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(54) **Title**: $CO_2$ CAPTURE SYSTEM AND METHOD

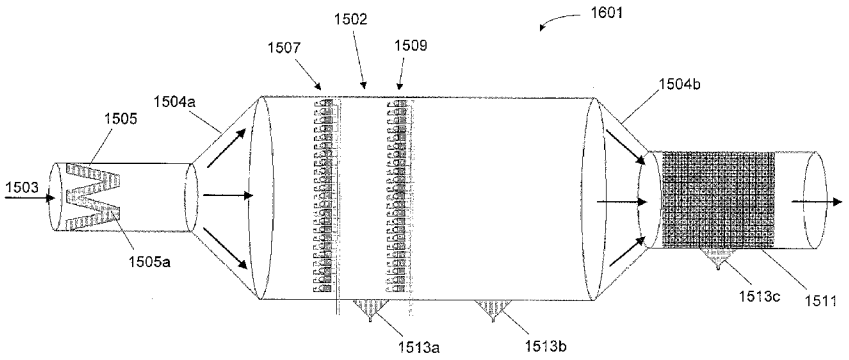


FIG. 16

(57) **Abstract**: A method for removing contaminants from industrial exhaust gas includes contacting the exhaust gas with granular activated carbon, contacting the exhaust gas with a water mist to capture $C0_2$ in the water mist, and extracting the captured $C0_2$.

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# $CO_2$ CAPTURE SYSTEM AND METHOD

## CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Serial No. 61/866,874, filed on August 16, 2013, which is incorporated herein by reference in its entirety.

## BACKGROUND

[0002] Concerns over the future effects of global climate change are increasingly leading to the desire to control and reduce carbon dioxide ($CO_2$) emission into the atmosphere. $CO_2$ originates from a variety of sources, many of which involve the combustion of an organic fuel such as coal, natural gas, gasoline, fuel oil, and methane. Specifically, combustion processes that are used for the generation of electricity and/or heat are a significant source of $CO_2$. Furthermore, $CO_2$ capture from emissions may be used for other purposes, *e.g.*, enhanced oil recovery.

## SUMMARY

[0003] In general, in one aspect, the invention relates to a method for removing contaminants from industrial exhaust gas. The method includes contacting the exhaust gas with granular activated carbon, contacting the exhaust gas with a water mist to capture $CO_2$ in the water mist, and extracting the captured $CO_2$.

[0004] In general, in one aspect, the invention relates to a system for capturing $CO_2$ from an industrial stream of exhaust gas. The system includes an activated carbon stage configured to receive the stream of exhaust gas and to contact the stream of exhaust gas with granular activated carbon to remove contaminants from the exhaust gas stream. The system further includes a first fogging stage configured to receive the stream of exhaust gas and to contact the stream of exhaust gas with a water mist to capture $CO_2$ in the water mist. The system further includes a condensing medium configured to condense the contacted exhaust gas including the captured $CO_2$ from the stream of exhaust gas and to collect on the surface of the condensing medium a wetted film including dissolved $CO_2$.

[0005] Other aspects of the invention will be apparent from the following description and the appended claims.

## BRIEF DESCRIPTION OF DRAWINGS

[0006] FIG. 1 shows a system in accordance with one or more embodiments of the invention.

[0007] FIG. 2 shows a flow chart describing a method of multi-pollution abatement using coal or oil as a fossil fuel in accordance with one or more embodiments of the invention.

[0008] FIG. 3 shows a flowchart describing a method of multi-pollution abatement using natural gas as a fossil fuel in accordance with one or more embodiments of the invention.

[0009] FIG. 4 shows a system for creating an exhaust gas stream that includes NO, $NO_2$, $SO_2$, HCL, Hg, $Hg_2$, $CO_2$ and particulate from a combustion process in accordance with one or more embodiments of the invention.

[0010] FIG. 5 shows a receiving system to receive a stream of exhaust gas in accordance with one or more embodiments of the invention.

[0011] FIGs. 6A-6D show various views of a modular system for multi-pollutant abatement in accordance with one or more embodiments of the invention.

[0012] FIGs. 7A-7D show a high pressure fogging array system in accordance with one or more embodiments of the invention.

[0013] FIG. 8 shows an activated carbon frame section in accordance with one or more embodiments of the invention.

[0014] FIG. 9 shows an example of a high-pressure fogging rod in accordance with one or more embodiments of the invention.

[0015] FIG. 10A-10C show cross-sectional views through a high-pressure fogging rod in accordance with one or more embodiments of the invention.

[0016] FIG. 11 shows a high-pressure fogging rod circuit in accordance with one or more embodiments of the invention.

[0017] FIGs. 12A-12B show a high-pressure fogging rod support tray in accordance with one or more embodiments of the invention.

[0018] FIGs. 13A-13D show a plot of pollution removal rates of a multi-pollution abatement device in accordance with one or more embodiments of the invention.

[0019] FIG. 14 shows a $CO_2$ capture system in accordance with one or more embodiments of the invention.

[0020] FIGs. 15A-15B show a $CO_2$ capture system in accordance with one or more embodiments of the invention.

[0021] FIG. 16 shows a $CO_2$ capture system in accordance with one or more embodiments of the invention.

[0022] FIG. 17 shows test data for a $CO_2$ capture system in accordance with one or more embodiments of the invention.

## DETAILED DESCRIPTION

[0023] Specific embodiments of the invention will now be described in detail with reference to the accompanying figures. Like elements in the various figures are denoted by like reference numerals for consistency.

[0024] In the following detailed description of embodiments of the invention, numerous specific details are set forth in order to provide a more thorough understanding of the invention. However, it will be apparent to one of ordinary skill in the art that the invention may be practiced without these specific details. In other instances, well-known features have not been described in detail to avoid unnecessarily complicating the description.

[0025] In general, embodiments of the invention provide for a device and method for multi-pollution abatement and $CO_2$ removal. More specifically, one or more embodiments of the invention provide for creating carbonic acid ($H_2CO_3$) from an exhaust gas stream that includes $CO_2$ and combining the $H_2CO_3$ with a reagent to create alcohol. The invention may further provide for creating other acids from the exhaust gas stream, including but not limited to sulfuric acid ($H_2SO_4$) and nitric acid

($HNO_3$) and combining those other acids with one or more reagents to create one or more alcohols.

**[0026]** In general, embodiments of the invention provide for a device and method for $CO_2$ removal that employs contacting the exhaust gas stream with a high speed, high pressure water mist, also referred to herein as a fog. The system captures the $CO_2$ in the water mist/fog and later condenses and/or collects the mist/fog for removal to a waste water treatment system. In general, embodiments of the invention also provide for a waste water treatment system configured to remove the captured $CO_2$ from the collected waste water.

**[0027]** In accordance with one or more embodiments, the piping and associated fittings, pumps, valves, and other equipment are made of materials resistant to the chemicals transported, transformed, pressurized, created, or otherwise handled within those fittings, pumps, valves, and other equipment. As used herein, the term "acid" or "acids" may refer to at least carbonic acid, sulfuric acid, and/or nitric acid. As used herein, "amine" refers to the ammonia derivative class of molecules given by the formula $RNH_2$. Examples of amines that may be used in accordance with one or more embodiments of the present invention include monoethanolamine (MEA), diethanolamine (DEA), methyl-diethanolamine, and diisopropylamine (DIPA). MEA is an organic chemical compound with the formula $RNH_2$ that is both a primary amine and primary alcohol. Like other amines, monoethanolamine acts as a weak base. DEA is an organic compound with the formula $HN(CH_2CH_2OH_2)$ which is polyfunctional, being secondary amine and diol. MDEA is a clear, colorless or pale yellow liquid with an ammonia odor. It has a formula $CH_3N(C_2H_4OH)_2$. MDEA is a tertiary amine and is widely used as a solvent for exhaust gas treatment. DIPA is a secondary amine with a chemical formula $(CH_3)_2HC\text{-}NH\text{-}CH\ (CH_3)_2$ which is best known as its lithium salt, lithium diisopropylamine.

**[0028]** As used herein, the term "granular carbon" or "granulated activated carbon" is used to refer to activated carbon particulate of a size that is greater than that of "powdered carbon," which is known to have an average diameter between .15 mm and .25 mm. Thus, as used herein, granular activated carbon has a larger average particle diameter compared to powdered activated carbon and consequently,

granular carbon presents a smaller external surface area than powdered carbon. The size of granulated activated carbon is designated by standard mesh sizes, *e.g.*, U.S. standard mesh sizes such as 4, 6, 8, 12, 20, 30, 40, 50, which correspond to openings having a size of 4.76 mm, 3.36 mm, 2.38 mm, 1.68 mm, 0.84 mm, 0.59 mm, 0.42 mm, and 0.030 mm, respectively. Thus, a 20×40 granulated carbon is made of particles that will pass through a U.S. Standard Mesh Size No. 20 sieve (0.84 mm) (generally specified as 85% passing) but be retained on a U.S. Standard Mesh Size No. 40 sieve (0.42 mm) (generally specified as 95% retained). In other words, a 20×40 granulated carbon is a carbon particulate having a granules of varying size, wherein 95% of the granules have a diameter greater than 0.42 mm and 85% of the granules have a diameter less than 0.84 mm.

**[0029]** In accordance with one or more embodiments of the present invention, a multi-pollution abatement device includes a condensing medium such as a demister or chlorinated polyvinyl chloride (CPVC) packing. In order to reduce exhaust gas temperatures before the exhaust gas enters the multi-pollution abatement device, in one embodiment, an economizer is disposed before the multi-pollution abatement device. Furthermore, in accordance with one or more embodiments, a third stage fogging array or misting apparatus that targets the removal of $CO_2$ composition from the exhaust gas is included. In addition, in accordance with one or more embodiments, an activated carbon section or sections may be added to reduce the remaining pollutants such as $NO_x$, $SO_x$, HCL, Hg, and Hg(II). While the embodiments disclosed herein show the stages of the multi-pollution abatement device in a particular order, the order or number of stages is not limited merely to those arrangements disclosed herein. One of ordinary skill will appreciate that any number of stages in any sequential arrangement may be used without departing from the scope of the present disclosure. For example, any number of economizer, fogger, demister, and activated carbon stages may be employed without departing from the scope of the present disclosure. Accordingly, one or more embodiments of the present invention provide a versatile modular multi-pollution abatement device that is adaptable for removing pollutants from many different types of industrial exhaust gas streams.

[0030] A multi-pollution abatement device in accordance with one or more embodiments of the invention may be deployed for removing pollutants from an exhaust gas stream generated from an industrial plant, *e.g.*, in processing and manufacturing for a number of market sectors, including, but not limited to, food processing and packaging, pulp and paper, printing, chemicals and allied products, rubber, plastics, hospitals, universities, metal industries, drug manufacturing, waste water and sewage treatment, beverages, utilities, incineration, steel, cosmetics, textile production, electronics, and petroleum refining.

[0031] For removal of the unwanted and or targeted pollutants such as NOx, SOx, HCl, Hg, Hg(II), $CO_2$, and particulate certain reactions must occur. Some examples of such reactions and methods and devices for removing pollutants from an exhaust gas stream are described below.

[0032] NOx

[0033] NOx is a generic term for the mono-nitrogen oxides nitric oxide (NO) and nitrogen dioxide ($NO_2$). Both NO and $NO_2$ are produced from the reaction of nitrogen and oxygen in the air during combustion. $NO_2$ may be removed by contacting the $NO_2$ with water vapor or steam, condensing the water vapor or steam out of the flue gas stream to create waste water, and then collecting and directed the waste water to a waste water treatment facility where it is neutralized and disposed of. NO cannot be removed by contact with water so NO has to first be chemically changed to $NO_2$, which is achieved by adding ozone ($O_3$) to the exhaust gas stream. The introduction of ozone gas into the flue gas stream causes the following reaction to occur:

$$NO + O_3 \rightarrow NO_2 + O_2$$

[0034] SOx

[0035] SOx is a generic term for the sulfur oxides $SO_2$ and $SO_3$. These oxides are formed as a result of combustion of a sulfur-containing fossil fuel such as coal or oil. With moisture in the combustion some of the $SO_2$ will be converted to $SO_3$. By adding a solution of hydrogen peroxide ($H_2O_2$) to the water at, *e.g.*, a 5% concentration, the $SO_2$ and $SO_3$ that come into contact with the solution can quickly

be converted to $H_2SO_4$(aq) waste water. The waste water is then condensed out of the flue gas stream and directed to a waste water facility for neutralization and disposal.

**[0036]** HCl

**[0037]** Hydrogen Chloride (HCl) is a monoprotic acid. This composition can be removed when it comes into contact with water. In aqueous hydrochloric acid, the $H^+$ joins a water molecule to form a hydronium ion, $H_3O^+$

**[0038]** $HCl + H_2O \rightarrow H_3O^+ + Cl^-$

**[0039]** Hg(0) and Hg(II)

**[0040]** Under normal conditions, mercury is extremely stable, does not oxidize readily, and is typically found as elemental mercury (Hg(0)). During the combustion of a fossil fuel such as coal, Hg(0) may be volatilized and converted to vapor. Furthermore, some of this Hg(0) vapor may be converted to ionic mercury (Hg(II)) compounds through oxidation reactions in the flue gas. Hg(II) compounds are generally water-soluble and, thus, can be removed by contacting the Hg(II) compound with water (vapor or steam), condensing the vapor or steam to form waste water, and directing the waste water to a waste water facility. However, Hg(0) vapor is insoluble in water and thus cannot be removed by contact with water. Fortunately, at flue gas temperatures Hg(0) will react with gaseous Cl to form mercuric chloride ($HgCl_2$), which is water-soluble and, thus, may be removed by contact with water (vapor, steam, or liquid).

**[0041]** $CO_2$

**[0042]** Carbon dioxide ($CO_2$) is a chemical compound composed of two oxygen atoms covalently bonded to a single carbon atom. $CO_2$ is soluble in water and, when contacted with water, reversibly converts to carbonic acid ($H_2CO_3$). However, the majority of the $CO_2$ is not converted to $H_2CO_3$ but remains in the water as dissolved $CO_2$. Accordingly, if any energy is applied to the water such as a vibration, low frequency wave or heat, the $CO_2$ molecule can escape to atmosphere. Accordingly, in order to hold the $CO_2$ molecule in the water, chilled water and/or a water solution such as amine (*e.g.*, $RNH_2$) should be present to absorb the $CO_2$.

**[0043]** FIG. 1 shows a multi-pollution abatement device in accordance with one or more embodiments of the invention. The multi-pollution abatement device may be deployed with a fossil fuel fired boiler or furnace 101, as shown, with the associated equipment such as a waste heat boiler and an electrostatic precipitator when using coal as a choice fuel. The system includes an $O_3$ aspirator 102 with the associated equipment such as ozone generator 103 and oxygen ($O_2$) supply 104. The system further includes a heat reclaim coil 105, *e.g.*, an economizer, to extract exhaust gas heat. The system further includes a heat exchanger 106 and a combustion air preheater 107 for energy savings of the system. The system includes a first stage fogging array 108 with a high pressure pump 109, a water supply 110 and an $H_2O_2$ supply 111. The system includes condensing medium 112, *e.g.*, a demister, that is connected to a drain pipe to direct all liquid waste to a waste water facility 117. The system further includes a second stage fogging array 113 that includes high pressure pump 114 and a water supply 115 with a second condensing medium 116, *e.g.*, a demister, following the second stage fogging array 113. The system further includes, a third stage fogging array 118 with associated equipment, such as high pressure pump 119, cooling unit 120, water supply 121, and an amine solution storage system 122. The system further includes a third condensing medium 123, *e.g.*, a demister 123, and connecting pipe leading to a captured $CO_2$ solution center 124. On the output of the system is an activated carbon frame section 125 and an exhaust fan 126.

**[0044]** Referring to FIG. 1, one of ordinary skill in the art will appreciate that embodiments of the invention are not limited only to the configuration shown in FIG. 1. Each component shown in FIG. 1, as well as any other component implied and described but not shown in FIG. 1, may be configured to receive material from one component (*i.e.*, an upstream component) of the system and to send material (either the same as the material received or material that has been altered in some way) to another component (*i.e.*, a downstream component) of the system. In all cases, the material received from the upstream component may be delivered through a series of pipes, pumps, or the like. Furthermore, while the embodiments of FIG. 1 show the stages of the multi-pollution abatement device in a particular order, the order or number of stages is not limited merely to those arrangements shown. One

of ordinary skill will appreciate that any number of stages in any sequential arrangement may be used without departing from the scope of the present disclosure. For example, any number of economizer, fogger, demister, and activated carbon stages may be employed without departing from the scope of the present disclosure.

