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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
24 July 2014 (24.07.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/113567 A2

(51) International Patent Classification:
G01N 33/00 (2006.01)

(21) International Application Number:
PCT/US2014/011846

(22) International Filing Date:
16 January 2014 (16.01.2014)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
13/743,789 17 January 2013 (17.01.2013) US

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(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, BN, BR, BW, BY, BZ, CA, CH, CL, 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, IR, IS, JP, KE, KG, 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, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, 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, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, 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, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to the identity of the inventor (Rule 4.17(i))*

[Continued on next page]

(54) Title: METHOD AND APPARATUS FOR ANALYSIS AND SELECTIVE CATALYTIC REDUCTION OF NO_X-CONTAINING GAS STREAMS

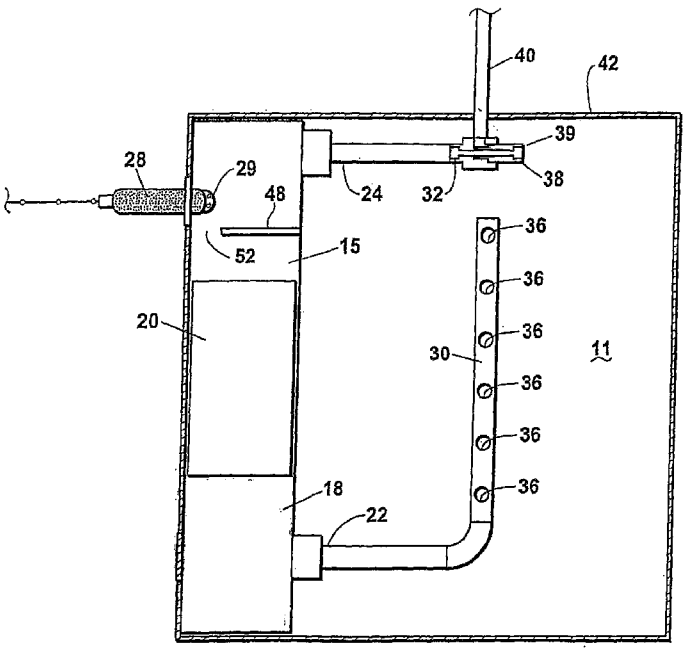


Fig. 3

(57) Abstract: An apparatus and method for measuring and controlling the NO_x content of a NO_x-containing gas stream such as, for example, a combustion engine exhaust stream discharged from a Selective Catalytic Reduction (SCR) system. The apparatus includes an analyzer container which holds an ammonia slip catalyst element and has a NOx sensor positioned therein. The NO_x sensor is positioned in the container between the ammonia slip catalyst and the container outlet. The apparatus is heated by positioning the container in the gas stream and can draw a representative gas sample from any size conduit.

WO 2014/113567 A2

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

METHOD AND APPARATUS FOR ANALYSIS AND SELECTIVE CATALYTIC REDUCTION OF NO_X-CONTAINING GAS STREAMS

FIELD OF THE INVENTION

The present invention relates to methods and apparatuses for the selective catalytic reduction of nitrogen oxide pollutants (NO_x) present in combustion engine exhaust streams, other combustion gas streams, chemical process flue or vent gas streams, recycling or recycle gas streams, or any other gas stream which may contain NO_x. The invention also relates to apparatuses and methods for measuring NO_x and ammonia slip concentrations in any NO_x-containing stream of this nature.

BACKGROUND OF THE INVENTION

Selective catalytic reduction (SCR) is used to reduce nitrogen oxide pollutant (NO_x) emissions in the exhaust gas streams produced by large combustion engines and in other NO_x-containing gas streams. Examples of large combustion engines include stationary industrial engines of all types and large diesel engines used in ships, locomotives and other transport vehicles.

By way of example, in an SCR process for a combustion engine exhaust, an ammonia source material is added to the engine exhaust and the exhaust stream is then delivered through an SCR catalyst. Examples of ammonia source materials typically used in SCR processes are urea, anhydrous ammonia, and aqueous ammonia. When the NO_x components are reacted with ammonia on the surface of the SCR catalyst, the resulting reaction products are N_2, water, and CO_2.

It is typically the case in SCR systems that an amount of unreacted urea, ammonia, or other unreacted ammonia source material will pass through the SCR catalyst. This unreacted material which passes through the SCR catalyst is referred to as "ammonia slip." Ammonia slip can occur, for example, when (a) an excessive amount of the ammonia source material is injected into the exhaust gas, (b) the temperature in the SCR system is too low, and/or (c) the activity of the SCR catalyst has declined due to fouling, degradation or other causes. If released to the atmosphere, the ammonia slip material is toxic, is a regulated pollutant, and can also react with other atmospheric constituents to form harmful pollutants.

Currently, the amount of urea, ammonia, or other ammonia source material injected into the engine exhaust upstream of the SCR catalyst is controlled based upon either (a) NO_x concentration measurements taken from the exhaust stream or (b) preexisting performance curves obtained, for example, from the engine manufacturer. Performance curves typically provide predetermined ammonia injection pump rates based upon the engine load.

Some SCR systems are also equipped with an ammonia slip catalyst element located downstream of the SCR catalyst for removing unreacted ammonia in the exhaust effluent. In theory, the addition of the ammonia slip catalyst will allow a greater amount of ammonia to be injected in order to further reduce NO_x emissions without producing increased ammonia slip emissions. However, current systems which rely upon the over-injection of urea or ammonia to achieve low NO_x emissions followed by delivering the entire exhaust stream through an ammonia slip catalyst element are disadvantageous because these systems require higher urea consumption, require the addition of an expensive ammonia slip catalyst layer, require a longer SCR reactor structure, and will not control NO_x emissions at a low single digit ppm set point.

A need therefore exists for an improved SCR system which will better control the injection of urea, ammonia, or other ammonia source material into an exhaust stream or other NO_x-containing gas stream such that (a) low NO_x emissions can be maintained or further reduced, (b) significant over-injection of the ammonia source material is prevented, and (c) the amount of ammonia slip released to the atmosphere is minimized without having to deliver the exhaust stream or other gas stream through an ammonia slip catalyst element.

In conjunction with these needed improvements, a need also exists for an improved, low cost analyzer which is effective for measuring both NO_x and ammonia slip levels in an exhaust stream or other NO_x-containing gas stream with sufficient accuracy to provide enhanced control of the ammonia injection rate while also controlling NO_x emissions at low set point values.

The analyzers currently available in the art for obtaining reliable NO_x readings for industrial engines are chemiluminescence units and chemical cell units. Unfortunately these analyzers are expensive and require complicated and/or frequent calibration procedures to provide and maintain an acceptable degree of accuracy. Moreover, neither

of these sensors measures the amount of ammonia slip remaining in the exhaust gas downstream of the SCR catalyst.

