SYSTEMS AND METHODS FOR PLASMA-BASED REMEDIATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Patent No. 62/816,694, filed March 11, 2019, which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] The present invention relates to transient plasma-based remediation systems. Specifically, the invention relates to electrode configurations for transient plasma-based remediation systems.

BACKGROUND

[0003] Diesel engines are used to transport large merchant shipping vessel across water routes. During operation of the diesel engines, a large amount of exhaust gas is created. The exhaust gas can include a number of harmful substances, such as NO_x compounds. The NO_x compounds emitted by the diesel engines are a substance source of air pollution. Thus, new systems and methods for removing NO_x compounds from diesel exhaust gas are needed.

SUMMARY

[0004] According to some implementations of the present disclosure, a system for plasma-based remediation comprises an engine including an exhaust port, the engine emitting exhaust gas from the exhaust port, the exhaust gas including NO molecules and NOx molecules via the exhaust port; a plasma reactor including a reactor tube and an electrode, the reactor tube defining an internal chamber, the electrode being at least partially disposed within the internal chamber inside the reactor tube, the internal chamber being fluidly coupled to the exhaust port of the diesel engine such that the exhaust gas flows into the internal chamber of the plasma reactor from the exhaust port; and a high voltage source electrically coupled to the electrode of the plasma reactor, the high voltage source being configured to deliver electrical pulses to the electrode to thereby form a plasma from the exhaust gas and remove at least a portion of the NO molecules and the NOx molecules from the exhaust gas.

[0005] According to some implementations of the present disclosure, a plasma reactor for plasma-based remediation comprises a first reactor tube and a second reactor tube; an input

port coupled to a first end of the first reactor tube and a second end of the second reactor tube, the input port being configured to fluidly couple an exhaust port of an engine to the first reactor tube and the second reactor tube such that the exhaust gas can flow through the first reactor tube and the second reactor tube; an output port coupled to the first end of the first reactor tube and the second end of the second reactor tube; a first electrode disposed in the first reactor tube and a second electrode disposed in the second reactor tube; and a high voltage connector coupled to the first reactor tube and the second reactor tube, the high voltage connector being configured to electrically connect both the first electrode and the second electrode to a high voltage source, wherein the high voltage connector is configured to deliver electrical pulses from the high voltage source to both the first electrode and the second electrode, to thereby form a plasma from the exhaust gas flowing through the first reactor tube and the second reactor tube.

[0006] According to some implementations of the present disclosure, a system for plasma-based remediation comprises one or more pairs of reactor tubes, each reactor tube of each pair of reactor tubes having an electrode disposed therein; an input port fluidly coupled to the one or more pairs of reactor tubes, the input port being configured to fluidly couple an exhaust port of an engine to the one or more pairs of reactor tubes such that the exhaust gas can flow through the one or more pairs of reactor tubes; one or more high voltage connectors, each high voltage connector being coupled to a respective one of the one or more pairs of reactor tubes, each high voltage connector being electrically connected to the electrode of each reactor tube of the respective one of the one or more pairs of reactor tubes, wherein each high voltage connector is configured to deliver electrical pulses from a high voltage source to the electrode of each reactor tube of the respective one of the one or more pairs of reactor tubes, to thereby form a plasma from the exhaust gas flowing through the one or more pairs of reactor tubes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The foregoing and other advantages of the present disclosure will become apparent upon reading the following detailed description and upon reference to the drawings.

[0008] FIG. 1 is a block diagram of a system for plasma-based remediation of diesel exhaust gas, according to some implementations of the present disclosure;

[0009] FIG. 2 shows profile views of a three-wire electrode, a four-wire electrode, and an extruded electrode, that can all be used with the system of FIG. 1, according to some implementations of the present disclosure;

[0010] FIG. 3A is a perspective view of a plasma reactor including four pairs of reactor tubes and four high voltage connectors for use in the system of FIG. 1, according to some implementations of the present disclosure;

[0011] FIG. 3B is a top plan view of the plasma reactor of FIG. 3A, according to some implementations of the present disclosure;

[0012] FIG. 4A is a top plan view of a pair of reactor tubes for use in the system of FIG. 1, according to some implementations of the present disclosure;