**[0045]** FIG. 2 shows a flow chart describing a method of multi-pollution abatement using coal or oil as a fossil fuel in accordance with one or more embodiments of the invention. Referring to FIG. 2, in Step 201, the stream of exhaust gas is brought into contact with ozone $O_3$ to convert NO present in the exhaust gas to $NO_2$. In Step 202, the stream of exhaust gas comes into contact with an economizer that extracts heat from the exhaust gas that is later reused in the system to generate an energy savings. In Step 203, the stream of exhaust gas is brought into contact with a mist of water and $H_2O_2$ to create a mixture of liquid acids. In accordance with one or more embodiments, the stream of exhaust gas may include one or more of NO, $NO_2$, $SO_2$, Hg, $Hg_2$, HCl, $CO_2$ and particulate generated during a typical fossil fuel combustion process. Accordingly, the mixture of liquid acids formed in Step 203 may include one or more of $HNO_3$, $H_2SO_4$, $H_2CO_3$, $HgCl_2$, and waste water. The mixture may also include other chemicals and/or materials.

**[0046]** In Step 204, the liquid acid waste water mixture is extracted from the exhaust stream, *e.g.*, by coming into contact with a condensing media such as a demister. In Step 205, the remaining compositions in the exhaust stream such as NO, $NO_2$, $SO_2$, Hg, $Hg_2$, HCl, $CO_2$, and particulate are brought into contact with a second water mist to create a mixture of liquid acids $HNO_3$, $H_2SO_4$, $H_2CO_3$, $HgC1_2$ and waste water. In Step 206, the liquid acid and waste water mixture is extracted from the stream of exhaust gas, *e.g.*, by coming into contact with a second condensing media such as a demister. In Step 207, the exhaust gas stream that now includes mostly $CO_2$ is brought into contact with a mist that includes a chilled amine (*e.g.*, MEA denoted as $RNH_2$, or the like) solution to absorb the $CO_2$ molecule and create a liquid absorbed $CO_2$ solution.

**[0047]** In accordance with one or more embodiments, the chilled amine solution mist may be maintained at a temperature at, or near, 50-55 degrees F to ensure that the amine and $CO_2$ stay as a chemical formation. Furthermore, in accordance with one

or more embodiments, the amine absorbs the $CO_2$ and serves as the starting base for an alcohol such as COOH or ROH depending on which amines are used. The amines and $CO_2$ will separate if heated above 180 degrees F and, thus, the chilled water is beneficial to ensure that the proper temperatures are maintained despite the potentially high temperature (up to 300 degrees F) of the exhaust gas. Furthermore, in accordance with one or more embodiments, in a natural gas fired application, as described in more detail below, the amine solution may be used to absorb the $CO_2$ and distillation of the solution is not necessary, but rather, aluminum lithium hydrate may be added to the solution. As described in more detail in U.S. Patent No. 8,084,652, which is incorporated by reference herein in its entirety.

**[0048]** In Step 208, the liquid absorbed $CO_2$ is extracted from the exhaust gas stream, *e.g.*, by coming into contact with a third condensing media such as a demister. In Step 209, the exhaust gas stream that now includes very small amounts of NO, $NO_2$, $SO_2$, Hg, $Hg_2$, and HCl, comes into contact with an activated carbon stage (*e.g.*, a granulated carbon frame section, as described in more detail below, in reference to FIGs. 5 and 8) where the now small traces (less than 3 ppm) of the NO, $NO_2$, $SO_2$, Hg, $Hg_2$, HCl, are absorbed into the granular activated carbon.

**[0049]** FIG. 3 shows a flowchart describing a method of multi-pollution abatement using natural gas as the fossil fuel in accordance with one or more embodiments of the invention. In Step 301, a stream of exhaust gas that includes at least NO, $CO_2$, and particulate, and is generated during combustion of natural gas is brought into contact with $O_3$ to convert the NO to $NO_2$. In Step 302, the stream of exhaust gas comes into contact with an economizer where the heat of the exhaust gas is extracted and used to generate an energy savings for the system. In Step 303, the stream of exhaust gas that includes $NO_2$, $CO_2$, and particulate is brought into contact with a mist of water and $H_2O_2$ to create a mixture of liquid acids $HNO_3$, $H_2CO_3$, and waste water. The mixture may also include other chemicals and/or materials.

**[0050]** In Step 304, the liquid acids and waste water are extracted from the exhaust stream by, *e.g.*, bringing them into contact with a condensing media such as a demister. In Step 305, the remaining compositions in the exhaust stream such as $NO_2$, $CO_2$, and particulate are brought into contact with a water mist to create a

mixture of acids including $HNO_3$, $H_2CO_3$, and waste water. In Step 306, the liquid acids and waste water are extracted from the exhaust gas stream, *e.g.*, by bringing them into contact with a second condensing media such as a demister. In Step 307, the exhaust gas stream that now includes mostly $CO_2$ is brought into contact with a mist formed from a chilled amine solution mist to absorb the $CO_2$ molecule and to create a liquid absorbed $CO_2$ solution. In Step 308, the liquid absorbed $CO_2$ solution is extracted from the exhaust stream by, *e.g.*, contacting the solution with a third condensing media such as a demister. In Step 309, the exhaust gas stream that now includes very small amounts of $NO_2$, comes in contact with an activated carbon stage (*e.g.*, a granulated carbon frame section, as described in more detail below, in reference to FIGs. 5 and 8) where the now small traces (less than 3 ppm) of $NO_2$, are absorbed in the granular activated carbon.

**[0051]** FIG. 4 shows a system for creating an exhaust gas stream including NO, $NO_2$, $SO_2$, HCL, Hg, $Hg_2$, $CO_2$ and particulate from a combustion process in accordance with one or more embodiments of the invention. In one or more embodiments, the boiler 401 is a fire-tube or water-tube boiler capable of producing millions of BTUs of steam per hour for producing electricity. The boiler 401 may utilize a conventional design that includes a burner 402 that receives a controlled quantity of pre-heated combustion air 403 and fuel 404 (*e.g.*, coal) with the safety of a level controller 405 to ensure proper boiler feed water level.

**[0052]** The boiler exhaust gas 400 may flow through a waste heat boiler 406 that removes heat from the exhaust gas after it exits the boiler. The waste heat boiler 406 produces high temperature, high pressure steam that drives a steam turbine 407 that in turn produces electricity through a generator set 408 to use at the facility or sell. The exhaust gas is directed from the waste heat boiler 406 to an electrostatic precipitator 409 (ESP) where particulate matter such as fly ash and other large particulate matter is removed from the exhaust gas stream.

**[0053]** The ESP is an effective treatment for removing particulate such as fine dust, smoke, fumes, and fly-ash in a limited space. Produced within an ESP is a unidirectional electrostatic field between two electrodes that sweeps the dust from the exhaust gas stream as it passes through the field. The dust or fly-ash is deposited

upon the outer surface of the chamber where it is removed by periodic shaking. A typical ESP includes of a bundle of vertical metallic tubes through which the exhaust gas stream flows. Through the center of each tube is a wire electrode that is fixed to and insulated from the tube. The positive pole of a high voltage direct current is attached to the center electrodes and the negative to the tubes. When the voltage is applied, the dust particles are charged and move transversely in the field until the particles reach the chamber wall.

**[0054]** After passing through the ESP 409, the exhaust gas stream 400 is then directed through an $O_3$ aspirator 410. The $O_3$ aspirator 410 is supplied with $O_3$ by an ozone generator 412 via a control valve 413 and a series of flow meters 414 that measure the linear volumetric flow rate of the $O_3$ directed to the aspirator 410. The ozone generator 412 is supplied with oxygen by an oxygen storage facility 411.

**[0055]** In accordance with one or more embodiments, the aspirator 410 is a flow-through nozzle device in which the kinetic energy of the substance being aspirated is increased in an adiabatic process. More specifically, in accordance with one or more embodiments, at the input end, the body of the aspirator forms a converging nozzle which decreases the flow area within the exhaust gas breeching and then, after a few feet, the body of the aspirator forms a diverging nozzle which increases the flow area of the exhaust gas breeching. This increase in kinetic energy involves a decrease in pressure and accomplished by the change in the flow area. The aspirator 410 may be a mechanical device that introduces ozone into the flow of flue gas through a nozzle where the ozone is mixed with the flue gas flow using the ozone as an oxidizing agent to convert nitric oxide (NO) to nitrogen dioxide ($NO_2$). In one or more embodiments, the ozone is introduced to the flue gas at 1:1 (stoichiometric) concentration. Accordingly, the introduction of ozone gas into the exhaust gas stream causes the following reaction to occur:

**[0056]** $$NO + O_3 \rightarrow NO_2 + O_2$$

**[0057]** The exhaust gas then passes through an economizer that may be a forced-flow, once through conversion heat transfer device, usually formed from steel tubes, to which feed-water is supplied at a pressure above that of the steam generating section and at a rate corresponding to the steam output of the boiler unit.

**[0058]** In accordance with one or more embodiments, any number of different types, or classifications, of economizers may be employed in the system without departing from the scope of the present disclosure. Generally, economizers are classified in a number of different ways. For example, an economizer may be classified as horizontal or vertical-tube type, according to its geometrical arrangement. An economizer may also be classified as longitudinal or cross flow, depending upon the direction of gas-flow with respect to the tubes of the economizer. An economizer may further be characterized as parallel or counter flow, with respect to the relative direction of gas and water flow. An economizer may still further be characterized as steaming or non-steaming, depending on the thermal performance. Other examples of economizer classification include return-bend or continuous-tube (depending upon the details of design) and base-tube or extended-surface (according to the type of heat-absorbing surface). Staggered or in-line tube arrangements may be used in an economizer. The arrangement of tubes in an economizer affects a number of factors, including but not limited to the gas flow through the tube bank, the draft loss, the heat transfer characteristics, and the ease of cleaning.

**[0059]** Returning to FIG. 4, heat from the exhaust gas stream is transferred by the economizer 415 to the preheated combustion air stage 403 by way of a heat transfer fluid, *e.g.*, water, that flows through a series of pipes and valves to the pre-heated combustion air stage 403. After being transferred into the combustion air within the pre-heated combustion air stage 403, the heat is then returned to the economizer 415 through a circulation pump 403a. In the event that water is lost due to evaporation in the economizer, city water may be added through control valve 418.

**[0060]** Furthermore, water in the boiler 401 that is lost to steam may be replenished by water (commonly called "boiler make-up" or "boiler feed water") supplied by a pump 417 from a source of water (not shown) through a deaeration (D/A) tank 416. From the D/A tank 416, the boiler feed water may be fed by a boiler feed pump 417 through a controlled modulating boiler feed valve 420 to the boiler. In one or more embodiments, the boiler feed valve 420 may be regulated by the level controller 405 to maintain a preselected volume of boiler feed water in the boiler 401. Furthermore, water that is lost to steam in the waste heat boiler 406 may be

replenished by city water directed through control valve 419 to the waste heat boiler 406.

**[0061]** In accordance with one or more embodiments, the exhaust gas that exits the economizer is at a temperature of about 220 F and is then sent through breeching 421 to a receiving system (not shown).

**[0062]** An example, shown in FIG. 5, describes a receiving system to receive a stream of exhaust gas in accordance with one or more embodiments of the invention. Specifically, the receiving system in FIG. 5 represents one example of a multi-pollution abatement device in accordance with one or more embodiments of the invention. In this example, a stream of exhaust gas 400 from an economizer, *e.g.*, as described above with respect to FIG. 4, is directed into a multi-pollution abatement unit 501. The multi-pollution abatement unit 501 includes a first stage fogging array 502, condensing media 503, second stage fogging array 504, second condensing media 505, third stage fogging array 506, a third condensing media 507 and an activated carbon section 508, with an exhaust fan 509 to direct the clean exhaust gas through the exhaust damper 510 to the exhaust stack 511.

**[0063]** The exhaust gas 400 enters the multi-pollution abatement unit 501 and comes into contact with the first fogging array 502 where the exhaust gas encounters a high pressure liquid solution fog directed against the exhaust gas flow for creating a hydrolysis reaction. As used herein, a hydrolysis reaction is a chemical reaction of a compound (or compositions) with water, resulting in a formation of one or more new compounds (or compositions). Each fogger in the fogging array 502 may be configured to release high pressure liquid solution fog. The fog is formed of small droplets (about 10 microns in diameter) and the fog covers a large surface area. For example, FIG. 5 shows a fogging array 502 that is a series of fogging nozzles connected to piping and fittings within the multi-pollution abatement unit 501. Accordingly, the array creates a fog pattern that sprays against the exhaust gas flow to ensure contact with the exhaust gas composition. Advantageously, the combination of small droplets and large surface area provides for reaction of the high pressure liquid solution fog with the various pollutants within the exhaust gas stream.

**[0064]** In accordance with one or more embodiments, the liquid solution used to generate the fog for fogging array 502 originates from the water storage tank 512, where city water or reverse osmosis water is collected and stored. A high pressure fogging pump 513 draws the water from the water storage tank 512 to the fogging array at the same time a chemical pump 516 sends liquid $H_2O_2$ from a $H_2O_2$ storage tank to the high pressure fogging pump 513. The amount of $H_2O_2$ that is mixed with the water *e.g.*, within the high pressure fogging pump 513, is modulated by a control valve 515 before being directed to the fogging array 502. From the high pressure fogging pump 513, the mixed solution is directed through a control valve 517 where the mixed solution is modulated to allow a proper amount of solution to be applied to the exhaust gas stream. The mixed solution is sent to the fogging nozzles of fogging array 502 by way of a series of piping and fittings 518. The mixed solution sprayed by the fogging array nozzles of the fogging array 502 is sprayed under a pressure of approximately 1000 psi to 3000 psi to achieve maximum hydrolysis within the exhaust gas stream. The droplets of the liquid solution absorb contaminants such as $NO_2$, $SO_2$, HCl, Hg(0), and Hg(II)

**[0065]** For example, the introduction of the mixed liquid solution of $H_2O_2$ and $H_2O$ into the exhaust gas may cause the following reactions to occur:

**[0066]** $SO_2 + H_2O_2 \rightarrow H_2SO_4$

**[0067]** $3NO_2 + H_2O \rightarrow 2HNO_3 + NO$

**[0068]** $HCl + H_2O \rightarrow H_3O^{+1} + Cl^{-1}$

**[0069]** $Hg_2^{+2} + 2Cl^{-1} \rightarrow Hg_2Cl_2$

**[0070]** In accordance with one or more embodiments, the exhaust gas, after passing through the first high pressure fogging array 502, comes in contact with a first condensing medium 503, *e.g.*, a demister. The saturated exhaust gas develops a wetted film on the first condensing medium 503, where the acids $H_2SO_4$, $HNO_3$, $(H_3O^{+1})(Cl^{-1})$, and $Hg_2Cl_2$ are captured and directed, under gravity, to the drain piping and fitting 519. The drain piping and fitting 519 directs the concentrated acids to an equalization tank 540 where the acids are contained. The acids are then distributed to either a neutralization process or sent on to a separation process such

as that described in U.S. Patent No. 8,084,652, incorporated by reference herein in its entirety.

**[0071]** As used herein, the term condensing medium includes any demister device that enhances the removal of liquid droplets entrained in an exhaust gas stream. For example, mesh type coalesce, vane pack, or other structures intended to aggregate the mist into droplets that are heavy enough to separate from the exhaust gas stream may be employed. Advantageously, demisters as used within the system serve to reduce the residence time required to separate a given liquid droplet size. One of ordinary skill having the benefit of this disclosure will appreciate that there exists many different types of demisters, *e.g.*, demisters that are made from knitted materials with interlocking asymmetrical loops of metal or plastic with typical diameters being 0.1 to 0.3mm. These types of demisters have high removal efficiencies of water droplets and low pressure drops. Accordingly, one or more embodiments of the invention may employ any demister known in the art or to be developed.

**[0072]** FIG. 5 further shows an example of a neutralization system 552, where the contained acids in the equalization tank 540 are directed through a waste water pump 541 to a PH control tank 542 where the acids are mixed with a chemical such as limestone to neutralize the acids, making them safe to dispose of. When the acids enter the PH control tank 542, an automatic PH control sensor 543 sends a signal to the chemical storage tank 545 to send a controlled amount of chemical (limestone) to the PH control tank 542 through a chemical pump 546 to be mixed with the acid liquids to neutralize the acids. The PH control tank has a chemical mixer 544 that mixes the chemical as it is received in the PH control tank. The neutralized acids now described as salts are directed from the PH control tank 542 through a waste water pump 547 to a waste water press 548 where the salts and particles are pressed to squeeze out the water so there is only wet solids remaining. The water that has been separated from the solids is re-directed through a water pump 549 back to the water storage tank 512 where the water is re-used in the process. An automated control valve 550 controls the volume and flow of the re-cycle water going to the water storage tank 512.

**[0073]** After the exhaust gas passes through the first demister 503, the exhaust gas comes into contact with the second high pressure fogging array 504. The second high pressure fogging array 504 may be configured to release high pressure liquid solution fog having droplets that are very small (about 10 microns in diameter) and cover a large surface area, thereby allowing the high pressure liquid solution fog to react to the various pollutants within the exhaust gas stream that were not converted or captured by the first stage of the system. A high pressure fogging pump 520 draws the water to the fogging array 504 from the water storage tank 512. The amount of water and water pressure is modulated by control valve 521 that delivers the water through a network of piping 522 to the second stage high pressure fogging array 504.