In contrast to the chemiluminescence and chemical cell analyzers used in some industrial applications, the engine control module NO_x sensors used in the catalytic converter systems of smaller automobile engines are much less expensive and do not require calibration. Unfortunately, however, these automotive NO_x sensors have not been suitable for use in large industrial applications.

Automotive-type NO_x sensors cannot distinguish between NO_x and ammonia slip present in the gas stream. Rather, the automotive-type sensors simply quantify both the NO_x and the ammonia slip material present in the gas stream as NO_x.

In addition, automotive-type NO_x sensors cannot accurately measure the overall NO_x concentration of an entire gas stream if the stream is flowing through a conduit which is more than three inches in diameter. In contrast, in an industrial SCR system, the exhaust plenum downstream of the SCR catalyst will commonly have either a circular cross-sectional diameter in the range from about 20 to about 60 inches, or will have a rectangular cross-section wherein the height and the width of the rectangular cross-section are each in the range of from about 24 to about 96 inches.

SUMMARY OF THE INVENTION

The present invention provides an apparatus and a method which address the needs and alleviate the problems discussed above. The inventive apparatus and method can be used for (a) the selective catalytic reduction of generally any type of combustion engine exhaust or other NO_x-containing stream, (b) determining both the NO_x and ammonia slip content of the gas stream, and/or (c) controlling or correcting the injection of ammonia source material in the SCR system. Moreover, in comparison to prior systems, the inventive apparatus and method (i) provide substantially the same degree of accuracy as a chemiluminescence analyzer for measuring NO_x concentration, (ii) are much less expensive, (iii) also provide ammonia slip concentration and O_2 percent concentration readings, (iv) do not require calibration, (v) do not require sample heating or filtration, and (vi) can be used in an exhaust gas conduit of any size.

Consequently, by way of example, the inventive apparatus and method are well suited for use with industrial or other large combustion engines such as (a) internal or

external reciprocating engines which burn diesel, gas, biofuels, and other fossil fuels and (b) combustion turbines which burn gas, oil, biofuels, or other fossil fuels.

In addition, by way of further example, the inventive apparatus and method are well suited for use with NO_x-containing gases generated by: boilers, burners, flares, cement kilns, other kilns, incinerators, landfill methane recovery, bio reactors, foundries, steel mills, heat treatment furnaces for steel, refineries, nitric acid plants, plants for producing explosives, semiconductor plants, glass smelting, other smelting processes, etc.

In one aspect, there is provided an apparatus for determining a NO_x content of a gas stream. The apparatus preferably comprises: a container; an ammonia slip catalyst positioned in the container; a sample inlet provided in the container upstream of the ammonia slip catalyst for receiving a sample of a gas stream; and a NO_x sensor having a sensor element positioned in the container downstream of the ammonia slip catalyst.

In another, there is provided an apparatus for determining a NO_x content and/or an ammonia slip content of a gas stream. The apparatus preferably comprises: a container; an ammonia slip catalyst positioned in the container; a sample inlet provided in the container upstream of the ammonia slip catalyst for receiving a sample of a gas stream; a first NO_x sensor having a sensor element positioned in the container upstream of the ammonia slip catalyst; and a second NO_x sensor having a sensor element positioned in the container downstream of the ammonia slip catalyst. The first and second NO_x sensors are preferably each of a type which will quantify both NO_x and ammonia present in the exhaust gas sample as NO_x. Most preferably, the first and second NO_x sensors are automotive engine control module NO_x sensors.

In another aspect, there is provided an apparatus for selective catalytic reduction comprising: a SCR catalyst; a flow passageway extending downstream from the SCR catalyst; a container, at least a portion of the container being positioned in the flow passageway; an ammonia slip catalyst positioned in the container; a sample inlet which is provided in the container upstream of the ammonia slip catalyst and is in fluid communication with the flow passageway for receiving a gas sample from the gas flow passageway; and a NO_x sensor having a sensor element positioned in the container downstream of the ammonia slip catalyst.

In another aspect, there is provided an apparatus for selective catalytic reduction comprising: a SCR catalyst; a flow passageway extending downstream from the SCR catalyst; a container, at least a portion of the container being positioned in the flow

passageway; an ammonia slip catalyst positioned in the container; a sample inlet which is provided in the container upstream of the ammonia slip catalyst and is in fluid communication with the flow passageway for receiving a gas sample from the gas flow passageway; a first NO_x sensor having a sensor element positioned in the container upstream of the ammonia slip catalyst; and a second NO_x sensor having a sensor element positioned in the container downstream of the ammonia slip catalyst. The first and second NO_x sensors are each preferably of a type which will quantify both NO_x and any ammonia present in the gas sample as NO_x. Most preferably, the first and second NO_x sensors are automotive engine control module NO_x sensors.

In another aspect, there is provided a method of determining a NO_x content of a gas stream. The method preferably comprises the steps of: (a) receiving a sample of the gas stream in an analyzer container having an ammonia slip catalyst therein; (b) conducting the sample through the ammonia slip catalyst; and (c) measuring a NO_x content value of the sample in the analyzer container downstream of the ammonia slip catalyst using a NO_x sensor which quantifies both NO_x and any ammonia present in the sample as of NO_x.

In another aspect, there is provided a method of determining a NO_x content, an ammonia slip content, or both a NO_x content and an ammonia slip content of a gas stream. The method preferably comprises the steps of: (a) receiving a sample of the gas stream in an analyzer container having an ammonia slip catalyst therein; (b) measuring a first NO_x content value of the sample in the analyzer container upstream of the ammonia slip catalyst using a first NO_x sensor which quantifies both NO_x and any ammonia present in the sample as NO_x; (c) conducting the sample through the ammonia slip catalyst; and (d) measuring a second NO_x content value of the sample in the analyzer container downstream of the ammonia slip catalyst using a second NO_x sensor which quantifies both NO_x and any ammonia present in the sample as NO_x.

In another aspect, there is provided a method for the selective catalytic reduction of a gas stream. The method preferably comprises the steps of: (a) adding an ammonia source material to the gas stream at an addition rate; (b) delivering the gas stream through an SCR catalyst; (c) obtaining a sample of the gas stream after step (b); (d) measuring a first NO_x content value of the sample using a first NO_x sensor which quantifies both NO_x and any ammonia present in the sample as NO_x; (e) delivering the sample through an ammonia slip catalyst after step (d); (f) measuring a second NO_x content value of the

sample after step (e) using a second NO_x sensor which quantifies both NO_x and any ammonia present in the sample as NO_x; and (g) controlling or correcting the addition rate of the ammonia source material used in step (a) based at least in part on the first and the second NO_x content values measured in steps (d) and (f).