[0013] FIG. 4B is a cross-section of one end of the pair of reactor tubes of FIG. 4A, according to some implementations of the present disclosure;

[0014] FIG. 5A is a perspective view of a high voltage connector for use in the system of FIG. 1, according to some implementations of the present disclosure;

[0015] FIG. 5B is a perspective view of a portion of the high voltage connector of FIG. 5A and an electrode positioned inside a plasma reactor, according to some implementations of the present disclosure;

[0016] FIG. 5C is a plan view of the high voltage connector of FIG. 5A coupled to two spacers, according to some implementations of the present disclosure;

[0017] FIG. 6A is a first perspective view of an extruded electrode coupled to a spacer, for use in the system of FIG. 1, according to some implementations of the present disclosure;

[0018] FIG. 6B is a second perspective view of the extruded electrode and the spacer of FIG. 6A, according to some implementations of the present disclosure;

[0019] FIG. 6C is a third perspective view of the extruded electrode and the spacer of FIG. 6A, according to some implementations of the present disclosure; and

[0020] FIG. 7 is a perspective view of a bypass network of capacitors for use in the system of FIG. 1, according to some implementations of the present disclosure;

[0021] While the present disclosure is susceptible to various modifications and alternative forms, specific implementations and implementations have been shown by way of example in the drawings and will be described in detail herein. It should be understood, however, that the present disclosure is not intended to be limited to the particular forms disclosed. Rather, the present disclosure is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present disclosure as defined by the appended claims.

DETAILED DESCRIPTION

[0022] While this invention is susceptible of implementation in many different forms, there is shown in the drawings and will herein be described in detail preferred

implementations of the invention with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and is not intended to limit the broad aspect of the invention to the implementations illustrated. For purposes of the present detailed description, the singular includes the plural and vice versa (unless specifically disclaimed); the words "and" and "or" shall be both conjunctive and disjunctive; the word "all" means "any and all"; the word "any" means "any and all"; and the word "including" means "including without limitation." Additionally, the singular terms "a," "an," and "the" include plural referents unless context clearly indicates otherwise.

[0023] Large merchant shipping vessels (such as general cargo vessels, container ships, tankers, dry bulk carriers, multi-purpose vessels, refer ships, etc.) operate using way of diesel engines that emit large amounts of exhaust gas. The exhaust gas emissions of these diesel engines can include nitrogen-based NO_x compounds such as nitric oxide (NO), nitrogen dioxide (NO_2), and other compounds. These NO_x compounds are considered to be pollutants, and can be harmful to the environment. In order to reduce the harmful emissions from these diesel engines, the exhaust gas of the diesel engines can be remediated to reduce and/or remove the amount of NO_x compounds in the exhaust gas.

[0024] FIG. 1 shows a system 100 for exhaust gas remediation that includes a high voltage source 108 and a plasma reactor 110. During operation, the plasma reactor 110 is fluidly coupled to the output of an engine 102 via a valve 111. The valve 111 is operable to control the amount of exhaust gas emitted by engine 102 that is directed to an input port 112 of the plasma reactor 110. Any gas and/or substances emitted by the plasma reactor can be emitted at output port 114. Exhaust gas not directed to the engine 102 can be sent to an exhaust port 104. In some implementations, the exhaust gas of the engine 102 includes NO_x molecules. In some implementations, the engine 102 is a diesel engine, and the exhaust gas is diesel exhaust. For example, the engine 102 can be the diesel engine of a large merchant shipping vessel. However, the engine 102 can be other types of diesel engines as well, as such as the diesel engines of smaller ships, trucks, sport utility vehicles (SUVs), submarines, trains, or any other type of vehicle that may include a diesel engine. In still other implementations, the engine 102 is a diesel engine of equipment such as a crane, a bulldozer, an excavator, etc. The engine 102 can also be a diesel engine of an electric power plant, or a diesel engine from any other source. In further implementations, the engine 102 is a non-diesel engine.