**[0074]** In one or more embodiments, the exhaust gas after passing through the second high pressure fogging array 504 becomes saturated, then comes in contact with the second condensing media 505, *e.g.*, a demister. The saturated exhaust gas develops a wetted film on the demister 505 where the acids $H_2SO_4$, $HNO_3$, $H_3OCl$, $Hg_2Cl_2$ are captured, and through gravity are directed to the drain piping and fitting 519. After the exhaust gas passes through the second demister 505, the exhaust gas comes in contact with the a third high pressure fogging array 506 where exhaust gas still containing a large amount of $CO_2$ contaminant reacts with the liquid which is mixed with a reactant solution, *e.g.*, an amine solution, to remove $CO_2$ from the exhaust gases.

**[0075]** As used herein, the term amine solution refers to a group of aqueous solutions of various alkylamines. For example, in accordance with one or more embodiments, many different amines may be used without departing from the scope of the present disclosure, *e.g.*, monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolime (MDEA), diisopropylamine (DIPA), and aminoethoxyethanol (DGA). In accordance with one embodiment, MDEA is used to remove large amounts, approximately 90% of $CO_2$. For example, in an exhaust gas having approximately 1,000 pounds of $CO_2$, the amine solution would remove approximately 900 pounds of the $CO_2$. Furthermore, in such cases where a large degree of $CO_2$ removal is necessary, the third high pressure fogging array 506 may be configured to spray the high pressure amine mixture fog against the exhaust gas

flow (*i.e.*, the fog is sprayed in a direction generally opposing (or antiparallel) the flow direction of the exhaust gas). This advantageously improves contact with the exhaust gas composition resulting in an increase in the rate of $CO_2$-MDEA reaction as compared to a non-opposing, *e.g.*, co-directional or parallel, flow configuration.

**[0076]** In accordance with one or more embodiments the invention, $CO_2$ reacts with primary and secondary amines to form carbamate according to the following chemical reaction

**[0077]** $CO_2 + H_2O + \text{Amine} \rightarrow [\text{amine}]COOH^+ + OH^-$

**[0078]** Because MDEA is a tertiary amine and does not have a hydrogen attached to the nitrogen, the $CO_2$ reaction can only occur after the $CO_2$ dissolves in water to form bicarbonate ion. The bicarbonate ion then undergoes an acid-base reaction with the amine to yield the overall $CO_2$ reaction:

**[0079]** $CO_2 + H_2O + R_2NCH_3 \leftrightarrow R_2NCH_4^+ + HCO_3^-$

**[0080]** In accordance with one or more embodiments, the $CO_2$ molecule is dissolved into the water by applying a cold water solution having a temperature of 55 F or below to effectively capture and contain the $CO_2$ molecule in the solution.

**[0081]** Returning to FIG. 5, a water make-up water valve 530 delivers, *e.g.*, city water, when required, to a water cooling unit control valve 532 that controls the quantity and flow to the water cooling unit 533. In accordance with one or more embodiments, the water cooling unit 533 cools the water from ambient temperature to approximately 55 F. The cold water is directed from the water cooling unit 533 through another control valve 534 to a cooling pump 535. The cooling pump 535 directs the cold water through a flow meter 536 and into a cold water storage tank 523. The water cooling unit 533 is cooled by a separate condenser water loop and connected to outdoor cooling tower 560 to expel heat to the atmosphere. The condenser water from the water cooling unit 533 is directed through a control valve 537 to maintain a specific flow and sent to a cooling tower where the heat is extracted. From the cooling tower the condenser water is directed through a condenser pump 539 then sent back to the water cooling unit 533 through a flow meter 538 where the condenser water starts its cooling cycle again.

**[0082]** From the cold water storage tank 523, the cold water is directed to a network of piping and fittings where the cold water is mixed with amine solution 525. The amine solution is directed through a chemical meter 526 and a chemical pump 527 where the amine solution is sent through a network of piping and mixed with the cold water. In accordance with one or more embodiments, the amine is mixed with the water at 40 % concentration of the amine solution. However, other mixing ratios may be used without departing from the scope of the present disclosure. The mixed solution is then directed through a high pressure pump 524 where the mixed solution is sent through a control valve 528 that modulates the flow and pressure of the mixture. The mixture is sent to the high pressure fogging array 506 via a network of piping and fittings 529. The mixed solution is sprayed by the high pressure fogging array 506 thereby directing a high pressure fog against the exhaust gas flow to create a hydrolysis reaction. The hydrolysis reaction captures the $CO_2$ and creates a liquid absorbed $CO_2$ solution.

**[0083]** The exhaust gas then passes a third demister 507 where the liquid absorbed $CO_2$ solution condenses on the demister. The condensed liquid falls under gravity and is directed to a drain and a network of piping to a separate $CO_2$ storage tank 551. In accordance with one or more embodiments, the captured liquid may be sent to a further process where the liquid can be converted to alcohol as described in U.S. Patent No. 8,084,652 the disclosure if which is incorporated by reference herein in its entirety.

**[0084]** After passing through the third demister 507, the exhaust gas comes into contact with the activated carbon frame section 508. More specifically, by contacting the activated carbon frame section 508, the exhaust gas passes through a granular activated carbon field, as described in more detail below in reference to FIG. 8. As used herein the term granular activated carbon is used to describe activated carbon that has a relatively large particle size compared to powder activated carbon. However, powder activated carbon creates a large pressure drop in the exhaust gas. Advantageously, granular activated carbon creates a lower pressure drop, thereby requiring less energy to ultimately expel the exhaust gas from the system.

**[0085]** Advantageously, in the multi-pollution abatement process described herein, where the exhaust gas passes through a series of stages such as a first high pressure fogging array 502 and first demister 503, a second high pressure fogging array 504 and second demister 505, and a third high pressure fogging array 506 and third demister 507 can remove up to 98% of the targeted pollutants (except $CO_2$), leaving only small amounts of targeted pollutants still in the exhaust gas.

**[0086]** It is well known in the industry that exhaust gases produced from a fossil fuel, the pollutants are measured and monitored in ppm (parts per million). Parts per million is the mass ratio between the pollutant component and the solution and the ppm is defined as: ppm = 1,000,000 MC/MS, where MC = mass of component (Kg, lbm) and MS = mass solution (Kg, lbm).

**[0087]** With the activated carbon frame section, the granular activated carbon will absorb the targeted pollutants such as NO, $NO_2$,$SO_2$, HCL, Hg(0), and Hg(II) reducing the remaining pollutants, *e.g.*, from 10 ppm to 2 ppm. In accordance with one or more embodiments, the activated carbon frame section is a screened frame section, which holds granular activated carbon pieces freely and can be replaced on a regular basis, as described in more detail below in reference to FIG. 8. A gram of activated carbon can have a surface area in excess of 500 $m^2$ with 1500 $m^2$ being readily achievable. When the activated carbon cannot adsorb anymore molecules it can easily be replaced with new activated carbon and the old activated carbon can be shipped to be re-activated or disposed of. Furthermore, the granular activated carbon absorbs the targeted pollutant molecule as the exhaust gas passes through the granular activated carbon field.

**[0088]** Returning to FIG. 5, after the exhaust gas passes through the activated carbon frame section 508, the exhaust gas is forced through an exhaust fan 509 that is necessary to maintain sufficient pressure to overcome the resistance to flow imposed by the burning equipment, tube banks, directional turns, fogging arrays, demisters and activated carbon section and flue and dampers in the system. The resistance to air and gas flow depends upon the arrangement of the equipment and varies with the rate of flow and the temperatures of the air and gas. The exhaust fan 509 can be, but is not limited to, a high quality, high efficiency airfoil fan, where the fan has unique

adjustable discharge position and wherein the housing can be easily rotated to any one of a number of positions, *e.g.*, four positions.

**[0089]** After the exhaust gas is guided out of the exhaust fan through a set of dampers 510. The dampers 510 are normally open during unit operational time and normally closed when the unit is not operating. After passing through the dampers 510, the exhaust gas is directed to atmosphere through an exhaust stack 511.

**[0090]** Furthermore, while the embodiments of FIG. 5 show the stages of the multi-pollution abatement device in a particular order, the order or number of stages is not limited merely to those arrangements shown. One of ordinary skill will appreciate that any number of stages in any sequential arrangement may be used without departing from the scope of the present disclosure. For example, any number of economizer, fogger, demister, and activated carbon stages may be employed without departing from the scope of the present disclosure.

**[0091]** FIGs. 6A-6D show various views of a modular system for multi-pollutant abatement in accordance with one or more embodiments of the invention. In accordance with one or more embodiments, the unit is built from modular sections 601-610, thereby allowing the units to be fitted and sized exactly with plant specifications. Turning to FIG. 6A, a top view of a modular system for multi-pollutant abatement in accordance with one or more embodiments of the invention is shown. The first section 601, is fitted to house a first high pressure fogging array (*e.g.*, high pressure fogging array 502), where the second section 602 is fitted to house the first demister (*e.g.*, demister 503). The third section 603 houses the second high pressure fogging array (*e.g.*, high pressure fogging array 504) and the fourth section 604 houses the second demister (*e.g.*, demister 505). The fifth section 605 is fitted to and houses the third fogging array (*e.g.*, high pressure fogging array 506) used for capturing the $CO_2$ with the sixth section 606 fitted to house the third demister (*e.g.*, demister 507). The seventh section 607 is fitted to house the granular activated carbon frame section 508 (*e.g.*, a granular activated carbon W-frame, as described in more detail below in reference to FIG. 8). On the top and bottom of seventh section 607 are a series of doors 608 that open to add activated carbon on the top and dispose of the de-activated carbon at the bottom of the unit. There are

door latches 609 that secure and seal the doors to prevent any exhaust gas leakage. The eighth section 610 is where a fan can be housed and maintained with a motorized discharge damper 611 installed at the end of the unit. The discharge damper is comprised of opposed steel blades, constructed, *e.g.*, of 14 gauge sheet metal. In accordance with one or more embodiments, the bearings are sealed for life lubrication and the damper linkage and shafts are zinc plated steel.

**[0092]** Turning to FIG. 6B, a side view of a modular system for multi-pollutant abatement in accordance with one or more embodiments of the invention. From the side view there is a collar 612 at the top of the unit and a collar 613 at the bottom of the unit that are both welded and sealed to the granular activated carbon W-frame to allow access to the top and bottom of the granular activated carbon for loading and unloading of the granular activated carbon material. Also shown in the side view, double doors 614 and single doors 615 are included to allow access to the internal components of the unit, *e.g.*, for the purpose of annual inspection of the internal lining and all of the unit's internal components.

**[0093]** FIG. 6C shows a unit from an end view in cross-section. In accordance with one or more embodiments, the external lining 616 is constructed of pre-galvanized sheet steel (*e.g.*, 16 gauge (2.4mm)) and is etched, epoxy coated and finished with durable enamel paint. In accordance with one or more embodiments, the internal media 617 in between the panels may be incombustible thermal acoustic, shot free glass fiber insulation with long resilient fibers bonded with thermosetting resin. In addition, the internal media 617 may be a bacteria and fungus resistant material that will not crumble or break and will conform to irregular surfaces and return to full thickness if compressed. In accordance with one or more embodiments, the internal media 617 has the required fiber properties as rated by underwriter's laboratories and, *e.g.*, meets UL standards MVSS-302 and UL94HF-1. The internal skin 618 is constructed of ICONEL alloy, *e.g.*, 12 (6.4mm) gauge, and welded water tight to withstand high temperatures and a moist acid environment. In addition, the internal lining may be constructed with, but not limited to, an ICONEL alloy that is high nickel, high chromium for resistance to oxidizing and reducing environments. In some cases HASTELLOY alloy maybe chosen over the ICNONEL alloy for

resistance to a wide range of organic acids and the resistance to chloride-induced SCC, and other reducing chemicals.

**[0094]** The structural frame 619 is constructed from, but not limited to, 6" x 6" x 0.187 high strength stainless steel (HSS) with all cut edges located within the unit having high quality welded joints and/or bolt fittings 622. At the bottom of the unit there is a continuous, sloping floor 620 so all condensed liquid droplets from the condensing media are directed to a floor drain 621 located and the lowest point of the floor. In accordance with one or more embodiments, the sloped floor is also constructed of ICONEL alloy, *e.g.*, 12 (6.4mm) gauge, and welded water tight to withstand a strong liquid acid concentration.

**[0095]** FIG. 6D shows an example of access doors in accordance with one or more embodiments of the invention. The access doors 623 of the unit will vary in size and are mounted on a steel frame (not shown) with multiple chrome door hinges 624, a cam-type door latch 626, and an inspection window 625. The access door 623 has a single rubber gasket seal 627 to withstand abnormal high temperature conditions, *e.g.*, 240-350 C. The door inspection window 629 is double glazed with wire 628 reinforced glass mounted in a channel and sealed. The internal skin 630 of the access door is constructed with inconel alloy and welded water tight. With the insulation or media 631 in between the door is incombustible thermal acoustic, shot free glass fiber insulation with long resilient fibers bonded with thermosetting resin.

**[0096]** FIGs. 7A-7D illustrate a high pressure fogging array 701 in accordance with one or more embodiments of the invention. For example, the high pressure fogging array 701 may be employed as the first, second, and/or third fogging arrays in a multi-pollution abatement device, as described above reference to FIG. 5 and/or the first and/or second fogging arrays in the system shown in FIGs. 14-16. The high pressure fogging array 701 can be side loaded into a module 702 of a multi-pollution abatement unit, as shown in FIG. 7A, where each individual rod includes multiple high pressure fogging nozzles 703. Advantageously, when replacement of the high pressure fogging array 701 is desired, the high pressure fogging array 701 may be drawn or pulled from the side of the multi-pollution abatement unit without needing to shut down the unit. As shown in FIG. 7B, the high pressure fogging array 701

can also be configured so that each fogging rod can be top loaded. Furthermore, in accordance with one or more embodiments, each individual rod can be drawn or pulled out from the top or side of the unit for replacement of the high pressure nozzles without shutting down the unit. In such an arrangement, each rod has quick connect and disconnect fittings 704 to allow each individual rod to be disconnected and pulled out from the multi-pollution abatement unit so each high pressure fogging nozzle can be inspected and replaced when needed without interfering with the operation of the multi-pollution abatement unit or boiler system.

**[0097]** FIG. 7A also shows an example of a water supply system that may be used in conjunction with a high pressure fogging array in accordance with one or more embodiments of the invention. In FIG. 7, RO water, or in some cases, city water is directed through piping valves and fitting 715 and enters an inline water filter bag filter 714 where solids, oil, and hydrocarbons are removed from the water to prevent plugging of the high pressure nozzles. The filtered water is directed through a high pressure pump 713 where the water is increased in pressure from normal city water pressure (about 60 psi) up to about 3000 psi. The high pressure pump 713 is equipped with a variable speed drive to increase and decrease the water pressure as required for modulation of the exhaust gases. The high pressure water or solution is directed through visible pressure gauges 712, one located on the suction side of the high pressure pump 713 and the other located on the discharge side of the high pressure pump 713. These gauges are used by the operator to ensure that the pump is operating in a normal fashion. The high pressure water or solution is then directed through a flow meter 711 where the quantity of high pressure water or solution is monitored as it is being delivered to the high pressure fogging nozzles 703. The high pressure water or solution is then directed through a control valve 709 that controls the quantity of the high pressure water or solution that flows to the high pressure fogging nozzles. There is a shut off valve 710 before the control valve 709 and a shut off valve 708 after the control valve 709 as well as a globe valve 707 to by-pass the control valve 709 if the control valve 709 needs repair or replacement. The high pressure water or solution is then directed to a common header 706 where the high pressure water is collected and distributed to the individual high pressure fogging rods and nozzles through a series of valves piping and fittings 705.

[0098] Furthermore, in one or more embodiments, the high pressure fogging rod 716 is a seamless tube constructed of 316L stainless steel, Inconel alloy, or Hastelloy alloy for resistance to a wide range of organic acids and other reducing chemicals and for resistance to chloride-induced stress corrosion cracking. As shown in FIG. 7B-7C, along the high pressure fogging rod 716 are multiple high pressure fogging nozzles 717 engineered and installed to be a specific distance from one another, *e.g.*, 3 feet and at a downward angle from the exhaust flow, *e.g.*, 2 degrees to prevent plugging of orifices and to ensure that the fog ball or cloud is propelled against the exhaust gas flow thereby covering the full surface area of the exhaust gas flow. The high pressure fogging rod 716 also has a quick disconnect 718 on one end while the other end is capped and welded. Furthermore in one example, a quick disconnect 718 is a double union compression fitting where the compression fitting joins two tubes together. One of ordinary skill will appreciate that many different types of suitable connection fittings are known and may be employed without departing from the scope of the present disclosure.

[0099] FIG. 7D shows a high pressure nozzle 719 in accordance with one or more embodiments. High pressure nozzle 719 is designed with multiple orifices. Each orifice is manufactured so as to deliver a small water or liquid droplet about 10 microns in diameter. The high pressure fogging nozzle 719 has a standard pipe thread at one end so as to be screwed into a coupling 720 that is welded into the high pressure fogging rod 716.