In another aspect, there is provided a method for selective catalytic reduction of a gas stream wherein the method preferably comprises the steps of: (a) adding an ammonia source material to the gas stream at an addition rate; (b) delivering the gas stream through an SCR catalyst; (c) obtaining a sample of the gas stream after step (b); (d) delivering the sample through an ammonia slip catalyst; (e) measuring a NO_x content value of the sample after step (d) using a NO_x sensor; and (f) controlling or correcting said addition rate of the ammonia source material used in step (a) based at least in part on the NO_x content value measured in step (e). The ammonia slip catalyst is preferably located in an analyzer container and the sensor element of the NO_x sensor is also preferably located in the analyzer container between the ammonia slip catalyst and the outlet of the analyzer container.

Further aspect features and advantages of the present invention will be apparent to those of ordinary skill in the art upon examining the accompanying drawings and upon reading the following detailed description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A and 1B schematically illustrate an embodiment **2** of the SCR apparatus and method provided by the present invention.

FIG. 2 schematically illustrates an embodiment of the NO_x and ammonia slip analyzer **15** provided by the present invention.

FIG. 3 schematically illustrates an alternative embodiment of the inventive analyzer **15** for measuring the NO_x content and the O_2 content of a gas stream.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

An embodiment **2** of the inventive selective catalytic reduction (SCR) apparatus provided by the present invention for treating a combustion engine exhaust stream is illustrated in FIGS. 1 and 2. However, it will be understood that, as explained above, the applications and uses of the inventive apparatuses and methods described and claimed

herein extend well beyond the analysis and treatment of just engine exhaust streams but can be used for any NO_x-containing gas stream.

The inventive SCR apparatus **2** comprises: an SCR housing **6** having an SCR catalyst element **8** positioned therein; a pipe, housing, duct, manifold, or other conduit **10** which delivers an engine exhaust gas stream from a diesel or other combustion engine **4** to the SCR catalyst housing **6**; and injection line **12** for injecting urea, anhydrous ammonia, aqueous ammonia, or other suitable ammonia source material into the conduit **10** upstream of the SCR catalyst element **8**; an exhaust gas discharge passageway **11** formed inside the latter portion of the SCR housing **6** and/or inside a discharge conduit **13** connected to the SCR housing **6**; an embodiment **15** of an inventive NO_x and ammonia slip analyzer positioned in the exhaust discharge passageway **11** downstream of the SCR catalyst element **8;** and an exhaust stack **16** for discharging the exhaust gas stream to the atmosphere.

As noted above, the engine **4** can be generally any type of industrial, stationary, and/or other large combustion engine. Due to the volume of the exhaust gas which these engines produce, the cross-sectional area of the exhaust discharge passageway **11** wherein the inventive NO_x and ammonia slip analyzer **15** is located will typically be at least 4 ft^2 and will more typically be in the range of from 16 ft^2 to about 100 ft^2. Consequently, if the exhaust discharge passageway **11** in which the inventive analyzer **15** is located is substantially cylindrical, the cross-sectional diameter of the passageway **11** will typically be at least 20 inches and will more typically be in the range from 36 to about 96 inches. On the other hand, if the exhaust discharge passageway **11** has a substantially rectangular cross-sectional shape, the height and width of the passageway **11** will each typically be at least 20 inches and will more typically be in the range from 36 to about 120 inches.

The SCR catalyst **8** used in the inventive SCR apparatus **2** can be generally any type, structure, and composition of SCR catalyst used in the art for reducing NO_x emissions in a combustion engine exhaust. Examples include, but are not limited to, vanadium pentoxide, zeolite, zeolite copper, and three-way (TWC) SCR catalysts. SCR catalysts are also commonly supported on substrates such as, for example, ceramic honeycomb and metallic foil materials.

As noted above, the inventive NO_x and ammonia slip analyzer **15** is installed in the exhaust discharge passageway **11** of the SCR apparatus **2** downstream of the SCR catalyst element **8**. As illustrated in FIG. 2, the inventive NO_x and ammonia slip analyzer

15 preferably comprises: a sealed box or other container **18** which is entirely or at least partially positioned within the exhaust discharge passageway **11** such that the container **18** is contacted and heated by the exhaust gas stream; an ammonia slip catalyst **20** positioned inside the container **18**; a container inlet **22** upstream of the ammonia slip catalyst **20** for receiving an exhaust gas sample from the exhaust discharge passageway **11**; a container outlet **24** positioned downstream of the ammonia slip catalyst **20** for discharging the sample from the container **18**; a first NO_x sensor **26** having a sensor element **27** positioned in the container **18** upstream of the ammonia slip catalyst **20**; a second NO_x sensor **28** having a sensor element **29** positioned in the container **18** downstream of the ammonia slip catalyst element **20**; a sample tube **30** connected to the container inlet **22** for collecting a representative cross-sectional sample of the exhaust gas stream flowing through the exhaust discharge passageway **11**; and a suction device **32** connected to the container outlet **24** for drawing the exhaust gas sample into the sample tube **30** and pulling the sample through the analyzer container **18**. The suction device **32** preferably discharges the exhaust gas sample back into the exhaust gas stream flowing through the exhaust discharge passageway **11**.

The first and second NO_x sensors **26** and **28** used in the inventive analyzer **15** can be low cost sensors of the type which quantify both NO_x and unreacted ammonia as NO_x. Thus, for example, if the exhaust gas sample received in the container inlet **22** has an actual NO_x concentration of 10 ppm and an actual ammonia concentration of 5 ppm, the reading provided by the first NO_x sensor **26** will indicate that the NO_x concentration of the incoming sample is about 15 ppm.

The first and second NO_x sensors **26** and **28** used in the inventive analyzer **15** will most preferably be automotive engine control module NO_x sensors. Automotive engine control module NO_x sensors suitable for use in the inventive NO_x and ammonia slip analyzer **15** are commercially available, for example, from ECM, Continental, and NGK. The NO_x sensors **26** and **28** will preferably be electronically linked together by a CAN open bus.

In addition to measuring the NO_x concentration of the exhaust gas, automotive-type NO_x sensors **26** and **28** will also measure the actual oxygen concentration of the exhaust gas sample. As will be discussed below, the measurement of the actual oxygen concentration of the exhaust gas can be used along with the NO_x and ammonia slip readings provided by the inventive analyzer **15** to further enhance the ability of the

inventive SCR system to more precisely control the injection of the ammonia source material upstream of the SCR catalyst element **8**.

The sample tube **30** used in the inventive analyzer **15** can be generally any type of tube which is effective for drawing a representative sample of the exhaust gas stream across at least most of the cross-section of the exhaust discharge passageway **11**. The sample tube **34** preferably includes a plurality of sample inlet openings **36** and will preferably be oriented such that the series of openings **36** extends either vertically, horizontally, or diagonally across at least most of the cross-section of the exhaust discharge passageway **11**. The inlet openings **36** will preferably be drilled or other openings which are from about 1/8 to about 1/2 inch in diameter or width. In addition, the number of inlet openings **36** provided in the series of openings **36** will preferably be in the range from about 2 to about 6 openings **36** per ft.