[0025] The plasma reactor 110 is generally formed from at least one reactor tube that defines an internal chamber 116 (see FIG. 5B). The internal chamber 116 is fluidly connected

to the engine 102 through the input port 112, such that the exhaust gas can flow through the reactor tube. Electrodes are disposed within the internal chamber 116 of the reactor tube. The electrodes are electrically coupled to the high voltage source 108. The high voltage source 108 delivers electrical pulses to the electrodes when the internal chamber 116 contains the exhaust gas from the engine 102, to form a plasma from the exhaust gas. The electrical pulses and the resulting formation of the plasma removes at least a portion of the NO molecules and at least a portion of the NO_x molecules from the exhaust gas, thereby at least partially remediating the exhaust gas.

[0026] In some implementations, additional components can be added to system 100 in order to test the plasma reactor 110. These components can include a gas analyzer 105, an oscilloscope 107, and one or more sensors 109. The gas analyzer 105 can be used to analyze the gas emitted from the output port 114 of the plasma reactor 110. The sensors 109 can be coupled to the high voltage source 108, and are used to measure the voltage and current of the pulses being fed into the plasma reactor 110. The sensors 109 are used to measure the derivatives of the electrical field and magnetic field of these pulses. The outputs of the sensors 109 are sent to integrators coupled to the oscilloscope 107 to obtain oscilloscope waveforms, which are numerically reconstructed to form the actual voltage and current waveforms. The oscilloscope 107 can be housed in an electromagnetically compatible (EMC) cabinet, or another suitable enclosure, to protect the oscilloscope from any electromagnetic interference from the plasma reactor. In some implementations, some or all components of system 100 are grounded to aid in reducing electromagnetic interference issues.

[0027] In some implementations, one of the sensors 109 measures only the electric field D, and is positioned near a cable connecting the high voltage source 108 and the plasma reactor 110. The sensor can be formed from a metal plate placed adjacent to the cable, such that a capacitance C_D is formed. The voltage of the pulses from the high voltage source 108 are thus given by:

$$V_D = Z_{cable} C_D \frac{dV_{HV}}{dt},$$

where Z_{cable} is the impedance of the cable (for example, 50 ohms), V_{HV} is the voltage waveform that is reconstructed, and V_D is the output of the electric field sensor 109.

[0028] In some implementations, one of the sensors 109 measures only the electric field B, and is positioned near the cable connecting the high voltage source 108 and the plasma reactor 110. The sensor can be formed from a single metal loop placed adjacent to the cable. The magnetic field generated by current in the cable couples into the metal loop via a mutual

inductance M_B between the metal loop and the cable. The resulting change in magnetic flux in the metal loop induces a voltage across the loop, given by:

$$V_B = M_B \frac{dI_{HV}}{dt},$$

where I_{HV} is the current waveform that is reconstructed, and V_B is the output of the magnetic field sensor 109.

[0029] The full numerical reconstruction of the voltage and current waveforms is given by:

$$V_{HV} = \frac{1}{C_D R_2}\left[R_1 C_1 V_{D,int} + \left(1 + \frac{R_1}{Z_0}\right)\int V_{D,int}\, dt\right], \text{ and}$$

$$I_{HV} = \frac{1}{M_B}\left[R_1 C_1 V_{B,int} + \left(1 + \frac{R_1}{Z_0}\right)\int V_{B,int}\, dt\right],$$

where Z_0 is the input impedance of the oscilloscope 107, and both C_D and M_B are predetermined calibration values. The final integration term is a correction term for the impedance of the oscilloscope 107.

[0030] FIG. 2 illustrates various implementations and configurations of the electrodes, which can be solid extruded electrodes, or can be formed from a number of wires. The wire-based electrodes can be 1-wire electrodes, 2-wire electrodes 3-wire electrodes, 4-wire electrodes, 5-wire electrodes, 6-wire electrodes, or any other number of wires. The electrodes can include two different types of electrodes. Moreover, the plasma reactor 110 may include one electrode, or three or more electrodes. Shown in FIG. 2 are a 3-wire electrode 118A, a 4-wire electrode 118B, and an extruded electrode 118C. The multiple wire-based electrodes (such as 3-wire electrode 118A and 4-wire electrode 118B) can have a cross-section that is generally defined as the diameter of a circle connecting all of the wires of the electrode, as shown. The cross-section of the extruded electrode 118C has a central portion 120, and four arms 122A-122D. The cross-section of the extruded electrode 118C is defined as the distance between the ends of two opposing arms, such as arms 122A and 122B, or arms 122C and 122D. In some implementations, the 3-wire electrode 118A and the 4-wire electrode 118B have cross-sections of about 2.0 inches, about 2.25 inches, or about 2.5 inches. In other implementations, the 3-wire electrode 118A and the 4-wire electrode 118B have cross-sections of between about 1.0 inches and about 5.0 inches. Other electrode types and configurations are also contemplated. For example, the extruded electrode 118C could have more or less than the four arms 122A-122D, and could also have a different shape entirely. In other implementations, the cross-section of the electrodes can be between about 0.4 inches

and about 1.1 inches. Further, the electrodes can have an impedance of between about 70 ohms and about 300 ohms.