[00100] FIG. 8 illustrates an activated carbon stage, *e.g.*, a granular activated carbon frame ("the frame") in accordance with one or more embodiments. In accordance with one or more embodiments, the cross-section of the frame may generally take the form of a W, although other embodiments may take other shapes without departing from the scope of the present disclosure. As shown in FIG. 8, a W-frame has a cross-sectional structure that is generally "W-shaped." More specifically, the cross-sectional shape of the frame may include a series of bends in alternating directions along the length of the frame. In the embodiment shown in FIG. 8, the cross section includes three bends, thereby forming the generally W-shaped cross-section. In accordance with one or more embodiments, any number of bends may be

used to generate the cross-sectional shape, *e.g.*, one bend would form a V-shape, while more than three bends would generally form a zig-zag or saw tooth shape.

**[00101]** As shown in FIG. 8, the frame itself is formed from two collars, a top color 802a and a bottom collar 802b. Each collar includes at least two members 802d and 802e that form a single member having an opening angle α that is obtuse, or greater than 90 degrees. This obtuse member in combination with a third member 802f makes a generally V-shaped member. Finally, this portion of the frame may be of a general form having any number of V-shaped sub-members that, taken together make up one side of a collar 802a or 802b. The precise value of α depends on the number of bends present, and the length and width of the frame itself and, thus, will vary depending on the physical constraints of the particular installation. The frame itself is made up of a top collar 802a and a bottom collar 802b connected by several intervening vertical members 802k. In accordance with one or more embodiments, *e.g.*, the top collar 802a and bottom collar 802b may be welded to a series of vertical connecting members. Furthermore, the frame's top and bottom may be rigidly attached, *e.g.*, welded, to the multi-pollution abatement unit to limit the vibration or movement of the frame within the unit. In addition, a nickel wire mesh or screen 803 is welded to the frame to form a holding or containment field, while at the same time allowing exhaust gases to pass through the frame with very little pressure loss or resistance.

**[00102]** In accordance with one or more embodiments, the frame of the activated carbon stage may be constructed from 316L stainless or inconel alloy channel steel, where the channel is made in the shape of a W, as shown in FIG. 8. However, the frame is not limited to only 316L stainless or inconel alloy channel steel materials. In accordance with one or more embodiments, frame surface is covered with an acid resistant coating to ensure minimum erosion and corrosion. One of ordinary skill will appreciate that nickel wire mesh is also named nickel wire netting, nickel screen, and nickel cloth, and as such, these also may be used without departing from the scope of the present disclosure.

**[00103]** The wire mesh 803 may be made by advanced vacuum melting process, by forging, rolling, annealing, drawing and weaving. Examples of weaving methods

include twilled weaving and plain weaving. In accordance with one or more embodiments, nickel wire mesh is used for its advantageous heat and corrosion resistance properties. Furthermore, nickel wire mesh is readily available in many mesh and wire gauge sizes thereby allowing multiple choices of granular activated carbon particle sizes. As described above in reference to FIG. 7, the granular activated carbon 804 is loaded from the top of the multi-pollution abatement unit and the de-activated carbon is unloaded from the bottom of the multi-pollution abatement unit.

**[00104]** In accordance with one or more embodiments, materials containing high fixed carbon content may be activated and used as a source of granulated activated carbon. For example, coal, coconut shell, wood, peat and petroleum residues may be used. Most carbonaceous materials do have a certain degree of porosity and an internal surface area in the range of 10-15 $m^2/g$. During activation, the internal surface becomes more highly developed and extended by controlled oxidation of carbon atoms. After activation, the carbon will have acquired surface area between 700 and 1500 $m^2/g$. Granular activated carbon is a very non-selective sorbent and has a great affinity for a wide spectrum of organic compounds. Pore diameters of activated carbon may be categorized as follows:

**[00105]** micropores < 40 Angstroms

**[00106]** mesopores 40 – 5,000 Angstroms

**[00107]** macropores > 5,000 Angstroms (typically 5,000 – 20,000 Angstrom)

**[00108]** For example, in accordance with one or more embodiments, granular activated carbon from coconut shell having macro-pores may be used within the activated carbon stage. However, granular activated carbon having micropores, mesopores, and/or macropores may be used without departing from the scope of the present disclosure. Generally speaking smaller pore diameters results in activated carbon granules that have a higher surface area and, thus, in certain circumstances may work as a more effective sorbent. In addition, the physical size, or mesh size, of a granular activated carbon must be considered in relation to the exhaust gas flow rate in the system. The smaller the granular activated carbon mesh size the greater the resistance to exhaust gas flow. Thus, in accordance with one or more embodiments,

the smallest mesh size carbon that will satisfy the pressure drop limitations of the system is selected.

**[00109]** Returning to FIG. 8, in accordance with one or more embodiments, at the top and bottom of the multi-pollution abatement unit activated carbon stage are doors 805 and 807. These doors allow access to the interior of the frame so that granular activated carbon may be replaced, when necessary. Furthermore, the doors 805 and 807 may be closed and sealed with a rubber gasket 806 to prevent any exhaust gas leak during operation of the unit. The multi-pollution abatement unit carbon frame section doors 805 and 807 are installed with handles, locking hatch 808 and hinges 809 for easy opening of the doors and to ensure safe operation of the unit. Furthermore the doors 805 and 807 can be installed with connecting rod 810 having a universal linkage kit 811 and electric motor 812 so as to automatically open the doors 805 and 807 when needed.

**[00110]** FIG. 9 shows an example of a high-pressure fogging rod in accordance with one or more embodiments of the invention. The high-pressure fogging rod 901 is formed from a hollow metal rod 903. In accordance with one or more embodiments, the hollow metal rod may be formed of a solid-solution nickel-based alloy, *e.g.*, 686 alloy tubing. Hollow metal rod 903 includes multiple orifices 905. In accordance with one or more embodiments of the invention, the multiple orifices 905 pass through the wall 907 of the hollow metal rod 903. At one end 909 of the hollow metal rod 903 is an NPT threaded connection to allow for connecting the hollow metal rod 903 to a tubing manifold (not shown) as described in more detail below. Also located at the end 909 is an angle indicator line 919 that runs co-linear with a line drawn through all of the orifices. At the other end of the hollow metal rod 903 is a welded cap 911. In accordance with one or more embodiments of the invention, the internal surface 915 of the wall 907 is formed so that the internal diameter of the internal volume 913 of the hollow metal rod 903 varies along the length of the hollow metal rod 903. For example, in accordance with one or more embodiments of the invention, the internal diameter 917 between two orifices is smaller than the internal diameter 921 that is located at an axial position that includes an orifice along an axial direction 923 of the tube. In accordance with one or more embodiments of the invention, employing a hollow metal rod 903 that is fabricated

to have a decrease in diameter after an orifice followed by an increased diameter before the next orifice hole creates a flow through nozzle or Venturi effect, as described above.

**[00111]** FIGs. 10A-10C show cross-sectional views through the high-pressure fogging rod taken through a line that passes through plurality of orifices 905 (*e.g.*, line 925 in FIG. 9). In accordance with one or more embodiments of the invention, a fine mist or fog 1001 is created by forcing fluid at high-pressure through the orifices 905. In accordance with one or more embodiments, the orifices may be of circular cross-sectional shape and may have diameters on the order of 0.008 in. With orifices of this size, a 3,000 psi fluid forced therethrough may form a fog ball having individual droplet sizes in the range of 5 to 10 microns. Furthermore, the fluid drop velocity exiting the orifice is near or at the speed of sound (Mach 1). In accordance with one or more embodiments of the invention, the angle indicator 919 shown in FIG. 9 may be used to orient the line of orifices in a known direction. For example, FIG. 10A shows an orientation of the high-pressure fogging rod that results in a fog ball being created in a direction substantially horizontal with respect to the exhaust gas flow direction 1007. FIG. 10B shows an orientation of the high-pressure fogging rod that results in a fog ball being created in a downwardly direction with respect to the exhaust gas flow direction 1007, *i.e.*, at an angle $\theta$ with respect to the gas flow. Thus, in accordance with one or more embodiments of the invention, the high-pressure fogging rod may be positioned in any desired orientation. In accordance with one or more embodiments of the invention, an optional pinion 1003 may be positioned directly in front of orifices 905 to disrupt the spherical spray pattern of the orifice, with pinion 1003 and fixedly attached to the high-pressure fogging rod 901 shown in FIG. 10C as a side view. Thus, the positioning of the pinion 1003 across a diameter of the orifice results in a fog ball that is asymmetric, elongated, or oval shaped rather than one having a substantially circular cross-section.

**[00112]** In accordance with one or more embodiments of the invention, the orifices 905 may be placed along the length of the high-pressure fogging device to ensure sufficient overlap of the fog balls, thus, ensuring full coverage across the exhaust stream. One of ordinary skill will also appreciate that the high-pressure fogging rod in accordance with one or more embodiments of the invention may employ various

sizes for the orifices without departing from the scope of the present disclosure. One of ordinary skill will appreciate that a larger orifice will produce a fog ball comprised of large droplets. One of ordinary skill will appreciate that a smaller orifice will produce a fog ball comprised of small droplets.

**[00113]** FIG. 11 shows a high-pressure fogging rod circuit in accordance with one or more embodiments of the invention. The high-pressure fogging rod circuit 1101 includes high-pressure pumping stage 1103 and high-pressure fogging rod assembly 1105. High-pressure pumping stage 1103 and high-pressure fogging rod assembly 1105 may be connected by way of connectors 1107. The high-pressure fogging rod circuit 1101 begins with a fluid feed from relatively large tubing 1109. In accordance with one or more embodiments of the invention, the fluid feed tubing may be 1 inch diameter stainless steel (SS) made from 316L steel. The fluid is then routed through filters 1111 and into high-pressure pumps 1113. After the high-pressure pumps 1113 are various pressure gauges 1112a-1112b, valves and flow meters 1114a-1114b, as shown. The pressurized fluid then enters one or more tubing manifolds 1115. As shown in FIG. 11, in accordance with one or more embodiments of the invention, the tubing manifolds may be formed from 1 inch 316L SS tube and may provide pressurized fluid to a plurality of feed tubes 1117, that, in turn, provide the pressurized fluid to the array of high-pressure fogging rods 1119. Interposed between the array of high-pressure fogging rods 1119 and feed tubes 1117 are intermediate tubes 1121. In accordance with one or more embodiments of the invention, the intermediate tubes may be formed from ¾ inch SS 316L tubing and the high-pressure fogging rods 1119 may be formed of ½ inch 686 alloy tubing. However, one of ordinary skill will appreciate that other tube sizes and tube materials may be employed in any given system, depending on the type of fluid used and the amount of fluid volume desired. Accordingly, FIG. 11 is intended as one example of a high-pressure fogging rod circuit in accordance with one or more embodiments of the invention and, thus, the attached claims are not limited to only that shown in FIG. 11.

**[00114]** In accordance with one or more embodiments of the invention both fogging rods 1119 and intermediate tubes 1121 are connected by way of quick disconnect fittings 1125. Accordingly, the removal of individual fogging rods for service is

made easier and more time efficient. In particular, the design of the high-pressure fogging rod circuit shown in FIG. 11 allows for the removal of single fogging rods without the hassle of removing the whole fogging rod assembly.

**[00115]** As shown in FIG. 11, the high-pressure fogging rod circuit 1101 may be employed within an HRPA device wherein the array of high-pressure fogging rods 1119 may form the first and second fogging stages on either side of a condensing medium stage 1123. Accordingly, as described above in reference to FIG. 5, the high-pressure fluid may include any composition of any number different fluids, *e.g.*, $H_20$ or $H_2O_2$.

**[00116]** FIG. 12A shows a high-pressure fogging rod support tray in accordance with one or more embodiments of the invention. More specifically, the high-pressure fogging rod support tray 1201 may include a support frame that further includes two or more support members 1203, 1205 for supporting a high-pressure fogging rod 203. More specifically, the high-pressure fogging rod may be threaded through supported brackets 1203a and 1205 in order to support the high-pressure fogging rod within the support tray 1201. Accordingly, an array of high-pressure fogging rods may be arranged as a high-pressure fogging rods assembly by stacking any number of support trays 1201, as shown in FIG. 12B. Accordingly, the support trays 1201 may be integrated within the HRPA device and with the individual high-pressure fogging rods 203 being configured to be individually removable from a corresponding support tray. In accordance with one or more embodiments of the invention, the support tray 1201 and high-pressure fogging rod 903 may be an integrated unit that may be removable as a unit from the HRPA device. While shown in a substantially horizontal mounting arrangement, in accordance with one or more embodiments of the invention, the high-pressure fogging rods may be mounted in a vertical direction. In accordance with one or more embodiments of the invention one or more arrays of fogging rods may be mounted in any direction that is substantially perpendicular to the gas flow direction without departing from the scope of the present invention.

**[00117]** In accordance with one or more embodiments, the high-pressure fogging rods are used to spray a high-pressure liquid against the exhaust flow to create the

hydrolysis needed to convert the pollutants such as NOx, SOx, HCL, particulate, mercury, and $CO_2$. The high-pressure fogging rod in accordance with one or more embodiments of the invention eliminates all mechanical joints within the HRPA device ensuring that there will be no equipment down time because of failed fogging devices due to mechanical joints that were exposed to the acid environment inside the HRPA device.

**[00118]** The high-pressure fogging rods will be placed in the HRPA device unit to cover the surface area of the exhaust flow to ensure full coverage of the polluted exhaust stream comes in contact with the high-pressure water droplets.

**[00119]** FIGs. 13A-D show examples of test data that illustrates the multi-pollution abatement capability of the system in accordance with one or more embodiments. The system used to acquire the data shown in FIG. 13 was a system, similar to that shown in FIG. 5, but employing two fogging stages, rather than three, as shown in FIG. 5, and an activated carbon frame section of the W-frame type, shown and described in reference to FIGs. 5 and 8. The first fogging stage employed an $H_20$ + $H_20_2$ mixture and the second fogging stage employed a water only fogging stage, as described above in reference to FIG. 5. The system was deployed on the output of a fossil fuel fired boiler burning eastern bituminous coal having the composition shown in FIG. 13A: 69.9% carbon, 6.4% oxygen, 2.2% sulfur, 2.4% moisture, 4.7% hydrogen, 1.2% nitrogen, 13.2% ash; and having a heating value of 12,644 Btu/lb. As shown in FIG. 13B, the exhaust gas entering the unit was at a temperature of 257 F (125 C) and the composition of the exhaust gas entering the multi-pollution abatement unit was 43.36 ppm NOx, 216.58 ppm $SO_2$, and 13,865 ppm $CO_2$. After passing through the multi-pollution abatement unit (*i.e.*, at the outlet of the unit) the exhaust gas was at a temperature of 89 F (32 C) and had a composition of 0.44 ppm NOx, 0.00 ppm $SO_2$ and 3,352 ppm $CO_2$. FIG. 13C shows time series data for SOx removal from the exhaust gas using the above described multi-pollution abatement unit over roughly a one hour time period. Series 1301 shows the input level of $SO_2$ (ppm) and series 1303 and 1305 show the output $SO_2$ level (ppm) and $SO_2$ removal fraction (%), respectively. FIG. 13C shows that despite a fluctuating input $SO_2$ level the $SO_2$ was effectively removed (nearly 100% at all times over the one hour period) from the exhaust gas stream. Likewise, FIG. 13D shows time series data for NOx

removal from the exhaust gas using the above described multi-pollution abatement unit over roughly a one hour time period. Series 1307 shows the input level of NOx (ppm) and series 1309 and 1311 show the output NOx level (ppm) and NOx removal fraction (%), respectively. FIG. 13D shows that despite a fluctuating input NOx level the NOx was effectively removed (greater than 95% at all times over the one hour period) from the exhaust gas stream. Furthermore, FIG. 13B illustrates that approximately 76% of the $CO_2$ was also removed from the exhaust gas stream.

**[00120]** FIG. 14 shows one example of a $CO_2$ capture system 1401 in accordance with one or more embodiments of the invention. In accordance with one or more embodiments of the invention, $CO_2$ capture system 1401 may remove $CO_2$ from an exhaust gas stream that is produced from a fossil fuel application, such as a natural gas fired turbine (not shown). To that end, the $CO_2$ capture module 1403 may be deployed as one of a series of modules that make up a multi-pollution abatement system, *e.g.*, the multipollution abatement system shown in FIGS. 1 and 5 and described in more detail above. Thus, the $CO_2$ capture system 1401 may be deployed with the various other modules and equipment associated with a fossil fuel fired boiler or furnace, *e.g.*, as described above in reference to FIG. 4.