As noted above, automotive-type NO_x sensors are not highly effective for direct use in conduits which are more than 3 inches in diameter or width. Consequently, as one alternative, the container **18** of the inventive analyzer **15** can be an elongate container which extends either horizontally or vertically within the exhaust discharge passageway **11** and has either a substantially circular cross-section of not more than 3 inches in diameter or a substantially rectangular cross-section of equivalent size. More preferably, however, the container will have a larger rectangular or similar cross-sectional shape in the range of from about 3 x 3 inches to about 12 x 12 inches, most preferably about 6 x 6 inches, but will also include interior baffles **46** and **48** which increase the sample flow velocity in the vicinity of the NO_X sensor elements **27** and **29**. The interior baffles **46** and **48** preferably form reduced flow areas **50** and **52** in the vicinity of the NO_x sensor elements **27** and **29** which are each less than 10 in^2 in size. The baffles **46** and **48** will more preferably form reduced flow areas **50** and **52** which are each less than 9 in^2 and which are most preferably about 7.5 in^2 in size.

The analyzer container **18** is preferably formed of stainless steel or other suitable material which is corrosion resistant and will conduct heat energy. The container **18** is entirely or at least partially located inside the exhaust discharge passageway **11** so that the exhaust gas flowing through the exhaust discharge passageway **11** will contact the analyzer container **18** and will heat the container **18** and the ammonia slip catalyst element **20** contained therein. Preferably, a sufficient portion of the container will be contacted and heated by the exhaust gas such that most, and more preferably all or

substantially all, of the ammonia slip material in the exhaust gas sample will be reacted as it passes through the ammonia slip catalyst **20**. Typically, therefore, the ammonia slip catalyst will be heated to a temperature of at least 500°F and will preferably be heated to a temperature in the range of from about 500°F to about 1100°F.

The ammonia slip catalyst **20** used in the inventive NO_x and ammonia slip analyzer **15** can be of generally any structure and composition effective for removing at least most and preferably all or substantially all of the ammonia slip material present in the exhaust gas sample. Ammonia slip catalysts are readily available in the market and substantially any commercially available ammonia slip catalyst can be used in the inventive NO_x and ammonia slip analyzer **15.** By way of example, but not by way of limitation, ammonia slip catalyst elements are commercially available from Johnson-Matthey, HVG, ECOCAT, and other manufacturers.

The suction device **32** used with the inventive NO_x ammonia slip analyzer **15** will preferably be a device capable of pulling a sample in the range from about 2 to about 6 actual cubic feet per minute, more preferably about 4 actual cubic feet per minute, through the sample tube **30**, the container **18**, and the ammonia slip catalyst **20**. The suction device **32** will also preferably return the sample to the exhaust gas flow stream.

As illustrated in FIG. 2, the suction device **32** preferably comprises a venturi vacuum element **38** wherein the venturi element **38** and the discharge outlet **39** thereof are positioned within the exhaust discharge passageway **11** downstream of the SCR catalyst element **8**. A motive fluid line **40** extends through the wall **42** of the exhaust gas passageway **11** to the venturi vacuum element **38** to deliver a motive fluid, preferably compressed (i.e., pressurized) air, to the venturi device **38** to create a vacuum at the container outlet **24**. The amount of compressed air required to operate the venturi vacuum device **38** will typically be in the range from about 2 to about 6 standard cubic feet per minute, more preferably about 4 standard cubic feet per minute, and will simply be discharged along with the used exhaust sample into the exhaust gas flow stream.

In the method of the present invention, the exhaust from the combustion engine **4** flows through the tailpipe or other conduit **10** to the SCR housing **6**. To reduce and control NO_x emissions from the combustion engine **4**, urea, anhydrous ammonia, aqueous ammonia, or other ammonia source material is injected into the engine exhaust stream via the injection line **12** and mixes with the exhaust stream as the exhaust stream flows through the conduit **10**.

Following the injection of the ammonia source material, the exhaust gas and ammonia source material mixture flow through the SCR catalyst element **8**. If the ammonia source material is urea, at least a portion of the NO_x and urea present in the engine exhaust are converted by contact with the SCR catalyst to nitrogen, water and carbon dioxide. If the ammonia source material is ammonia, at least a portion of the NO_x and ammonia present in the engine exhaust will be converted to nitrogen and water.

Subsequently, as the treated exhaust gas stream leaves the SCR catalyst element **8** and flows through exhaust discharge passageway **11**, the suction element **38** of the inventive NO_x and ammonia slip analyzer **15** pulls a representative cross-sectional sample of the exhaust gas stream through the sample tube **34** and into the inlet **22** of the analyzer container **18**. Inside the inlet portion of the analyzer container **18**, the first NO_x sensor **26** operates to provide an actual NO_x concentration reading and an actual oxygen concentration reading for the exhaust gas sample. However, because the first NO_x sensor **26** is not capable of distinguishing NO_x from ammonia slip material remaining in the exhaust gas, any ammonia slip material in the exhaust gas is also included in the total NO_x concentration reading provided by the first sensor **26**.

Next, the exhaust gas sample is pulled by the suction device **38** through the ammonia slip catalyst element **20**. At the same time, the ammonia slip catalyst element **20** is heated by the exhaust gas stream flowing through the exhaust discharge passageway **11** due to the contact between the exhaust gas stream and the analyzer container **18**. Thus, all or substantially all of the ammonia slip material present in the exhaust gas sample reacts in the presence of the catalyst **20** and is effectively eliminated from the sample stream.

Consequently, as the sample stream flows out of the ammonia slip catalyst element **20** toward the container outlet **24**, the second NO_x sensor **28** is able to obtain an actual NO_x concentration reading which cannot be affected by the presence of any significant amount of ammonia slip material. The NO_x reading provided by the second NO_x sensor **28** can therefore be subtracted from or otherwise compared to the NO_x reading provided by the first NO_x sensor **26** to provide values which are substantially equal to, or which at least sufficiently approximate, the actual NO_x concentration and ammonia slip concentration of the exhaust gas stream.

In one embodiment of the inventive method, NO_x and/or ammonia slip concentration values provided by the inventive analyzer **15** can be used in a feedback

control loop to directly control the ammonia source injection rate (e.g., the injection pump speed) for the inventive SCR apparatus **2**. For example, the corrected NO_x value provided by subtraction, or by otherwise comparing the NO_x reading of the second sensor **28** to the NO_x reading of the first sensor **26,** can (by means, e.g., of a proportional-integral-derivative (PID) controller) be used to control the ammonia source injection rate against a NO_x set point entered by the operator.