[0031] FIG. 3A illustrates a perspective view of one implementation of the plasma reactor 110, while FIG. 3B illustrates a top plan view of one implementation of the plasma reactor 110. In this implementation, the plasma reactor includes a first pair of reactor tubes 124A and 124B, a second pair of reactor tubes 126A and 126B, a third pair of reactor tubes 128A and 128B, and a fourth pair of reactor tubes 130A and 130B. Each reactor tube 124A-130B defines a hollow internal chamber (such as hollow internal chamber 116 shown in FIG. 5B) in which an electrode can be disposed. The plasma reactor 110 in FIGS. 3A and 3B also include four high voltage connectors 132A-132D.

[0032] High voltage connector 132A is coupled to the electrodes positioned inside the first pair of reactor tubes 124A, 124B. High voltage connector 132B is coupled to the electrodes positioned inside the second pair of reactor tubes 126A, 126B. High voltage connector 132C is coupled to the electrodes positioned inside the third pair of reactor tubes 128A, 128B. High voltage connector 132D is coupled to the electrodes positioned inside the fourth pair of reactor tubes 130A, 130B. The high voltage connectors 132A-132D deliver electrical pulses from the high voltage source 108 to the electrodes positioned inside the reactor tubes 124A-130B. The input port 112 and the output port 114 are positioned at opposite ends of the reactor tubes 124A-130B, and are both fluidly coupled to the internal chambers of all of the reactor tubes 1284-130B, so that the exhaust gas from the engine 102 can flow through the plasma reactor. In some implementations, each high voltage connector 132A-132D is coupled to the same high voltage source 108. In other implementations, each high voltage connector 132A-132D is coupled to its own respective high voltage source 108.

[0033] FIG. 4A shows a top plan view of a pair of reactor tubes 134A and 134B. The input port 112 is coupled to one end of both reactor tubes 134A, 134B. The output port is coupled to the other end of both reactor tubes 134A, 134B. A single high voltage connector 136 is coupled to both the first reactor tube 134A and the second reactor tube 134B. The reactor tubes 134A and 134B may be the same as or similar to reactor tubes 124A-130B. The high voltage connector 136 may be the same as or similar to high voltage connectors 132A-132D. The high voltage connector 136 generally extends between the reactor tubes 134A, 134B in a direction that is perpendicular to the direction along which the reactor tubes 134A, 134B extend.

[0034] In some implementations, the pair of reactor tubes 134A, 134B and the high voltage connector 136 form an individual plasma reactor 110 on their own. In other

implementations, the pair of reactor tubes 134A, 134B and the high voltage connector 136 are components of a larger plasma reactor 110, such as the plasma reactor 110 illustrated in FIGS. 3A and 3B. The high voltage connector 136 includes a housing 137 and a cable 138 extending from the housing 137. A distal end of the cable 138 electrically connects to the high voltage source 108, while the proximal end of the cable extends into the housing 137 of the high voltage connector 136.

[0035] FIG. 4B shows a cross-section of one end of the plasma reactor 110 of FIG. 4A, showing the inside of the reactor tubes 134A, 134B, and the inside of the high voltage connector 136. The high voltage connector 136 includes two insulating members 142A, 142B extending from the housing 137. A first portion of each insulating member 142A, 142B is disposed within the housing 137. A second portion of insulating member 142A extends from the housing 137 and is positioned inside the internal chamber of reactor tube 134A, while the second portion of insulating member 142B extends from the housing 137 and is positioned inside the internal chamber of reactor tube 134B. The first portion of each insulating member 142A, 142B has a generally cylindrical shape. The second portion of each insulating member 142A, 142B is generally cone-shaped, and tapers down to the end that is disposed in the respective reactor tube 134A, 134B.