**[00121]** In accordance with one or more embodiments, exhaust gas 1405 produced from a fossil fuel application, such as natural gas turbine, is directed into the $CO_2$ capture module 1403. In one embodiment, the exhaust gas 1405 may already have passed through some form of pollution abatement system, *e.g.*, the multipollution abatement system described above in reference to FIGS. 1 and 5, or any other known pollution abatement system. In accordance with one or more embodiments, the exhaust gas 1405 comes into contact with activated carbon stage 1407, where further removal of NOx occurs. In accordance with one or more embodiments, the activated carbon stage may be of the "W-frame" type, as described above in reference to FIG. 8. Furthermore, in an embodiment where exhaust gas 1405 had already passed through a system for NOx control, the W-frame activated carbon stage may remove 99 % of the remaining NOx. After passing through activated carbon stage 1407, the exhaust gas 1405 encounters a fogging stage 1409 that directs a high-velocity water fog in a direction that is counter, or substantially opposite to, the direction of exhaust gas flow. In accordance with one or more embodiments, the

fogging stage 1409 may be an ultrasonic fogging array that may produce ultra-fine water droplets having a diameter within a range of 5-20 microns in one or more embodiments, or 10-15 microns in other embodiments. In an embodiment where the fogging stage 1409 is embodied as an ultrasonic fogger, the fogging stage 1409 uses compressed air 1411 and water 1413 to produce the water mist (also referred to herein as fog). As used herein, the term mist may also be used synonymously with the term steam, as the mist may be all or partially converted to steam after contacting the hot exhaust gas, depending on the temperature of the exhaust gas. The compressed air 1411 is generated using an air compressor 1450 and air dryer 1452. In accordance with one or more embodiments, the compressed air 1411 and water 1413 is directed against the exhaust flow thereby creating a high energy because of both the expanding air and the relative speed of the water droplet (mach-1) and the $CO_2$ molecule. As a result of the high energy collision between the water droplet and $CO_2$ molecule, the $CO_2$ is very quickly dissolved in the water droplets; but the solution may not be stable.

**[00122]** After contact with the fogging stage 1409, the exhaust gas 1405, now including water mist with dissolved $CO_2$ is directed to a condensing medium 1461, *e.g.*, a mist eliminator or demister, as described above in reference to FIG. 5. The water mist including dissolved $CO_2$ then condenses onto the surface of the condensing medium 1461, forming a wetted film including dissolved $CO_2$. In accordance with one or more embodiments, the surface of the condensing medium 1461 may include a wired structure. The wetted film is then directed by gravity to a waste water drain system 1415, where waste water 1421 is collected and redirected to a waste water processing system 1419.

**[00123]** After coming into contact with the condensing medium 1461, the exhaust gas 1405 continues through the condensing medium 1461 and is then directed to the exhaust stack 1417 where the exhaust gas is eventually directed to atmosphere (not shown). The captured $CO_2$ in the waste water 1421 is directed through a network of piping and enters into the waste water settling tank 1423. In accordance with one or more embodiments, when the $CO_2$ is captured by the water fog, most of the $CO_2$ molecules may persist as aqueous $CO_2$ in the waste water; a small percentage converts to $H_2CO_3$ that is unstable and may convert back to $CO_2$. Furthermore, any

particulate that has been captured from the exhaust gas 1405 is directed to the waste water settling tank 1423 and will settle to the bottom of the waste water settling tank 1423.

**[00124]** In accordance with one or more embodiments, the waste water settling tank 1423 is subject to regular maintenance, *e.g.*, on a monthly basis, to dispose of collected particulate. While the aqueous $CO_2$ is settling in the waste water settling tank 1423, some of the $CO_2$ releases back into a gas form and is directed through a gas vent 1425 to a membrane system 1427. In accordance with one or more embodiments, the membrane system 1427 may be a polymeric membrane system that may separate the vented $CO_2$ from the other vented gases, *e.g.*, $O_2$ (Oxygen) and $H_1$ (Hydrogen).

**[00125]** Returning to the waste water processing system 1419, the waste water 1421 is directed from the waste water settling tank 1423 through a first chemical pump 1429 to an aggravator tank 1431, where the waste water is vigorously mixed to help the aqueous $CO_2$ convert into a gas form. The $CO_2$ gas is then directed through a gas vent 1433 on the aggravator tank and sent to the membrane system 1427. In accordance with one or more embodiments, there may be $O_2$ (Oxygen) and $H_1$ (Hydrogen) mixed with the $CO_2$ gas when leaving the aggravator tank.

**[00126]** These mixed gases from gas vents 1425 and 1433 enter into the membrane system 1427, where the vented $CO_2$ is separated from the other vented gases. The separated $CO_2$ is then directed through a network of piping 1435 to a $CO_2$ compressor station (not shown). All other gases such as $O_2$ (Oxygen) and $H_1$ (Hydrogen) is directed to the exhaust stack 1417.

**[00127]** The waste water from the aggravator tank 1431 is directed through chemical pump 1437 and sent to the recycled water holding tank 1439. In accordance with one or more embodiments, the recycled water holding tank 1439 has a pH controller 1441, a level controller 1443, a chemical feed 1445 and a mixer 1447. In some cases, there may be small quantities of nitric acid present in the recycled water from the holding tank 1439, whose pH is controlled by the pH controller 1441. When pH levels in the recycled water decrease, the chemical feed 1445 may introduce reagents through chemical pump 1149, *e.g.*, limestone, to neutralize the acids. In accordance

with one or more embodiments, when chemicals are fed into the tank, the mixer 1447 may automatically turn on to mix the chemicals thoroughly. Furthermore, in accordance with one or more embodiments, there may be a level controller 1443 on the recycled water holding tank 1439 to maintain a required water level in the tank.

**[00128]** From the recycled water holding tank 1439, the water is directed to the RO system 1451 through chemical 1453, where the recycled water is re-introduced to the fogging stage 1409. Thus, the RO water 1413 that is consumed by the fogging stage 1409 is captured and recycled back to the RO system. In accordance with one or more embodiments, over 80% of the RO water may be recycled; most of the loss of water is because of evaporation caused in the $CO_2$ capture module. In accordance with one or more embodiments, the typical exhaust gas temperature going into the $CO_2$ capture module for a nature gas application may be approximately 220°F and the water temperature may be approximately 70°F.

**[00129]** In accordance with one or more embodiments, the RO system 1451 may purify city water 1455 and the recycled water (with the salts, particles and other impurities removed) is then directed to an RO water holding tank 1457, where it is ready to be used by the fogging stage 1409. From the RO holding tank 1457 there is a RO water supply pump 1459 to direct the RO water to the fogging stage 1409.

**[00130]** $CO_2$ Capture Module material

**[00131]** In accordance with one or more embodiments, the $CO_2$ capture module 1403 may be made of fiberglass if exhaust gas temperature does not exceed 200°F. If the exhaust gas temperature is above 200°F, then a mild stainless steel such as 308 may be used. In accordance with one or more embodiments, the exhaust gas introduced to the fogging array may have a very mild acid environment, thereby allowing the module to be constructed of inexpensive materials. The geometry of the $CO_2$ capture module 1403 is not restricted to one shape or size and thus any shape and size may be employed without departing from the scope of the present disclosure. In accordance with one or more embodiments, the $CO_2$ capture module 1403 may be designed in a cylindrical shape to assist in space requirements on larger applications and to reduce costs associated with manufacture.

**[00132]** Ultrasonic Foggers

[00133] In accordance with one or more embodiments, any known ultrasonic fogger may be used for the fogging stage 1409. For example those typically used for various applications, including, for example, humidity conditioning of indoor environments, combustion air intake conditioning for combustion based systems such as gas turbine systems, and re-circulated flue gas fogging for boiler stack emission control systems may be used. In accordance with one or more embodiments the water droplets are propelled by the force of compressed air at velocities high enough to assure uniform mixing through direct flow injection into a receiving exhaust stream.

[00134] One example of an ultrasonic fogger is disclosed for example in U.S. Patent No. 5,454,518, a portion of which is summarized below. In accordance with one or more embodiments, an ultrasonic fogging stage includes a generally cylindrical body having an axial bore with an outlet at a front face of the body. The ultrasonic fogging stage further includes system for coupling a gas supply and a liquid supply to the bore. At least a portion of the front face of the body has a curved convex contour and a resonator may be spaced from and opposing the outlet end of the bore. A portion of the fogger body front face may have a curved convex contour which substantially reduces turbulence, and facilitates a smooth and efficient entrainment of air into the medium reflected from the fogger's resonator. In accordance with one or more embodiments, the curved convex contour has a surface area that is at least half of the total front surface area of the fogger body. A spherical contour, having a radius of curvature that is between 60 to 80 percent of the diameter of the cylindrical fogger body may be used. Because compressed air reflectance from the resonator to the fogger face may be important to the fogger's operation, the front face may be flattened in the annular region surrounding the bore outlet.

[00135] In another embodiment, an ultrasonic fogging stage may include a generally cylindrical body having an axial bore therethrough with an inlet at a rear face of the body and an outlet at a front face of the body. A system for coupling a gas supply to the inlet end of the bore is also employed. A chamber in the body is in communication with the bore. In addition, a system for coupling a liquid supply to the chamber is also employed. The ultrasonic fogging stage may also include a resonator spaced from and opposing the outlet end of the bore. The body includes

an inner cylindrical body portion and an outer cylindrical body portion surrounding the inner body portion, and the chamber comprises a cylindrical groove in the outer surface of the inner body portion. The chamber communicates with the axial bore via a plurality of radial feed holes. In accordance with one or more embodiments, the groove has a depth of about D/2 and a length of about 3D, where D is the diameter of said axial bore.

**[00136]** Typical foggers tend to employ pulsating flow. Furthermore, the fogger liquid delivery has been found to be related to the root mean square of pulsations, and this means that an excess of compressed air was being used in propagating the pulses of fog. It has been determined that there were instantaneous back-ups of air at the pressure peaks. Thus, come fogging stages may employ an elongated water groove which acts as an agitation chamber that pre-shears, through agitation, the liquid stream, and the pre-sheared water flow is further sheared by subsequent passage through the radial water feed holes prior to entrainment into the compressed air flow in the bore. Operation, to obtain fog droplets of a particular size, can be at a lower air to water pressure differential than in prior art foggers, and at lower noise levels.

**[00137]** An apparatus is provided for sensing contaminants in an exhaust stream (including, but not limited to, ozone, volatile organic compounds, and volatile inorganic compounds) and automatically fogging to capture the contaminants with fog (by absorption, adsorption, and/or adhesion). The capture process is particularly efficient, as the air and its contaminants are entrained in the region of the fogger gap. The contaminants are separated from the exhaust stream by subsequent cooling and condensing of the fog. An ultrasonic fogger which receives a fogger gas supply and a fogger liquid supply, and produces a fog in the input exhaust stream; means for determining the level of contaminants in the exhaust stream, and for producing a control signal in response thereto; means responsive to the control signal for controlling the fogging output of the ultrasonic fogger; and means for cooling the fogged exhaust stream to condense the fog to liquid containing the captured contaminants.

**[00138]** Membrane systems

[00139] An artificial membrane, or synthetic membrane, is a synthetically created membrane which is usually intended for separation purposes in laboratory or in industry. Synthetic membranes have been successfully used for small and large-scale industrial processes since the middle of twentieth century. A wide variety of synthetic membranes is known. They can be produced from organic materials such as polymers and liquids, as well as inorganic materials. Most of commercially utilized synthetic membranes in separation industry are made of polymeric structures. They can be classified based on their surface chemistry, bulk structure, morphology, and production method. The chemical and physical properties of synthetic membranes and separated particles as well as a choice of driving force define a particular membrane separation process. The most commonly used driving forces of a membrane process in industry are pressure and concentration gradients. The respective membrane process is therefore known as filtration. Synthetic membranes utilized in a separation process can be of different geometry and the respective flow configuration. They can be also categorized based on their application and separation regime. The best known synthetic membrane separation processes include water purification, reverse osmosis, dehydrogenation of natural gas, removal of cell particles by microfiltration and ultra-filtration, removal of microorganisms from dairy products, and dialysis.

[00140] Membrane types and structure

[00141] Synthetic membranes can be fabricated from a large number of different materials. It can be made from organic or inorganic materials including solids such as metal or ceramic, homogeneous films (polymers), heterogeneous solids (polymeric mixes, mixed glasses), and liquids. Ceramic membranes are produced from inorganic materials such as aluminum oxides, silicon carbide, and zirconium oxide. Ceramic membranes are very resistant to the action of aggressive media (acids, strong solvents). They are very stable chemically, thermally, and mechanically, and biologically inert. Even though ceramic membranes have a high weight and substantial production costs, they are ecologically friendly and have long working life. Ceramic membranes are generally made as monolithic shapes of tubular capillaries.

[00142] Polymeric Membranes

[00143] Polymeric membranes lead the membrane separation industry market because they are very competitive in performance and economics. Many polymers are available, but the choice of membrane polymer is not a trivial task. A polymer has to have appropriate characteristics for the intended application. In accordance with one or more embodiments, the polymer may offer a low binding affinity for separated molecules (as in the case of biotechnology applications), and may withstand the harsh cleaning conditions. Furthermore, the polymer may be compatible with chosen membrane fabrication technology. The polymer may be a suitable membrane former in terms of its chains rigidity, chain interactions, stereoregularity, and polarity of its functional groups. The polymers can form amorphous and semicrystalline structures (can also have different glass transition temperatures), affecting the membrane performance characteristics. The polymer may be obtainable and reasonably priced to comply with the low cost criteria of membrane separation process. Many membrane polymers are grafted, custom-modified, or produced as copolymers to improve their properties. The most common polymers in membrane synthesis are cellulose acetate, Nitrocellulose, and cellulose esters (CA, CN, and CE), polysulfone (PS), polyether sulfone(PES), polyacrilonitrile (PAN), polyamide, polyimide, polyethylene and polypropylene (PE and PP), polytetrafluoroethylene (PTFE), polyvinylidene fluoride (PVDF), polyvinylchloride (PVC).

[00144] Synthetic membrane chemistry usually refers to the chemical nature and composition of the surface in contact with a separation process stream. The chemical nature of a membrane's surface can be quite different from its bulk composition. This difference can result from material partitioning at some stage of the membrane's fabrication, or from an intended surface postformation modification. Membrane surface chemistry creates very important properties such as hydrophilicity or hydrophobicity (related to surface free energy), presence of ionic charge, membrane chemical or thermal resistance, binding affinity for particles in a solution, and biocompatibility (in case of bioseparations). Hydrophilicity and hydrophobicity of membrane surfaces can be expressed in terms of water (liquid) contact angle $\theta$. Hydrophilic membrane surfaces have a contact angle in the range

of $0°<\theta<90°$ (closer to 0°), where hydrophobic materials have $\theta$ in the range of $90°<\theta<180°$. The contact angle is determined by solving the Young's equation for the interfacial force balance. At equilibrium three interfacial tensions corresponding to solid/gas ($\gamma SG$), solid/liquid ($\gamma SL$), and liquid/gas ($\gamma LG$) interfaces are counterbalanced. The consequence of the contact angle's magnitudes is known as wetting phenomena, which is important to characterize the capillary (pore) intrusion behavior. Degree of membrane surface wetting is determined by the contact angle. The surface with smaller contact angle has better wetting properties ($\theta=0°$-perfect wetting). In some cases low surface tension liquids such as alcohols or surfactant solutions are used to enhance wetting of non-wetting membrane surfaces. The membrane surface free energy (and related hydrophilicity/hydrophobicity) influences membrane particle adsorption or fouling phenomena. In most membrane separation processes (especially bioseparations); higher surface hydrophilicity corresponds to the lower fouling. Synthetic membrane fouling impairs membrane performance. As a consequence, a wide variety of membrane cleaning techniques have been developed. Sometimes fouling is irreversible, and the membrane needs to be replaced. Another feature of membrane surface chemistry is surface charge. The presence of the charge changes the properties of the membrane-liquid interface. The membrane surface may develop an electrochemical potential and induce the formation of layers of solution particles which tend to neutralize the charge.

**[00145]** Membrane morphology

**[00146]** Synthetic membranes can be also categorized based on their structure (morphology). Three such types of synthetic membranes are commonly used in separation industry: dense membranes, porous membranes, and asymmetric membranes. Dense and porous membranes are distinct from each other based on the size of separated molecules. Dense membrane is usually a thin layer of dense material utilized in the separation processes of small molecules (usually in gas or liquid phase). Dense membranes are widely used in industry for gas separations and reverse osmosis applications.

**[00147]** Dense membranes can be synthesized as amorphous or heterogeneous structures. Polymeric dense membranes such as polytetrafluoroethylene and

cellulose esters are usually fabricated by compression molding, solvent casting, and spraying of a polymer solution. The membrane structure of a dense membrane can be in a rubbery or a glassy state at a given temperature depending on its glass transition temperature. Porous membranes are intended on separation of larger molecules such as solid colloidal particles, large biomolecules (proteins, DNA, RNA) and cells from the filtering media. Porous membranes find use in the microfiltration, ultrafiltration, and dialysis applications. There is some controversy in defining a "membrane pore." The most commonly used theory assumes a cylindrical pore for simplicity. This model assumes that pores have the shape of parallel, nonintersecting cylindrical capillaries. But, in reality, a typical pore is a random network of the unevenly shaped structures of different sizes. The formation of a pore can be induced by the dissolution of a "better" solvent into a "poorer" solvent in a polymer solution. Other types of pore structure can be produced by stretching of crystalline structure polymers. The structure of porous membrane is related to the characteristics of the interacting polymer and solvent, components concentration, molecular weight, temperature, and storing time in solution. The thicker porous membranes sometimes provide support for the thin dense membrane layers, forming the asymmetric membrane structures. The latter are usually produced by a lamination of dense and porous membranes.

