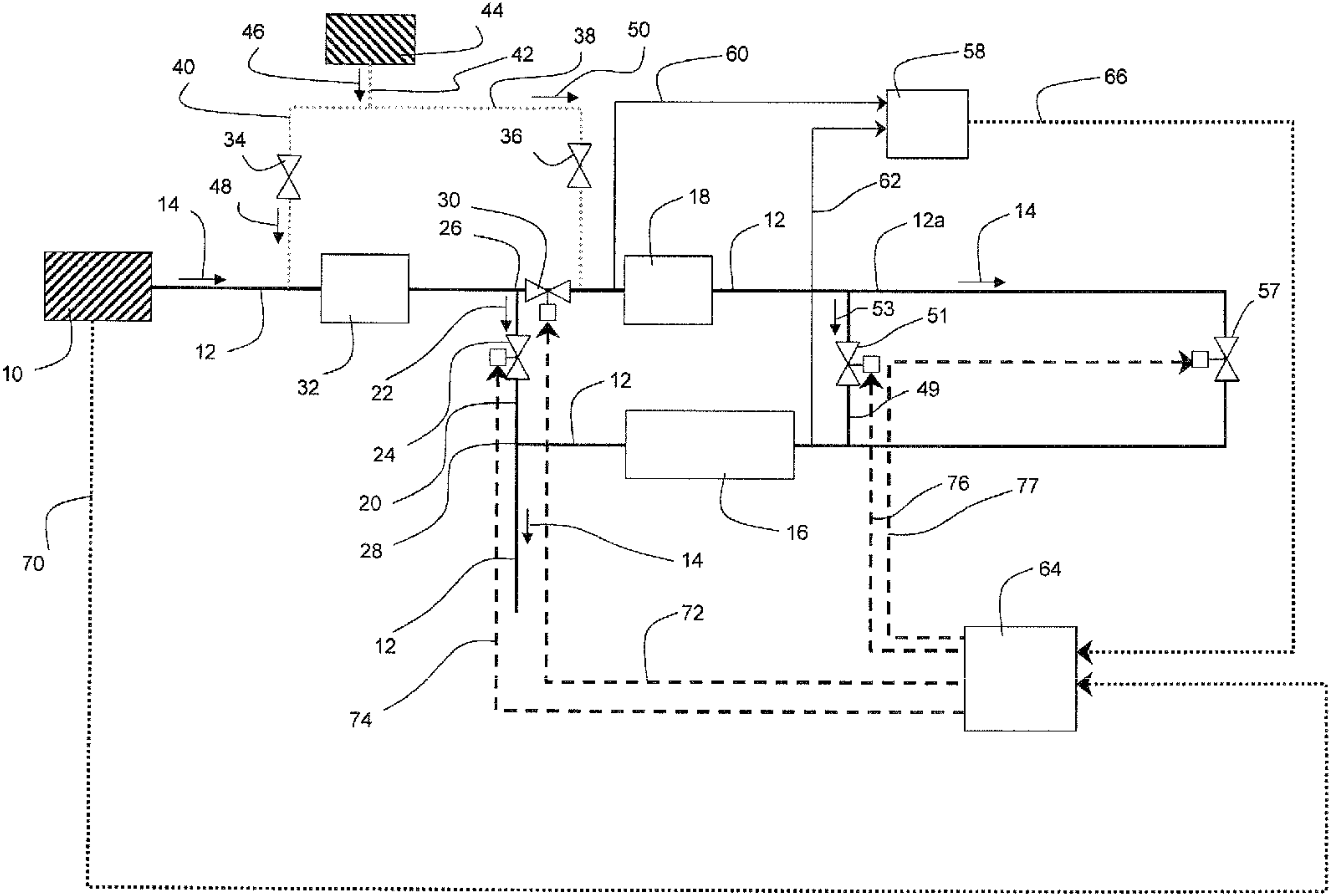


FIG. 2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