[0036] The cable 138 extends into the housing 137, where it is electrically connected to into two separate electrically conductive members 140A, 140B. Electrically conductive member 140A extends through the interior of the insulating member 142A to the tapered end disposed in reactor tube 134A. Electrically conductive member 140B extends through the interior of the insulating member 142B to the tapered end disposed in reactor tube 134B. Thus, the electrically conductive members 140A, 140B generally extend perpendicular to the length of the reactor tubes 134A, 134B.

[0037] An electrode 144A is coupled to electrically conductive member 140A, and extends along the length of the internal chamber of reactor tube 134A. Similarly, an electrode 144B is coupled to electrically conductive member 140B, and extends along the length of the internal chamber of reactor tube 134B. Electrode 144A is formed from wires 145A, 145B, and 145C. Electrode 144B is formed from wires 145D, 145E, and 145F. Spacers 146A, 146B may be coupled to electrodes 144A, 144B, respectively. Spacers 146A, 146B aid in maintaining the position of the electrodes 144A, 144B within the internal chambers of the respective reactor tubes 134A, 134B, and prevent the electrodes 144A, 144B from contacting the interior surface of the reactor tubes 134A, 134B. Electrodes 144A and 144B can be 3-wire electrodes (such as electrode 118A), 4-wire electrodes (such as 118B), extruded

electrodes (such as electrode 118C), or any other suitable type or shape of electrode. When the electrodes are multi-wire electrodes, the spacers 146A, 146B also aid in maintaining separation of the wires. In some implementations, the spacers 146A, 146B are made of an electrically insulating material, such as fiberglass.

[0038] The arrangement of the high voltage connector 136 and the electrodes 144A, 144B can be used for any implementation of the plasma reactor 110. For example, the plasma reactor 110 can include the four pairs of reactor tubes 124A-130B as shown in FIGS. 4A and 4B. The plasma reactor 110 could also include a single reactor tube coupled to the input port 112 and the output port 114, a single pair of reactor tubes coupled to the input port 112 and the output port 114, or any number of reactor tubes coupled to any number of input ports 112 and any number of output ports 114.

[0039] FIG. 5A shows a perspective view of the high voltage connector 136 without the cable 138 attached. In some implementations, the housing 137 includes one or more ports 139A, 139B, 139C that are open to the interior of the housing. Ports 139A, 139B, and 139C can be used to allow coolant or other fluids to circulate within the housing 137, in order to cool the high voltage connector 136 and maintain the high voltage connector 136 at a desired temperature. In some implementations, the coolant is oil. In some implementations, the electrically conductive members 140A, 140B extend out of their respective insulating members 142A, 142B parallel to the length of the reactor tubes 134A, 134B. Thus, the electrically conductive members 140A, 140B can have a right-angled shape, e.g., an "L" shape.

[0040] FIG. 5B shows an end view of reactor tube 134A with an end cap removed, such that the internal chamber 116 is visible. As shown, the electrode 144A extends away from the insulating member 142A toward the opposite end of the internal chamber 116. In the implementation shown in FIG. 5B, electrode 144A is a 3-wire electrode formed from wires 145A, 146B, 145C, and spacer 146A aids in maintaining separation of the three wires 145A, 145B, 145C.

[0041] FIG. 5C shows the high voltage connector 136 from the opposite side as compared to FIG. 5B. In the implementation illustrated in FIG. 5C, the spacers 146A, 146B have large circular shapes, with an outer diameter generally equal to an inner diameter of the reactor tubes 134A, 134B. These types of spacers 146A, 146B are generally used with extruded electrodes 118C.

[0042] FIGS. 6A, 6B, and 6C all show an extruded electrode 118C with a spacer 147 (which can be the same as or similar to any of the spacers 146 discussed herein). As shown,

extruded electrode 118C is formed from four arms 122A-122D extending from a central portion 120. The extruded electrode 118C is mounted to an electrically conductive member 141 (which can be the same as or similar to electrically conductive members 140A, 140B). The electrically conductive member 141 extends through the center of the spacer 147, and is used to conduct pulses from the high voltage source 108 to the electrode 118C.