**[00148]** R.O. System

**[00149]** Reverse osmosis (RO) is a water purification technology that uses a semipermeable membrane. This membrane-technology is not properly a filtration method. In RO, an applied pressure is used to overcome osmotic pressure, a colligative property, that is driven by chemical potential, a thermodynamic parameter. RO can remove many types of molecules and ions from solutions and is used in both industrial processes and in producing potable water. The result is that the solute is retained on the pressurized side of the membrane and the pure solvent is allowed to pass to the other side. To be "selective," this membrane should not allow large molecules or ions through the pores (holes), but should allow smaller components of the solution (such as the solvent) to pass freely.

[00150] In the normal osmosis process, the solvent naturally moves from an area of low solute concentration (High Water Potential), through a membrane, to an area of high solute concentration (Low Water Potential). The movement of a pure solvent is driven to reduce the free energy of the system by equalizing solute concentrations on each side of a membrane, generating osmotic pressure. Applying an external pressure to reverse the natural flow of pure solvent, thus, is reverse osmosis. The process is similar to other membrane technology applications. However, there are key differences between reverse osmosis and filtration. The predominant removal mechanism in membrane filtration is straining, or size exclusion, so the process can theoretically achieve perfect exclusion of particles regardless of operational parameters such as influent pressure and concentration. Moreover, reverse osmosis involves a diffusive mechanism so that separation efficiency is dependent on solute concentration, pressure, and water flux rate. Reverse osmosis is most commonly known for its use in drinking water purification from seawater, removing the salt and other effluent materials from the water molecules.

[00151] Process

[00152] Osmosis is a natural process. When two liquids of different concentration are separated by a semipermeable membrane, the fluid has a tendency to move from low to high solute concentrations for chemical potential equilibrium.

[00153] Formally, reverse osmosis is the process of forcing a solvent from a region of high solute concentration through a semipermeable membrane to a region of low solute concentration by applying a pressure in excess of the osmotic pressure. The largest and most important application of reverse osmosis is the separation of pure water from seawater and brackish waters; seawater or brackish water is pressurized against one surface of the membrane, causing transport of salt-depleted water across the membrane and emergence of potable drinking water from the low-pressure side.

[00154] The membranes used for reverse osmosis have a dense layer in the polymer matrix—either the skin of an asymmetric membrane or an interfacially polymerized layer within a thin-film-composite membrane—where the separation occurs. In most cases, the membrane is designed to allow only water to pass through this dense layer, while preventing the passage of solutes (such as salt ions). This process

requires that a high pressure be exerted on the high concentration side of the membrane, usually 2–17 bar (30–250 psi) for fresh and brackish water, and 40–82 bar (600–1200 psi) for seawater, which has around 27 bar (390 psi) natural osmotic pressure that must be overcome. This process is best known for its use in desalination (removing the salt and other minerals from sea water to get fresh water), but since the early 1970s it has also been used to purify fresh water for medical, industrial, and domestic applications.

**[00155]** Osmosis describes how solvent moves between two solutions separated by a permeable membrane to reduce concentration differences between the solutions. When two solutions with different concentrations of a solute are mixed, the total amount of solutes in the two solutions will be equally distributed in the total amount of solvent from the two solutions. Instead of mixing the two solutions together, they can be put in two compartments where they are separated from each other by a semipermeable membrane. The semipermeable membrane does not allow the solutes to move from one compartment to the other, but allows the solvent to move. Since equilibrium cannot be achieved by the movement of solutes from the compartment with high solute concentration to the one with low solute concentration, it is instead achieved by the movement of the solvent from areas of low solute concentration to areas of high solute concentration. When the solvent moves away from low concentration areas, it causes these areas to become more concentrated. On the other side, when the solvent moves into areas of high concentration, solute concentration will decrease. This process is termed osmosis. The tendency for solvent to flow through the membrane can be expressed as "osmotic pressure," since it is analogous to flow caused by a pressure differential. Osmosis is an example of diffusion.

**[00156]** In reverse osmosis, in a similar setup as that in osmosis, pressure is applied to the compartment with high concentration. In this case, there are two forces influencing the movement of water: the pressure caused by the difference in solute concentration between the two compartments (the osmotic pressure) and the externally applied pressure.

[00157] FIG. 15A shows one example of a $CO_2$ capture system 1501 installed in the vertical position (with respect to gravity) in accordance with one or more embodiments of the invention. The $CO_2$ capture system 1501 removes $CO_2$ from an exhaust gas stream 1503 that is produced from a fossil fuel application, such as a natural gas fired turbine (not shown). In accordance with one or more embodiments, exhaust gas 1503 produced by the fossil fuel application is directed through the $CO_2$ capture system 1501 where the exhaust gas first comes into contact with a granular activated carbon frame section 1505, such as a W-frame section described above in reference to FIG. 8. Unwanted pollutants, such as $NO_x$ (nitrogen oxides), are absorbed by the granular activated carbon 1505a of the granular activated carbon frame section 1505.

[00158] The exhaust gas flow 1503 next encounters breaching 1504 that serves to expand the exhaust gas stream, thereby decreasing the flow velocity as the stream enters the fogging region 1502. In accordance with one or more embodiments, reducing the exhaust gas flow velocity in the fogging region 1502 may allow for more time for a given $CO_2$ molecule to undergo one or more collisions with one or more $H_2O$ molecules. Accordingly, a decrease in exhaust gas flow velocity may increase the rate of reaction between molecules between the $CO_2$ and the $H_2O$. In accordance with one or more embodiments, a reduction in exhaust gas flow velocity may be accomplished by a breaching 1504 that serves to increase the cross-sectional area of the exhaust gas flow from $A_1$ to $A_2$ over a flow distance L. For example in an embodiment employing a 122.5MW natural gas combined cycle turbine, an exhaust gas flow of 667,917 acfm may be directed through a breeching having an area ($A_1$) of 278 $ft^2$, diameter of 19 ft, and a length of 30 ft. The exhaust flow is directed into the fogging region by the breaching having a cross sectional area ($A_2$) of 9,438 $ft^2$, diameter of 110 ft, and a height that will vary from 60 to 80 ft. After passing through the $CO_2$ capture system, the exhaust gas flow is now 566,278 acfm and is directed to the stack where the exhaust gas is dispersed to atmosphere. One of ordinary skill having the benefit of this disclosure will appreciate that every application will be different and instead of one $CO_2$ capture system the installation may employ any number of systems and the systems may be smaller or larger than the examples provided herein. Accordingly, there is no restriction on the maximum

or minimum size of these vessels, and $A_1$, $A_2$, and L may vary according to the needs of a particular installation and thus the above values are set forth above merely for the sake of example.

**[00159]** After passing through the breaching 1504, the expanded exhaust gas stream enters the fogging region 1502 and comes into contact with high speed (*e.g.*, mach-1), high pressure water droplets produced from the first and second fogging stages 1507 and 1509, respectively, causing a high energy contact and reaction. In accordance with one or more embodiments, the fogging stages may be configured as fogging arrays in a manner that is similar to that described above, *e.g.*, in reference to FIG. 14.

**[00160]** As the exhaust comes into contact with the water fog from the first fogging stage 1507, the exhaust gas begins to cool because of the temperature differential between the hot exhaust gas and the cooler water droplets. As the exhaust gas continues through the system, it comes into contact with high-speed (*e.g.*, mach-1), high-pressure water droplets produced from the second fogging array 1509 causing further reaction between the $CO_2$ molecules and the water fog. After exiting the fogging stage 1502, the exhaust gas 1503 continues through ductwork 1510 and is redirected toward demister 1511 where the water fog that includes the captured $CO_2$ is condensed onto the demister wetted medium and then directed to the vessel drains 1513. Inside the vertical vessel walls and equipment, some of the captured $CO_2$ will, by weight and gravity, direct itself to the bottom of the vessel wall and will be collected by drain 1514.

**[00161]** FIG. 15B shows a front cross-sectional view of the fogging nozzle array created by the two fogging stages as seen by the incoming gas stream. The fogging nozzle array 1515 is designed to create full surface coverage to capture the $CO_2$ molecules from the exhaust gas stream in an efficient manner. Each fogging nozzle is placed adjacent to another fogging nozzle and is designed to produce a fog ball that will overlap with the adjacent fog ball, thereby maximizing the capture rates of the $CO_2$ molecule for a given cross-sectional area.

**[00162]** FIG. 16 shows an example of a $CO_2$ capture system 1601 installed in the horizontal position (with respect to gravity) in accordance with one or more

embodiments of the invention. For simplicity, repeated elements that are common to FIG. 15 are labeled with common numbers and the description of these common elements will not be repeated here. Due to the horizontal arrangement of the capture system 1601, drains 1513a, 1513b, and 1513c are placed on the bottom wall of the unit to collect waste water that is collected within the fogging unit 1502 and to collect waste water that is accumulated by the demister 1511. In accordance with one or more embodiments, the waste water collected by the drains 1513a, 1513b, 1513c, and 1514, shown in FIGs. 15-16, may be then sent to a waste water processing system, *e.g.*, a waste water processing system similar to system 1419 described above in reference to FIG. 14.

**[00163]** Like the vertical system 1501, the horizontal system 1601 includes a breaching 1504a designed to expand the exhaust gas stream before it enters the fogging region 1502. In addition, the embodiment shown in FIG. 16 also includes a breaching 1504b that serves to connect the larger diameter fogging region 1502 to the smaller diameter ductwork that houses demister 1511. The precise configuration of ductwork used to eventually direct the exhaust gas stream to atmosphere will depend on the details of the particular installation and thus, the breaching 1504b is shown here as but one example.

**[00164]** FIG. 17 shows test data for a horizontal $CO_2$ capture system like that shown in FIG. 16, deployed with a natural gas fired boiler in accordance with one or more embodiments of the invention. The data shown in FIG. 17 was taken over a two hour period with the natural gas fired boiler operating to produce a relatively low exhaust gas temperature. As can be seen from the table, the average exhaust gas temperature as measured just after the waste heat boiler was 315 °F over the two hour period. In addition, the average exhaust gas flow rate was just under 28,000 lb/hr. The density of the exhaust gas was 0.0649 $lb/ft^3$ with a flow of 7,070 acfm. For the test, the two fogging arrays used on average 1.42 and 1.46 gpm of water, respectively. In addition, an average of 2.63 gpm (1,315 lb/hr) of waste water was collected at a $CO_2$ concentration of 0.1211 lb/lb of water. In the input exhaust gas stream, the average $CO_2$ was 5,037 ppmvd and the average $CO_2$ in the output exhaust stream after passing though the $CO_2$ removal unit was 817 ppmvd. As can

be seen from the table and the above numbers, the unit successfully removed over 83% of the $CO_2$ in the exhaust gas stream.

**[00165]** While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised that do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.

# CLAIMS

What is claimed is:

1. A method for removing contaminants from industrial exhaust gas comprising:
   contacting the exhaust gas with granular activated carbon;
   contacting the exhaust gas with a water mist to capture $CO_2$ in the water mist;
   extracting the captured $CO_2$.

2. The method of claim 1, further comprising, after contacting the exhaust gas with the water mist, extracting a liquid solution of $CO_2$ by condensing contacted exhaust gas on a first condensing medium.

3. The method of claim 2, further comprising:
   collecting the extracted liquid solution of $CO_2$; and
   venting a gas comprising $CO_2$ from the collected extracted liquid solution.

4. The method of claim 3, further comprising:
   separating $CO_2$ gas from the vented gas comprising $CO_2$ and redirecting to separated $CO_2$ to a $CO_2$ compressor station.

5. A system for capturing CO2 from an industrial stream of exhaust gas, the system comprising:
   an activated carbon stage configured to receive the stream of exhaust gas and to contact the stream of exhaust gas with granular activated carbon to remove contaminants from the exhaust gas stream;
   a first fogging stage configured to receive the stream of exhaust gas and to contact the stream of exhaust gas with a water mist to capture $CO_2$ in the water mist; and
   a condensing medium configured to condense the contacted exhaust gas comprising captured $CO_2$ from the stream of exhaust gas and to collect on the surface of the condensing medium a wetted film including dissolved $CO_2$.

6. The system of claim 5, wherein the exhaust gas is created by combustion of coal.

7. The system of claim 5, wherein the exhaust gas is created by combustion of natural gas.

8. The system of claim 5, wherein a mulipollution abatement system is located upstream from the activated carbon stage.

9. The system of claim 5, wherein the activated carbon stage comprises:
granular activated carbon having an average size that is greater than 0.25 mm.

10. The system of claim 5 further comprising a fan configured to direct the clean exhaust gas stream out of the system.

11. The system of claim 5 further comprising a waste water processing system configured to receive a water film comprising the wetted film including dissolved $CO_2$.

12. The system of claim 5, wherein the condensing medium comprises a coating of one selected from a group consisting of Teflon and critical polyvinal chloride (CPVC).

13. The system of claim 5, wherein the activated carbon stage comprises a hollow frame configured to receive and hold activated carbon, wherein the hollow frame comprises a plurality of V-shaped members.

14. The system of claim 13, wherein the hollow frame comprises a wire mesh attached to a front side and a back side of hollow frame.

15. The system of claim 13, wherein the plurality of V-shaped members form a hollow frame having a W-shaped cross-section.

16. The system of claim 14, wherein the activated carbon stage comprises a top opening for loading activated carbon and a bottom opening for unloading de-activated carbon.

17. The system of claim 16, wherein the activated carbon stage comprises sealed access doors on the top opening of the activated carbon stage and sealed access doors on the bottom opening of the activated carbon stage.

18. The system of claim 11, the waste water processing system further comprising:

a tank fluidly connected to the condensing medium and configured to hold waste water that accumulates as the water film is received from the condensing medium;

a gas vent that directs gases comprising $CO_2$ that are vented from the accumulated water film in the tank;

a membrane system configured to separate the $CO_2$ from the vented gases comprising $CO_2$.

19. The system of claim 5, further comprising a second fogging stage disposed between the first fogging stage and the condensing medium.

20. The system of claim 5, further comprising a breaching disposed before the first fogging stage and adapted to expand a cross-sectional area of the stream of exhaust gas and to reduce a flow velocity of the stream of exhaust gas.