Moreover, if the NO_x control set point for the SCR system is based upon a referenced oxygen percent value for the exhaust which is different from the actual oxygen concentration of the exhaust gas as measured by the inventive analyzer **15**, any NO_x concentration value determined using either or both of the dual NO_x sensors **26** and **28** of the inventive analyzer **15** can be converted from an actual to a referenced oxygen concentration basis using the following formula:

NO_x reference = NO_x actual * (21-reference percent oxygen)/(21-actual percent oxygen).

Alternatively or in addition, the ammonia slip concentration value provided by the inventive analyzer **15** can be used as a feedback correction or control factor, for example, to either (a) correct the ammonia source injection rate against an ammonia slip set point entered by the operator or (b) modify either a predictive or feedback NO_x control signal for controlling the ammonia source injection rate.

In a presently preferred embodiment of the inventive method, the ammonia source injection rate will be controlled using both (a) a predicted injection rate provided by an injection map based upon the operating load (e.g. KW or brake horsepower) or other output of the engine **4** and (b) one or more feedback correction factors based upon the NO_x and/or ammonia slip content values provided by the inventive analyzer **15**. The predictive injection map for the engine **4** and SCR system **2** will either be provided by the engine manufacturer or will be generated when the engine **4** is installed and commissioned. The map will preferably provide predicted ammonia injection rates for meeting the designated NO_x set point for the SCR system over a range of engine loads.

By way of example, but not by way of limitation, the feedback correction factor(s) provided in this embodiment by the inventive analyzer **15** could be based upon: (i) a corrected NO_x content value (with actual O_2 content correction if needed) obtained by comparing the NO_x reading of the second NO_x sensor **28** to the NO_x reading of the first NO_x sensor **26;** (ii) the NO_x reading provided by the first NO_x sensor **26** corrected (e.g.,

either by inclusion in the same control algorithm or separately) by the ammonia slip content value provided by the inventive analyzer **15**; and/or (iii) an injection rate correction provided by comparing the ammonia slip content value provided by the inventive analyzer **15** to an ammonia slip set point.

An alternative embodiment of the inventive analyzer **15** is illustrated in FIG. 3. As with the embodiment illustrated in FIG. 2, the embodiment of the inventive analyzer **15** shown in FIG. 3 is positioned downstream of the SCR catalyst **8** in the exhaust discharge passageway **11** of the same SCR apparatus **2** illustrated in FIGS. 1A and 1B. In addition, the embodiment of the inventive analyzer **15** in FIG. 3 is identical to the embodiment of FIG. 2 except that the FIG 3 embodiment does not include a NO_x sensor **26** and flow baffle **46** upstream of the ammonia slip catalyst **20**. All other components of the FIG. 3 embodiment of the inventive analyzer **15** are preferably of the same type and are preferably constructed and operate in the same manner as all of the correspondingly numbered components which are shown in FIG. 2 which have already been described above.

Because it does not include an additional NO_x analyzer upstream of the ammonia slip catalyst **20**, the FIG. 3 embodiment of the inventive analyzer **15** does not provide a calculation of the ammonia slip content of the gas stream. However, given that most existing SCR systems provide warranted ammonia slip control values of less than 10 ppm and that the warranted slip control values of the newest SCR systems are less than 5 ppm, the single NO_x measurement provided by the sensor **28** downstream of ammonia slip catalyst **20** will be sufficiently accurate for use in most systems for (a) measuring the NO_x content of the exhaust gas downstream of the SCR catalyst **8** and/or (b) controlling or correcting the addition rate of the ammonia source material injected into the SCR system **2** upstream of the SCR catalyst **8**. In addition, the NO_x analyzer **28** will also measure the O_2 content of the gas stream for use, if needed as explained above, in converting the actual NO_x concentration value measured by the analyzer **28** to a normalized concentration value based upon a referenced oxygen concentration used in establishing a control set point for the SCR system.

By way of example, if the exhaust gas flowing through the exhaust passageway **11** downstream of the SCR catalyst **8** has a NO_x content of 15 ppm and an ammonia content of 0 ppm, the analyzer **15** of FIG. 3 will measure and report the NO_x content of the gas stream as 15 ppm.

On the other hand, if for example the gas stream flowing through the exhaust discharge passageway **11** downstream of the SCR catalyst **8** has a NO_x content of 15 ppm and an ammonia content of 5 ppm, the analyzer **15** of FIG. 3 will measure and report a NO_x concentration value of from 15 to 16 ppm, which is acceptable for recordation and control purposes. The ammonia slip catalysts of the type identified above which are currently used in the industry provide ammonia conversion values of from 80% to 90% or higher. Consequently, even assuming that (a) an excessive ammonia slip concentration of 5 ppm is present in the exhaust gas and (b) the ammonia slip catalyst **20** only provides a least favorable conversion of just 80%, only 1 ppm of ammonia would remain in the gas sample downstream of the slip catalyst **20** and would be measured and reported by the NO_x sensor **28** as NO_x.

In addition, however, if it is desired that the ammonia slip content of the exhaust gas or other gas stream downstream of an SCR catalyst also be determined, an ammonia sensor of the type currently available from Delphi can readily be installed in the inventive analyzer **15** of FIG. 3 upstream of the ammonia slip catalyst **20**.

* * * *

Thus, the present invention is well adapted to carry out the objects and attain the ends and advantages mentioned above as well as those inherent therein. While presently preferred embodiments have been described for purposes of this disclosure, numerous changes and modifications will be apparent to those of ordinary skill in the art. Such changes and modifications are encompassed within the invention as defined by the claims.

CLAIMS

What is claimed is:

1. An apparatus for determining a NO_x content of a gas stream comprising:

a container;

an ammonia slip catalyst positioned in said container;

said container having a sample inlet upstream of said ammonia slip catalyst for receiving a sample of a gas stream; and

a NO_x sensor having a sensor element positioned in said container downstream of said ammonia slip catalyst.

2. The apparatus of claim **1** wherein said NO_x sensor is of a type which will quantify both NO_x and any ammonia present in said sample as NO_x.

3. The apparatus of claim **1** wherein;

said container further comprises a sample outlet downstream of said ammonia slip catalyst and

said apparatus further comprises a suction device connected to said sample outlet for drawing said sample into said sample inlet, through said ammonia slip catalyst, and out of said sample outlet.

4. The apparatus of claim **3** wherein said suction device comprises a venturi vacuum element.

5. The apparatus of claim **3** further comprising a sampling tube for delivering said sample to said sample inlet of said container, said sampling tube having a series of sample receiving openings provided therein.

6. The apparatus of claim **5** wherein:

said sample receiving openings each have a diameter of at least ¼ inch,

said series of said sample receiving openings extends from a first to a last of said sample receiving openings, and

said series of said sample receiving openings has from about 2 to about 6 of said sample receiving openings per foot.