[0043] FIG. 7 shows a bypass network 150 that can be electrically coupled in parallel with the cable 138 of the high voltage connector 136. During use, the plasma reactor 110 can generate large amounts of electromagnetic interference (EMI) due to the operation of the high voltage source 108. In certain situations, a large amount of electrical energy can be reflected back to the high voltage source 108, such as when the connection to one of the electrodes 144A, 144B is short-circuited, or when the high voltage source 108 and the plasma reactor 110 are impedance mismatched. The reflected energy can be absorbed by the output of the high voltage source 108 (which could be, for example, a diode stack). To avoid this issue, the bypass network 150 can be electrically connected in parallel with the output of the high voltage source 108 and the high voltage connector 136. The bypass network 150 can act as a sink and absorb any reflected electrical energy. In the illustrated implementation, the bypass network 150 is one or more capacitors electrically connected in series. Other types of bypass networks 150 can also be utilized.

[0044] During operation, system 100 has a total system efficiency defined as $\eta_{system} = \eta_{source} \times \eta_{reactor} \times \eta_{plasma}$. η_{source} is the electrical efficiency at which electrical energy is taken from the electricity grid (or other ultimate source of electrical energy) by the high voltage source 108 and converted into short pulses. $\eta_{reactor}$ is the electrical efficiency at which the energy of the pulses is dissipated by the plasma formed in the plasma reactor 110, and can be defined as $\eta_{source} = \frac{E_{plasma}}{E_{pulse}}$, where E_{plasma} is the energy dissipated by the plasma, and E_{pulse} is the total available energy in the pulse. η_{plasma} is the chemical efficiency of the plasma, and is a measure of the amount of energy used by the plasma that is converted into chemically active species. The total system efficiency η_{system} is the product of all three efficiencies.

[0045] The reactor efficiency $\eta_{reactor}$ is influenced by the electric field strength in the plasma reactor 110, and the impedance matching of the plasma reactor 110. The impedance matching of the plasma reactor 110 determines how much of the pulse from the high voltage source 108 enters the plasma reactor 110. In a perfectly matched system, the impedance of the cable 138 delivering the pulses matches the impedance of the plasma reactor 110, and the

entire pulse enters the plasma reactor 110. When there is some amount of mismatch in the impedance, the pulse partially reflects off the plasma reactor 110, which can lead to a loss of energy and high voltage stress on the system. In some implementations of system 100, the cable 138 has an impedance of about 50 ohms, and each of the electrically conductive members 140A, 140B connected to the high voltage source 108 through the cable 138 have an impedance of about 100 ohms. In these implementations, a single high voltage source 108 is used to generate pulses for each pair of electrodes.

[0046] The reflectiveness of the system 100 is given by

$$R = \frac{Z_{reactor} - Z_{cable}}{Z_{reactor} + Z_{cable}},$$

where Z_{cable} is the impedance of the cable 138 and $Z_{reactor}$ is the impedance of the plasma reactor 110. For a perfectly matched system $R = 0$, and there is no reflection. For a mismatched system however, there is some degree of reflection. The maximum voltage stress V_{max} of the system 100 is the sum of the incoming pulse voltage and the reflected pulse voltage, and is generally given by $V_{max} = (1 + R)V_{peak}$, where V_{peak} is the applied peak voltage.

[0047] The effectiveness of the system 100 at removing NO molecules and NO_x molecules is measured by comparing the initial and final concentrations of NO and NO_x. This is measured as:

$$NO_{remediation} = 100\% \times \frac{NO_{initial} - NO_{final}}{NO_{initial}}$$

$$NO_{x,remediation} = 100\% \times \frac{NO_{x,initial} - NO_{x,final}}{NO_{x,initial}}$$

[0048] The NO removal efficiency of the system 100 is defined as how efficient the formed plasma removes NO and is measured in mol/kWh. The NO removal efficiency is measured by the following equation:

$$NO_{rem,eff} = \frac{\Delta NO \times 3.6}{V_m \epsilon},$$

[0049] ΔNO is the removed concentration of NO (in ppm), V_m is the molar volume (in L/mol, dependent on temperature) and ϵ is the energy density (in J/L). The energy density is given by:

$$\epsilon = \frac{f_{rr} E_{plasma} \times 60}{F},$$

[0050] Here, f_{rr} is the pulse repetition rate (in Hz), E_{plasma} is the dissipated energy in the plasma per pulse, and F is the gas flow rate (in L/min).