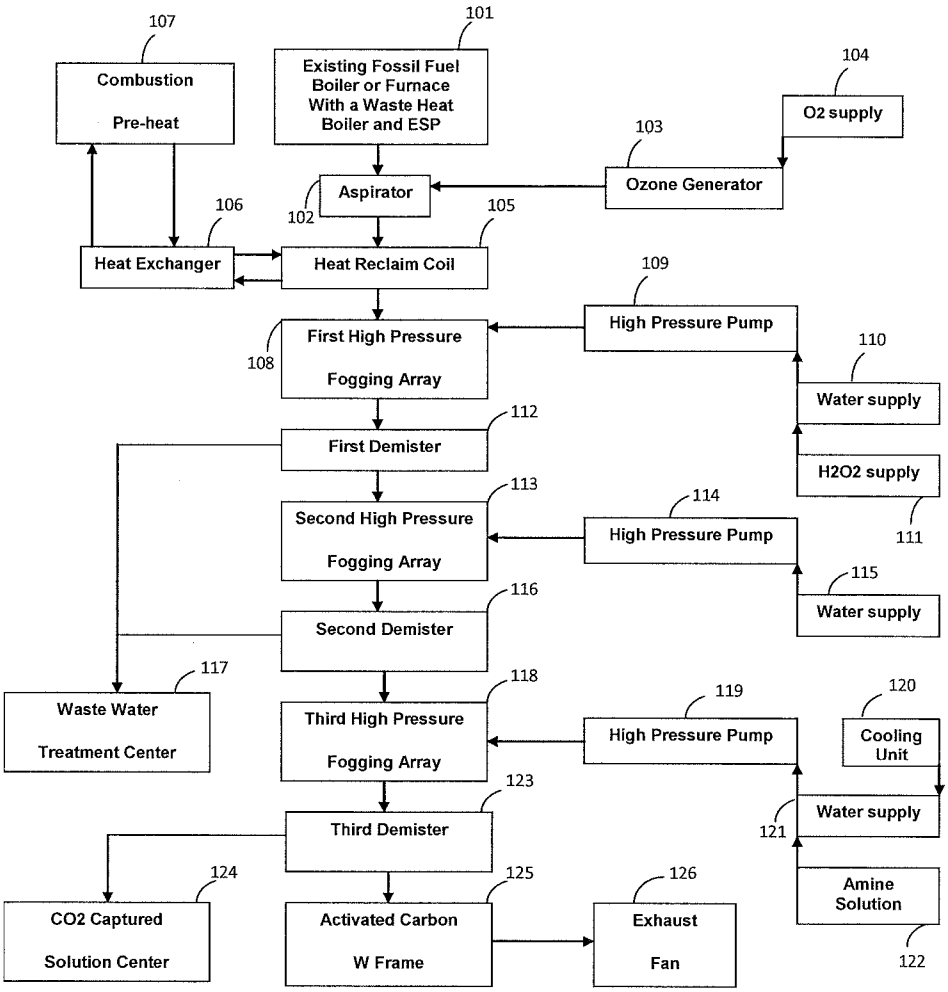

107
Combustion
Pre-heat
101
Existing Fossil Fuel Boiler or Furnace With a Waste Heat Boiler and ESP
104
O2 supply
103
Ozone Generator
Aspirator
102
106
105
Heat Exchanger
Heat Reclaim Coil
109
High Pressure Pump
First High Pressure
Fogging Array
108
110
Water supply
112
First Demister
H2O2 supply
111
113
Second High Pressure
Fogging Array
114
High Pressure Pump
115
Water supply
116
Second Demister
117
Waste Water
Treatment Center
118
Third High Pressure
Fogging Array
119
High Pressure Pump
120
Cooling Unit
123
Third Demister
121
Water supply
Amine Solution
122
124
CO2 Captured
Solution Center
125
Activated Carbon
W Frame
126
Exhaust
Fan

FIG. 1

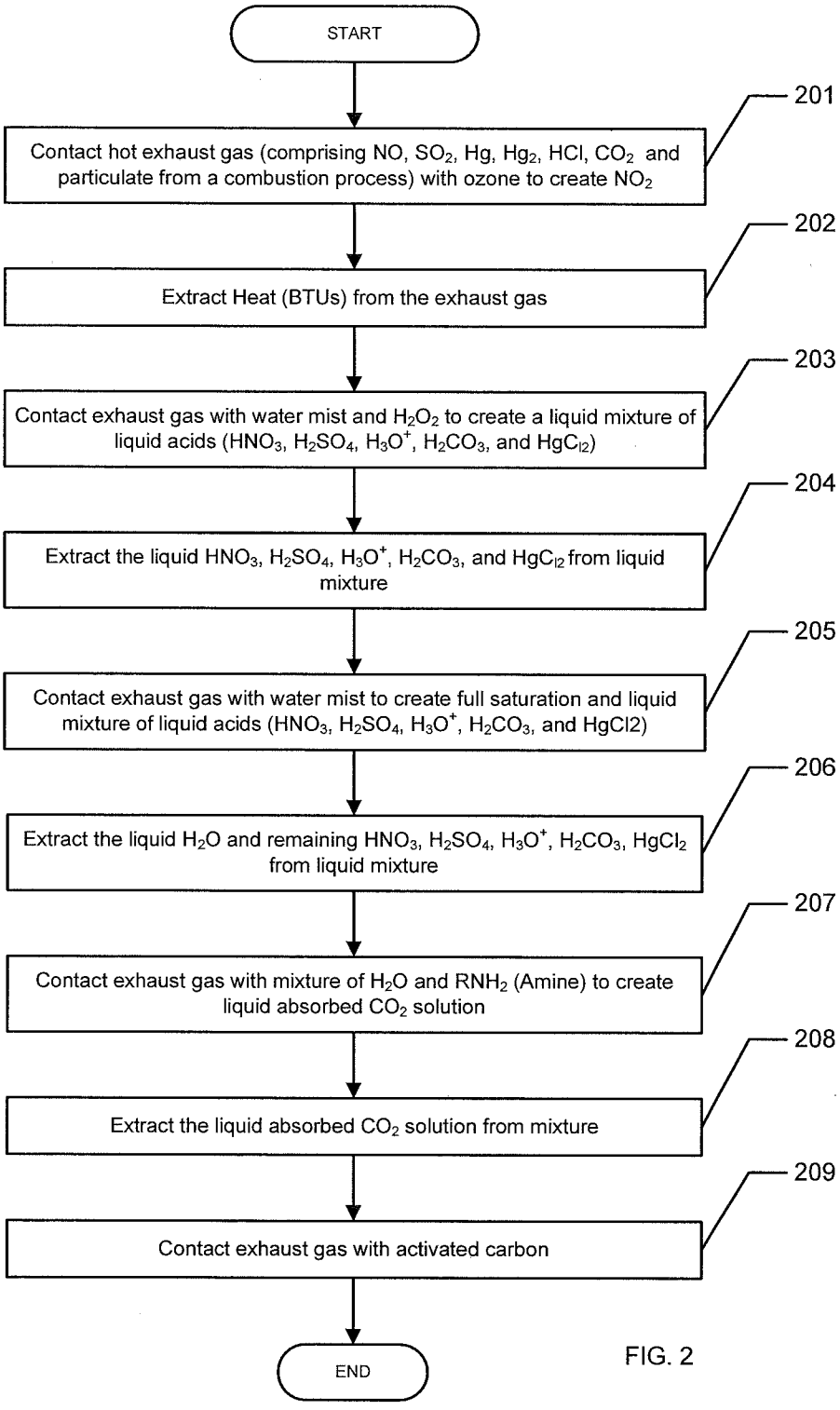

START
Contact hot exhaust gas (comprising NO, $SO_2$, Hg, $Hg_2$, HCl, $CO_2$ and particulate from a combustion process) with ozone to create $NO_2$
201
Extract Heat (BTUs) from the exhaust gas
202
Contact exhaust gas with water mist and $H_2O_2$ to create a liquid mixture of liquid acids ($HNO_3$, $H_2SO_4$, $H_3O^+$, $H_2CO_3$, and $HgC_{l2}$)
203
Extract the liquid $HNO_3$, $H_2SO_4$, $H_3O^+$, $H_2CO_3$, and $HgC_{l2}$ from liquid mixture
204
Contact exhaust gas with water mist to create full saturation and liquid mixture of liquid acids ($HNO_3$, $H_2SO_4$, $H_3O^+$, $H_2CO_3$, and HgCl2)
205
Extract the liquid $H_2O$ and remaining $HNO_3$, $H_2SO_4$, $H_3O^+$, $H_2CO_3$, $HgCl_2$ from liquid mixture
206
Contact exhaust gas with mixture of $H_2O$ and $RNH_2$ (Amine) to create liquid absorbed $CO_2$ solution
207
Extract the liquid absorbed $CO_2$ solution from mixture
208
Contact exhaust gas with activated carbon
209
END

FIG. 2

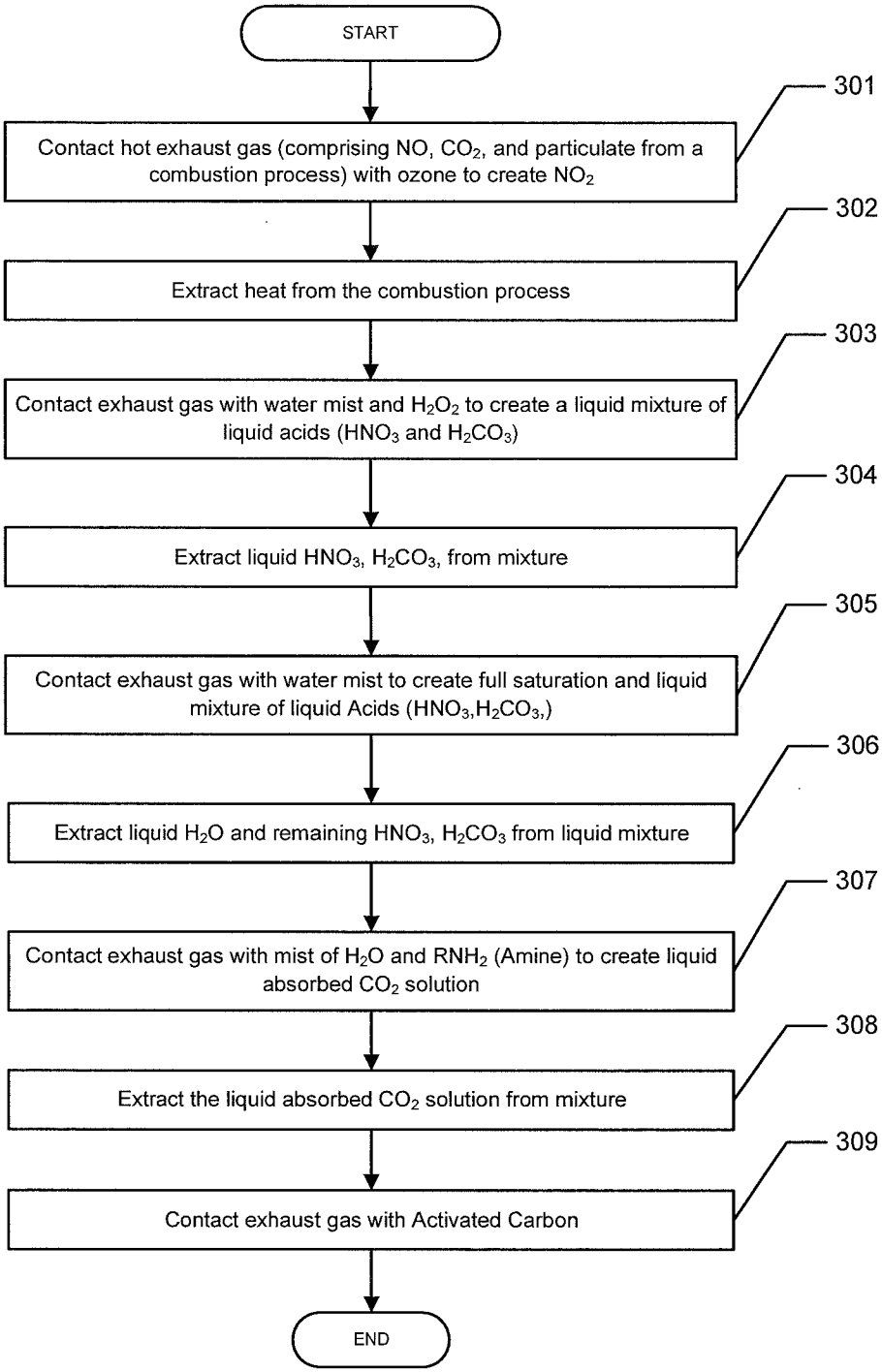

START
Contact hot exhaust gas (comprising NO, $CO_2$, and particulate from a combustion process) with ozone to create $NO_2$
301
Extract heat from the combustion process
302
Contact exhaust gas with water mist and $H_2O_2$ to create a liquid mixture of liquid acids ($HNO_3$ and $H_2CO_3$)
303
Extract liquid $HNO_3$, $H_2CO_3$, from mixture
304
Contact exhaust gas with water mist to create full saturation and liquid mixture of liquid Acids ($HNO_3$,$H_2CO_3$,)
305
Extract liquid $H_2O$ and remaining $HNO_3$, $H_2CO_3$ from liquid mixture
306
Contact exhaust gas with mist of $H_2O$ and $RNH_2$ (Amine) to create liquid absorbed $CO_2$ solution
307
Extract the liquid absorbed $CO_2$ solution from mixture
308
Contact exhaust gas with Activated Carbon
309
END

FIG. 3

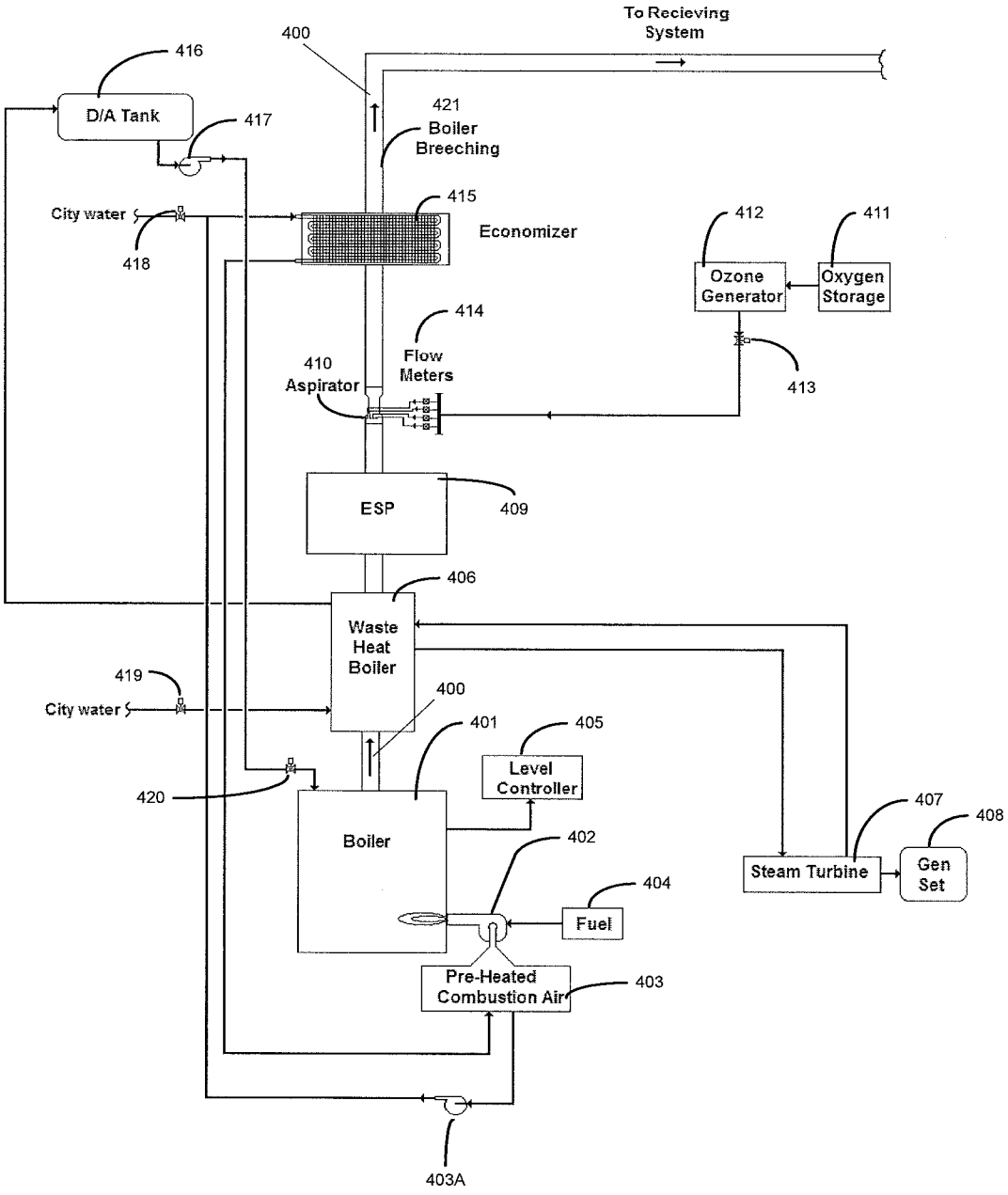
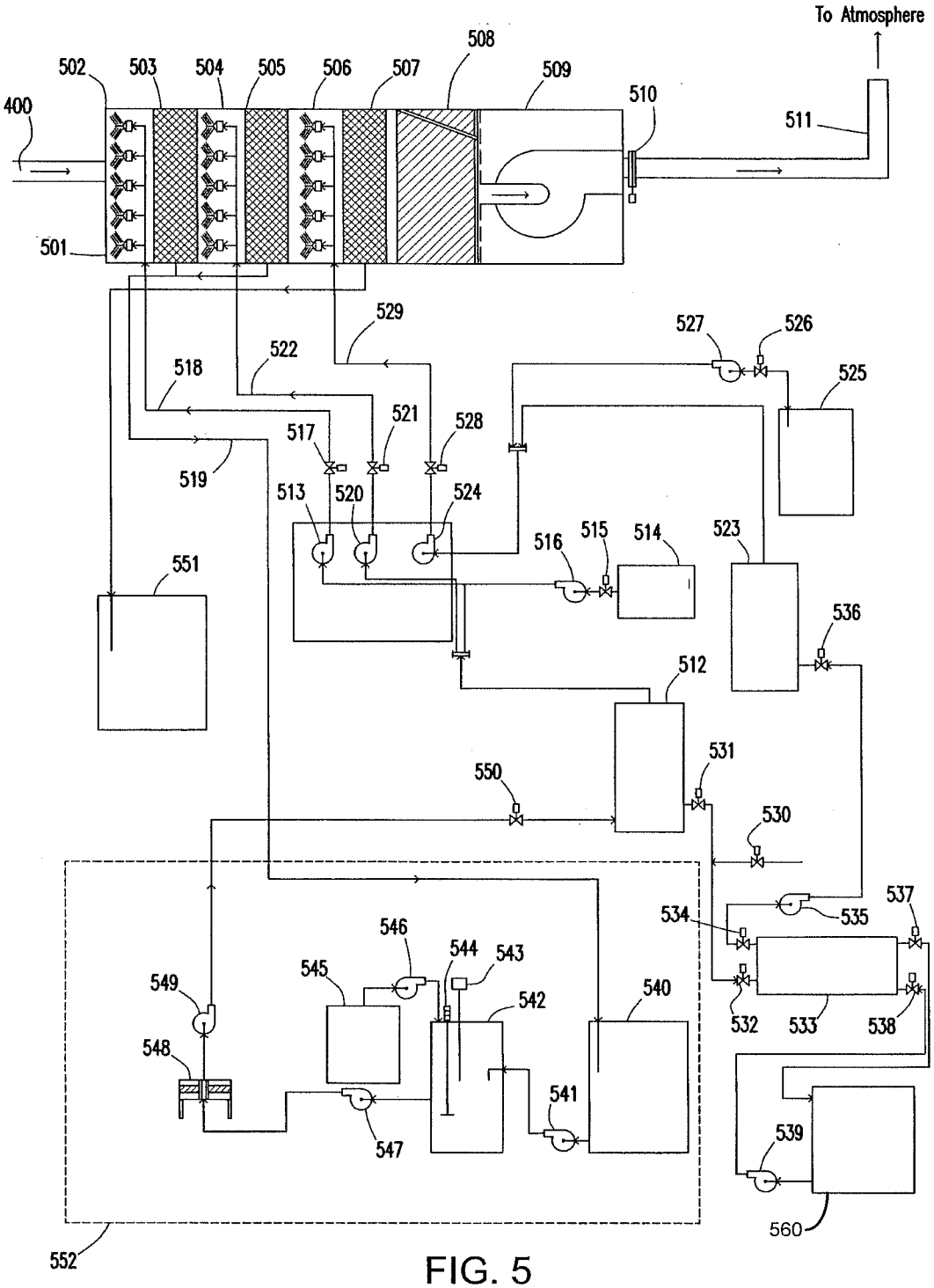