7. The apparatus of claim **1** wherein said NO_x sensor also measures an oxygen concentration value for said sample.

8. The apparatus of claim **1** further comprising an additional NO_x sensor having a sensor element positioned in said container upstream of said ammonia slip catalyst, wherein said NO_x sensor having a sensor element positioned downstream of said

ammonia slip catalyst and said additional NO_x sensor having a sensor element positioned upstream of said ammonia slip catalyst are each of a type which will quantify both NO_x and any ammonia present in said sample as NO_x.

9. An apparatus for selective catalytic reduction comprising:

a SCR catalyst;

a flow passageway extending downstream from said SCR catalyst;

a container, at least a portion of said container being positioned in said flow passageway;

an ammonia slip catalyst positioned in said container;

said container having a sample inlet upstream of said ammonia slip catalyst, said sample inlet being in fluid communication with said flow passageway for receiving a gas sample from said flow passageway; and

a NO_x sensor having a sensor element positioned in said container downstream of said ammonia slip catalyst.

10. The apparatus of claim **9** wherein said NO_x sensor is of a type which will quantify both NO_x and any ammonia present in said gas sample as NO_x.

11. The apparatus of claim **9** wherein:

said container further comprises a sample outlet downstream of said ammonia slip catalyst and

said apparatus further comprises a suction device connected to said sample outlet for drawing said gas sample from said gas flow passageway into said sample inlet, through said ammonia slip catalyst, and out of said sample outlet.

12. The apparatus of claim **11** wherein said suction device has a discharge outlet located in said flow passageway.

13. The apparatus of claim **12** wherein said suction device comprises a venturi vacuum element positioned in said flow passageway.

14. The apparatus of claim **13** further comprising a pressurized air line extending into said flow passageway to said venturi vacuum element.

15. The apparatus of claim **11** further comprising a sampling tube for delivering said sample to said sample inlet of said container, said sampling tube having a series of sample receiving openings provided therein and said series of sample receiving openings being positioned in said flow passageway.

16. The apparatus of claim **15** wherein said series of sample receiving openings of said sampling tube extends traversely across at least most of a cross-sectional width, a cross-sectional height, a cross-sectional diagonal dimension, or a cross-sectional diameter of said flow passageway.

17. The apparatus of claim **9** further comprising an additional NO_x sensor having a sensor element positioned in said container upstream of said ammonia slip catalyst, wherein said NO_x sensor having a sensor element positioned downstream of said ammonia slip catalyst and said additional NO_x sensor having a sensor element positioned upstream of said ammonia slip catalyst are each of a type which will quantify both NO_x and any ammonia present in said sample as NO_x.

18. A method of determining a NO_x content of a gas stream comprising the steps of:

(a) receiving a sample of said gas stream in an analyzer container having an ammonia slip catalyst therein;

(b) conducting said sample through said ammonia slip catalyst; and

(c) measuring a NO_x content value of said sample in said analyzer container downstream of said ammonia slip catalyst using a NO_x sensor which quantifies both NO_x and any ammonia present in said sample as NO_x.

19. The method of claim **18** wherein said ammonia slip catalyst operates in step (b) to convert at least most, if any, ammonia slip material present in said sample to reaction products comprising nitrogen and water.

20. The method of claim **18** wherein said NO_x sensor is an automotive-type NO_x sensor.

21. The method of claim **18** further comprising the step of heating said ammonia slip catalyst by contacting at least a portion of said analyzer container with said gas stream.

22. The method of claim **18** wherein:

said analyzer container has a sample outlet downstream of said ammonia slip catalyst and

said sample is drawn into said analyzer container in step (a) and through said ammonia slip catalyst in step (b) using a venturi vacuum element which also pulls said sample out of said sample outlet.

23. The method of claim **22** wherein said venturi vacuum element discharges said sample back into said gas stream.

24. The method of claim **18** wherein:

said gas stream is flowing through a flow passageway having a cross-sectional width, a cross-sectional height, a cross-sectional diameter, or other cross-sectional dimension of at least 20 inches and

said sample is drawn into said analyzer container from said flow passageway in step (a) through a sample tube having a series of inlet openings which extend transversely in said flow passageway across at least most of said cross-sectional dimension.

25. The method of claim **18** further comprising the step, prior to step (c), of measuring a NO_x content value of said sample in said analyzer container upstream of said ammonia slip catalyst using an additional NO_x sensor which quantifies both NO_x and any ammonia present in said sample as NO_x.

26. The method of claim **25** further comprising the step of determining an ammonia slip content value of said sample by comparing said NOx content value measured downstream of said ammonia slip catalyst to said NOx content value measured upstream of said ammonia slip catalyst.

27. A method for selective catalytic reduction of a gas stream comprising the steps of:

(a) adding an ammonia source material to said gas stream at an addition rate;

(b) delivering said gas stream through an SCR catalyst;

(c) obtaining a sample of said gas stream after step (b);

(d) delivering said sample through an ammonia slip catalyst ;

(e) measuring a NO_x content value of said sample after step (d) using a NO_x sensor; and

(f) controlling or correcting said addition rate of said ammonia source material used in step (a) based at least in part on said NO_x content value measured in step (e),

wherein said ammonia slip catalyst is located in an analyzer container and said NO_x sensor has a sensor element located in said analyzer container between said ammonia slip catalyst and an outlet of said analyzer container.

28. The method of claim **27** wherein said ammonia slip catalyst operates in step (d) to convert at least most, if any, ammonia slip material present in said sample to other reaction products, said other reaction products comprising nitrogen and water.

29. The method of claim **27** wherein said ammonia source material is urea or ammonia.

30. The method of claim **27** where said NO_x sensor quantifies both NO_x and any ammonia present in said sample as NO_x.

31. The method of claim **27** further comprising the step of heating said ammonia slip catalyst by contacting at least a portion of said analyzer container with said gas stream.

32. The method of claim **27** wherein said sample is obtained in step (c) by drawing said sample into an inlet of said analyzer container using a suction device connected to said outlet of said analyzer container.

33. The method of claim **32** wherein said suction device comprises a venturi vacuum element which returns said sample to said gas stream.

34. The method of claim **27** wherein:

in step (c), said gas stream is flowing through a flow passageway having a cross-sectional width, a cross-sectional height, a cross-sectional diameter, and other cross-sectional dimension of at least 20 inches and

said sample is obtained in step (c) by drawing said sample into said inlet of said analyzer container through a sample tube having a series of inlet openings which extend transversely in said flow passageway across at least most of said cross-sectional dimension.

35. The method of claim **34** wherein at least a portion of said analyzer container is positioned in said flow passageway.

36. The method of claim **27** further comprising the step, prior to step (d), of measuring a NO_x content value of said sample using an additional NO_x sensor having a sensor element located in said analyzer container between said ammonia slip catalyst and an inlet of said analyzer container and wherein said addition rate of said ammonia source material used in step (a) is controlled or corrected in step (f) based at least in part on a comparison of said NO_x content value of said sample measured after step (d) to said NO_x content value of said sample measured prior to step (d).