[0051] The overall efficiency of the system 100 is given by the following equation:

$$System\ efficiency = Reactor\ efficiency \times NO_{rem,eff}$$

[0052] The system 100 is operated according to a variety of settings, including engine loading, engine speed, pulse source voltage, pulse source repetition rate, flow through the plasma reactor 110, and electrode type and geometry. The engine speed can be between about 400 rpm and about 1,000 rpm, between about 1,000 rpm and about 1,800 rpm, between about 400 rpm and about 1,800 rpm, about 400 rpm, about 1,000 rpm, or about 1,800 rpm. The pulse source voltage can be about 250 volts, about 300 volts, about 325 volts, about 350 volts, or between about 250 volts and about 350 volts. The pulse source repetition rate can be about 100 Hz, about 500 Hz, about 1000 Hz, about 1,500 Hz, about 2,500 Hz, or generally any range between any two of these values. In some implementations, the average electrical reactor efficiency (e.g., $\eta_{reactor}$), can be between about 70% and about 90%, between about 78% and about 86%, between about 80% and about 90%,

[0053] While the present invention has been described with reference to one or more particular implementations, those skilled in the art will recognize that many changes may be made thereto without departing from the spirit and scope of the present invention. Each of these implementations and obvious variations thereof is contemplated as falling within the spirit and scope of the invention. It is also contemplated that additional implementations according to aspects of the present invention may combine any number of features from any of the implementations described herein.

CLAIMS

What is claimed is:

1. A system for plasma-based remediation, comprising:

an engine including an exhaust port, the engine emitting exhaust gas from the exhaust port, the exhaust gas including NO molecules and NO_x molecules via the exhaust port;

a plasma reactor including a reactor tube and an electrode, the reactor tube defining an internal chamber, the electrode being at least partially disposed within the internal chamber inside the reactor tube, the internal chamber being fluidly coupled to the exhaust port of the diesel engine such that the exhaust gas flows into the internal chamber of the plasma reactor from the exhaust port; and

a high voltage source electrically coupled to the electrode of the plasma reactor, the high voltage source being configured to deliver electrical pulses to the electrode to thereby form a plasma from the exhaust gas and remove at least a portion of the NO molecules and the NO_x molecules from the exhaust gas.

2. The system of claim 1, wherein the electrode is selected from a group comprising an extruded electrode, a 3-wire electrode, and a 4-wire electrode.

3. The system of claim 2, wherein the extruded electrode has a cross-section that is selected from a group comprising about 2.0 inches, about 2.25 inches, or about 2.5 inches.

4. The system of claim 2, wherein the extrude electrode has a cross-section of between about 1.0 inches and about 5.0 inches.

5. The system of claim 1, wherein the electrode is a 3-wire electrode with a cross-section of about 2 inches.

6. The system of claim 1, wherein the pulse source includes a bypass network electrically in parallel with the output of the pulse source.

7. The system of claim 6, wherein the bypass network is configured to absorb electrical energy reflected back to the pulse source to minimize electromagnetic interference from the pulse source.

8. The system of claim 6, wherein the bypass network includes a plurality of capacitors electrically connected in series.

9. The system of claim 1, wherein the engine is a diesel engine.

10. The system of claim 9, wherein the diesel engine is from a merchant shipping vessel.

11. The system of claim 1, further comprising a high voltage connector coupled to the reactor tube, the high voltage connector electrically coupling the high voltage source to the electrode, the high voltage connector being configured to deliver the electrical pulses from the high voltage source to the electrode.

12. The system of claim 11, wherein the high voltage connector includes a housing, an insulating member, and an electrically conductive member, the housing being coupled to the reactor tube, the insulating member being partially disposed in the housing and partially disposed in the reactor tube, the electrically conductive member extending through an interior of the insulating member to the electrode disposed in the reactor tube.

13. The system of claim 12, wherein the high voltage connector includes a cable electrically coupling the high voltage source to the electrically conductive member.