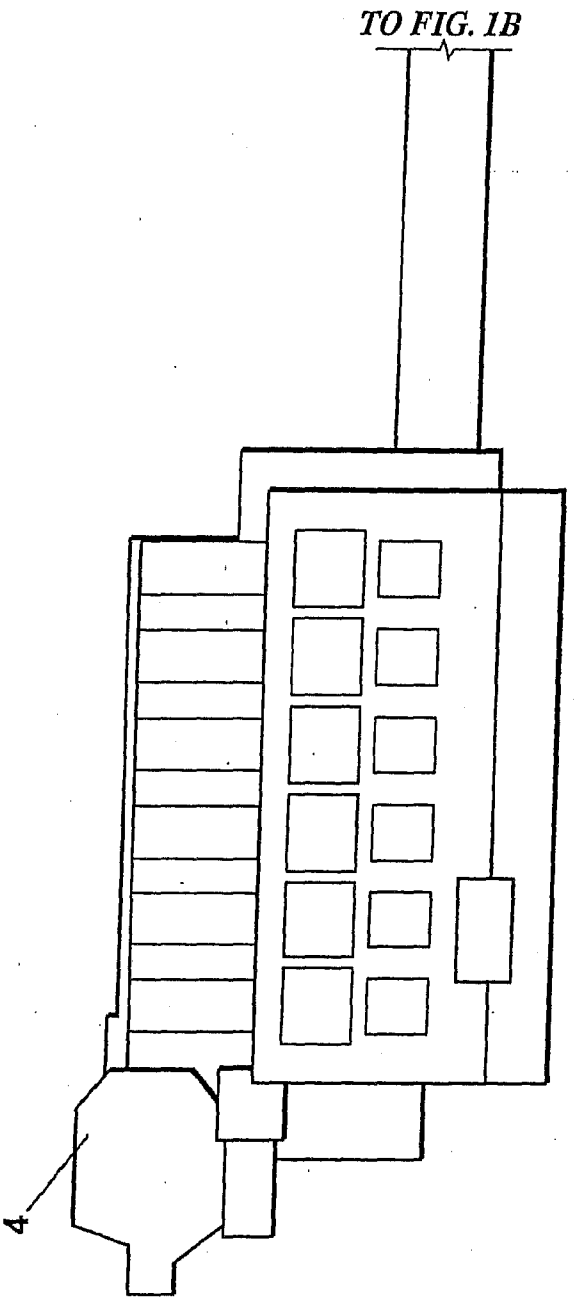


Fig. 1A

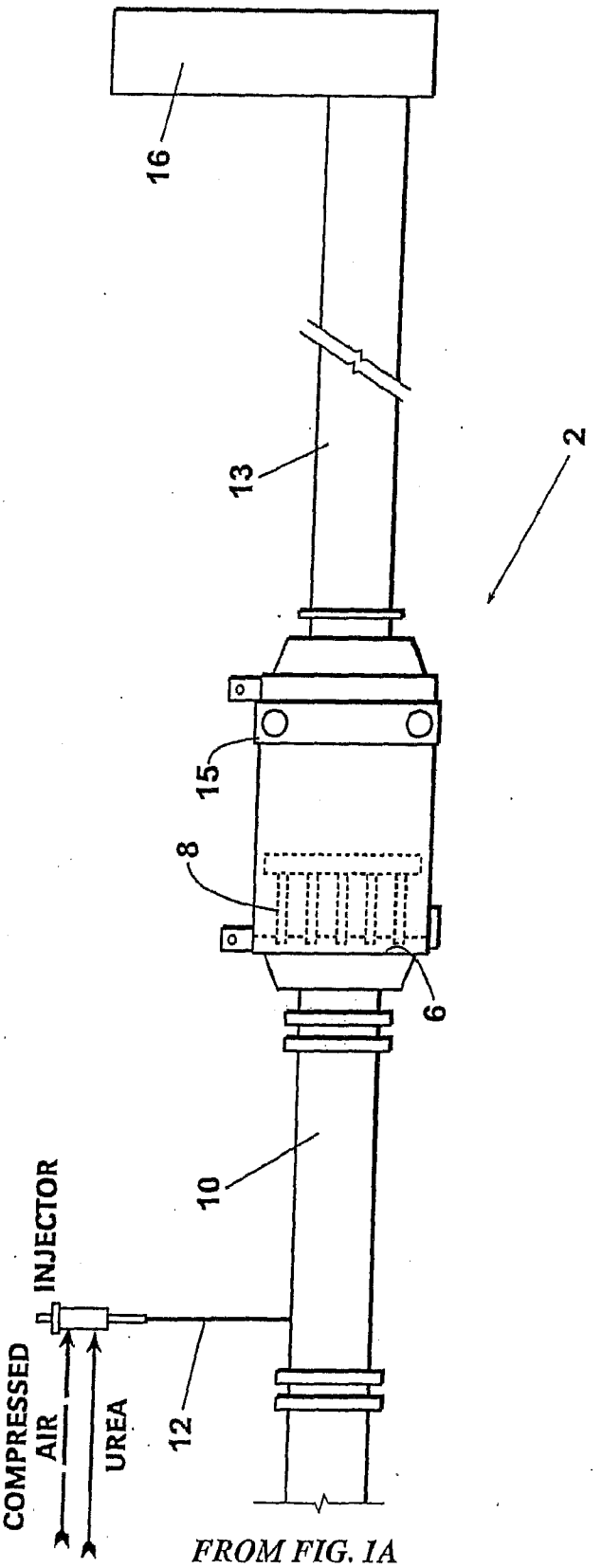


Fig. 1B

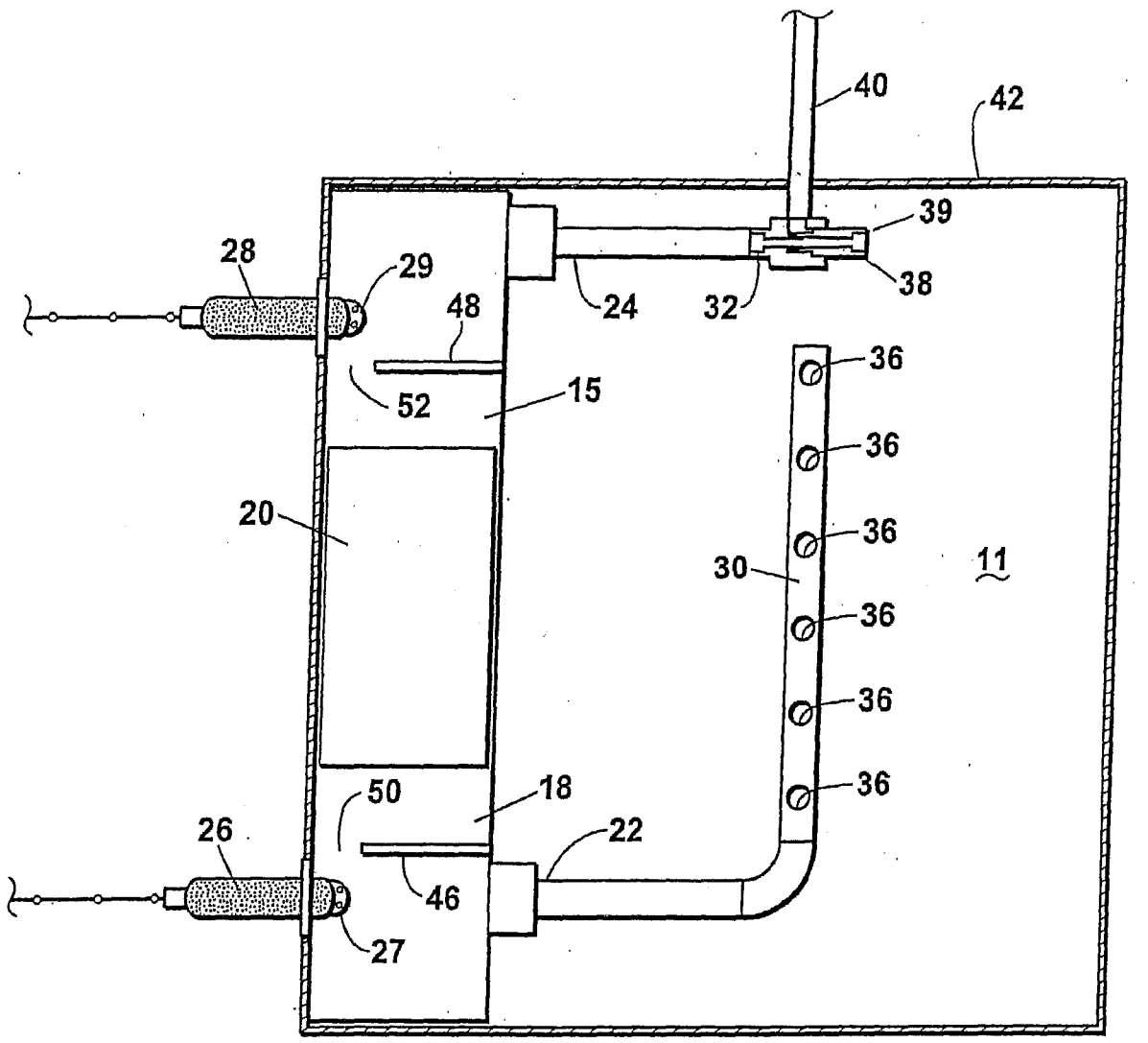