14. A plasma reactor for plasma-based remediation, comprising:

a first reactor tube and a second reactor tube;

an input port coupled to a first end of the first reactor tube and a second end of the second reactor tube, the input port being configured to fluidly couple an exhaust port of an engine to the first reactor tube and the second reactor tube such that the exhaust gas can flow through the first reactor tube and the second reactor tube;

an output port coupled to the first end of the first reactor tube and the second end of the second reactor tube;

a first electrode disposed in the first reactor tube and a second electrode disposed in the second reactor tube; and

a high voltage connector coupled to the first reactor tube and the second reactor tube, the high voltage connector being configured to electrically connect both the first electrode and the second electrode to a high voltage source,

wherein the high voltage connector is configured to deliver electrical pulses from the high voltage source to both the first electrode and the second electrode, to thereby form a plasma from the exhaust gas flowing through the first reactor tube and the second reactor tube.

15. The plasma reactor of claim 14, wherein the first reactor tube and the second reactor tube extend in a first direction between the input port and the output port, and wherein the high voltage connector extends in a second direction perpendicular to the first direction between the first reactor tube and the second reactor tube.

16. The plasma reactor of claim 15, wherein the high voltage connector includes a housing coupled to the first reactor tube and the second reactor tube, a first insulating member extending from the housing of the high voltage connector into the first reactor tube, and a second insulating member extending from the housing of the high voltage connector into the second reactor tube.

17. The plasma reactor of claim 16, where the high voltage connector includes a first electrically conductive member extending through an interior of the first insulating member to the first electrode disposed in the first reactor tube, and a second electrically conductive member extending through an interior of the second insulating member to the second electrode disposed in the second reactor tube.

18. The plasma reactor of claim 17, wherein the high voltage connector includes a cable having a first end disposed inside the housing and electrically connected to the first electrically conductive member and the second electrically conductive member, and a second end configured to be electrically connected to the high voltage source.

19. The plasma reactor of claim 18, wherein the first electrically conductive member electrically connects the first electrode to the cable, and wherein the second electrically conductive member electrically connects the second electrode to the cable.

20. The plasma reactor of claim 19, wherein the cable has an impedance of about 50 ohms, the first electrically conductive member has an impedance of about 100 ohms, and the second electrically conductive member has an impedance of about 100 ohms.

21. The plasma reactor of claim 17, further comprising a first spacer disposed in the first reactor tube and coupled to the first electrically conductive member and the first electrode, and a second spacer disposed in the second reactor tube and coupled to the second electrically conductive member and the second electrode, the first spacer being configured to maintain a position of the first electrode in the first reactor tube such that the first electrode does not contact an interior surface of the first reactor tube, the second spacer being configured to maintain a position of the second electrode in the second reactor tube such that the second electrode does not contact an interior surface of the second reactor tube.

22. The plasma reactor of claim 21, wherein both the first spacer and the second spacer are formed from an insulating material.

23. The plasma reactor of claim 14, wherein the first electrode or the second electrode is a three-wire electrode, a four-wire electrode, or an extruded electrode.

24. The plasma reactor of claim 23, wherein the extruded electrode includes a central portion and one or more arms extending from the central portion.

25. The plasma reactor of claim 14, wherein the engine is a diesel engine.

26. The plasma reactor of claim 25, wherein the diesel engine is from a merchant shipping vessel.

27. A system for plasma-based remediation, comprising:

one or more pairs of reactor tubes, each reactor tube of each pair of reactor tubes having an electrode disposed therein;

an input port fluidly coupled to the one or more pairs of reactor tubes, the input port being configured to fluidly couple an exhaust port of an engine to the one or more pairs of reactor tubes such that the exhaust gas can flow through the one or more pairs of reactor tubes;

one or more high voltage connectors, each high voltage connector being coupled to a respective one of the one or more pairs of reactor tubes, each high voltage connector being electrically connected to the electrode of each reactor tube of the respective one of the one or more pairs of reactor tubes,

wherein each high voltage connector is configured to deliver electrical pulses from a high voltage source to the electrode of each reactor tube of the respective one of the one or more pairs of reactor tubes, to thereby form a plasma from the exhaust gas flowing through the one or more pairs of reactor tubes.

28. The plasma reactor of claim 27, wherein the engine is a diesel engine.

29. The plasma reactor of claim 28, wherein the diesel engine is from a merchant shipping vessel.