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Fig. 2

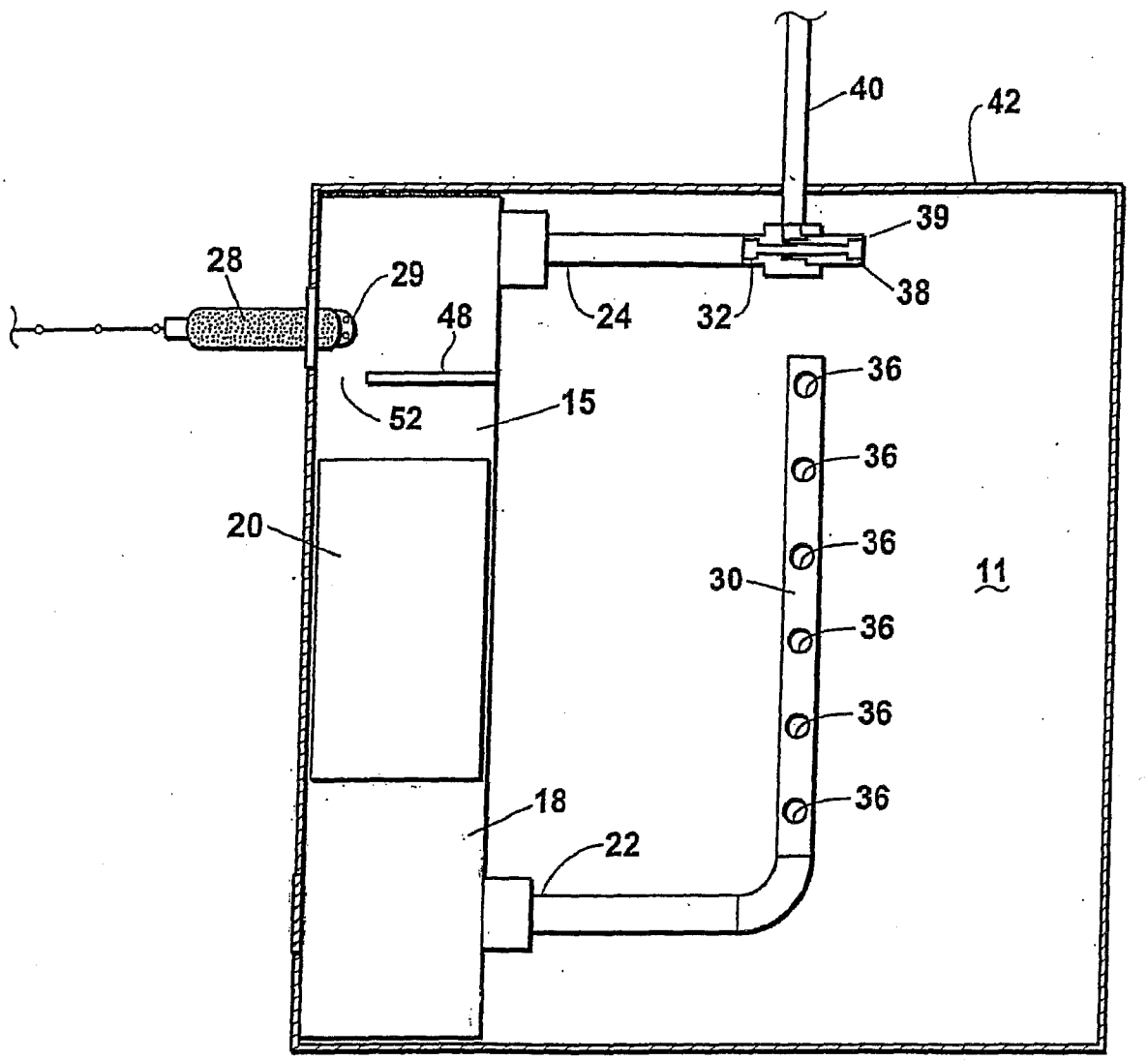


Fig. 3