To Recieving System
400
416
D/A Tank
417
421
Boiler Breeching
City water
418
415
Economizer
412
411
Ozone Generator
Oxygen Storage
414
Flow Meters
410
Aspirator
413
ESP
409
406
Waste Heat Boiler
419
City water
400
401
405
Level Controller
420
Boiler
402
407
408
Steam Turbine
Gen Set
404
Fuel
Pre-Heated Combustion Air
403
403A

FIG. 4


To Atmosphere
400
501
502
503
504
505
506
507
508
509
510
511
512
513
514
515
516
517
518
519
520
521
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540
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547
548
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550
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552
560

FIG. 5

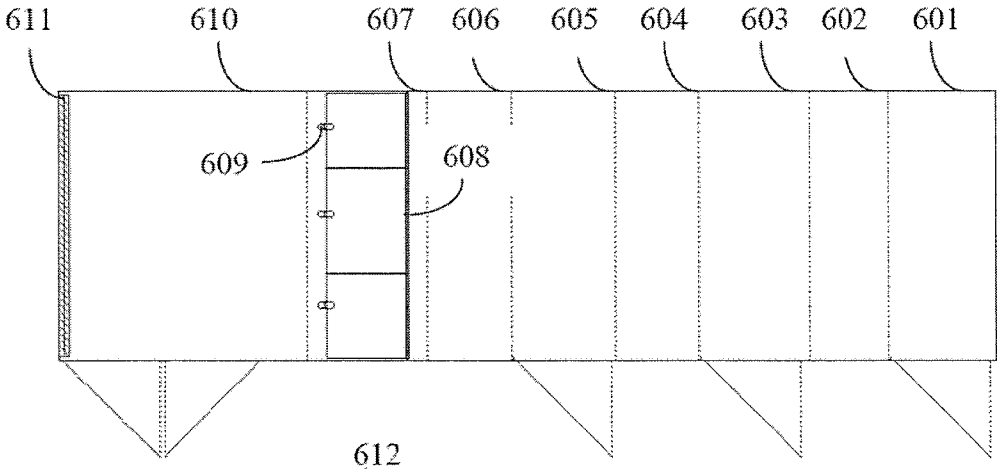


FIG. 6A

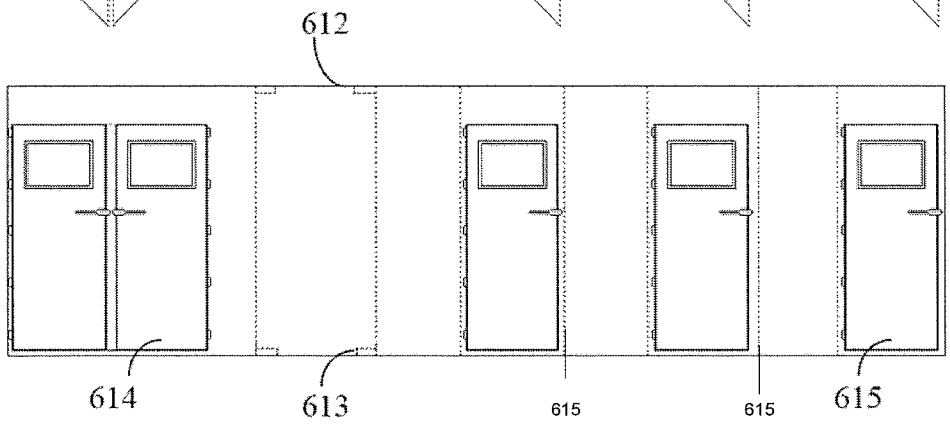


FIG. 6B

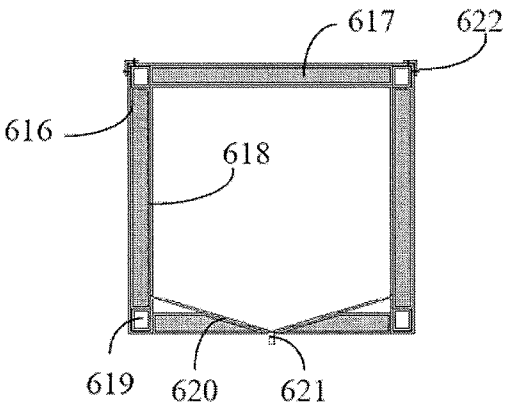


FIG. 6C

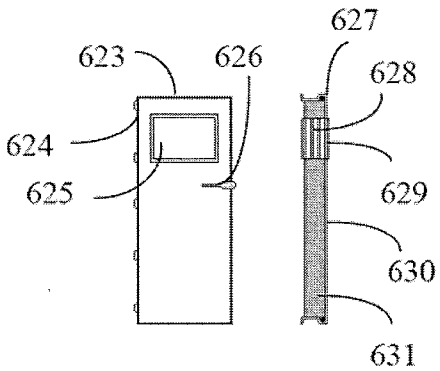


FIG. 6D

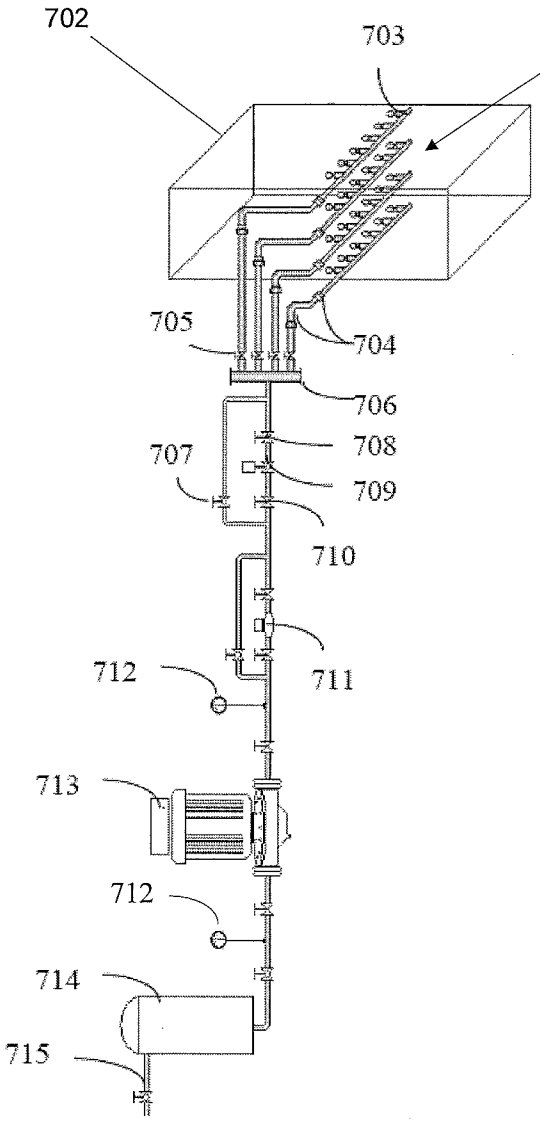


FIG. 7A

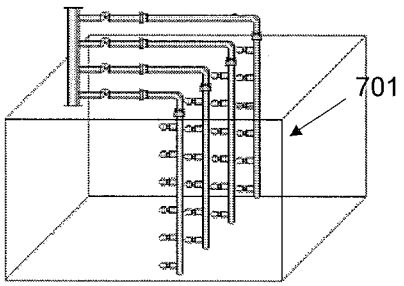


FIG. 7B

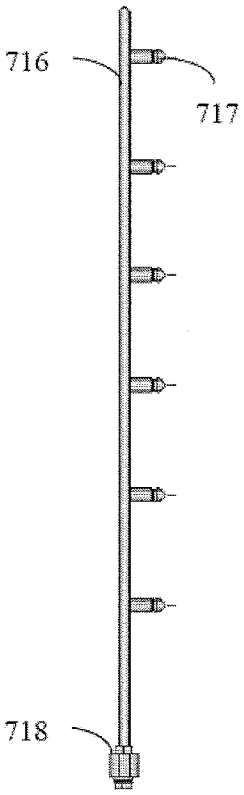


FIG. 7C

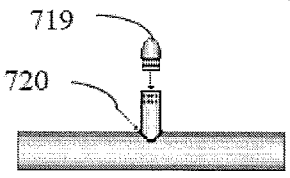


FIG. 7D

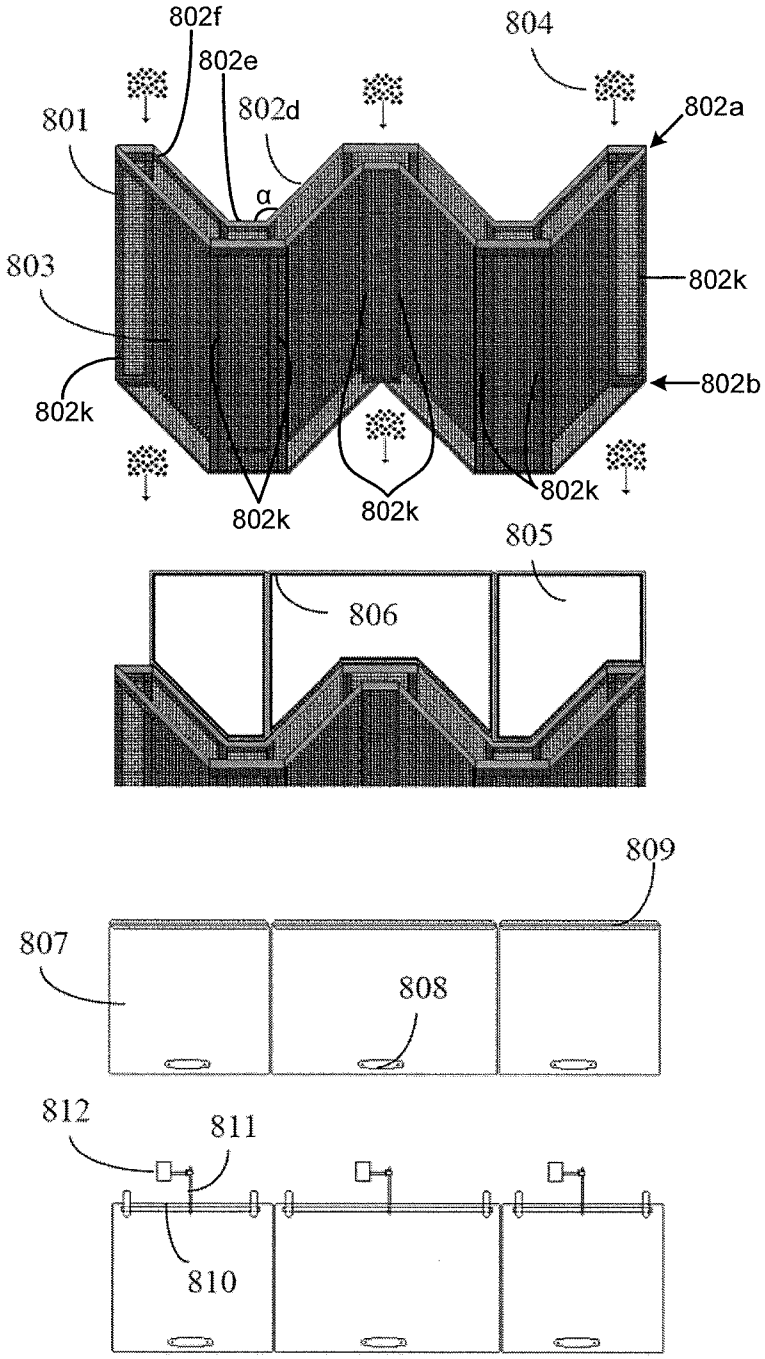
802f
802e
802d
804
802a
801
α
803
802k
802b
802k
802k
802k
802k
805
806
809
807
808
812
811
810

FIG. 8

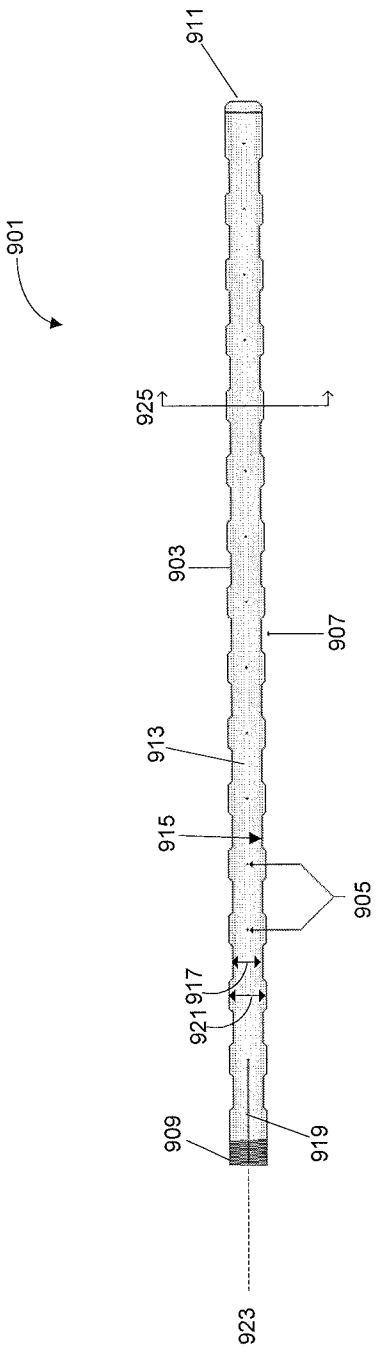


FIG. 9

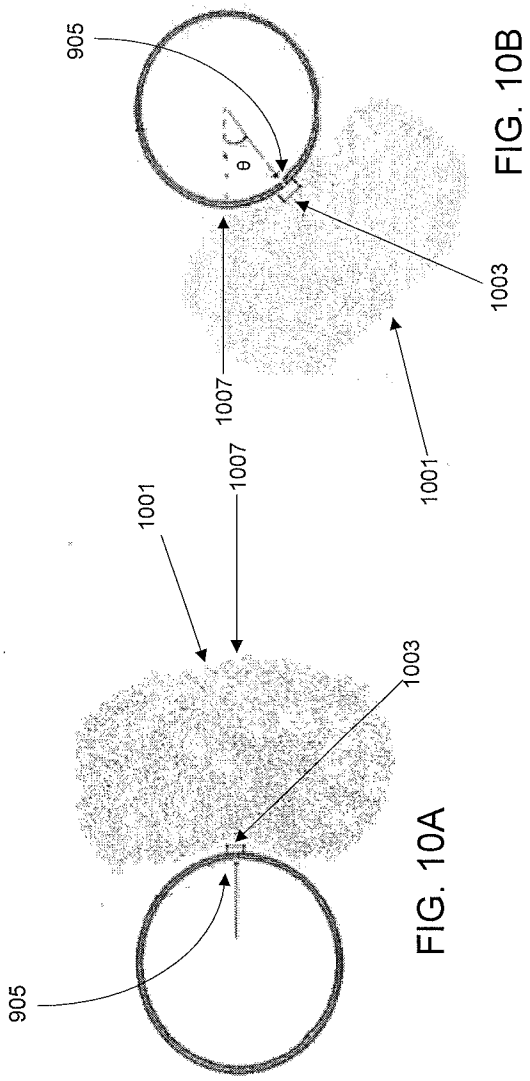


FIG. 10A




FIG. 10B

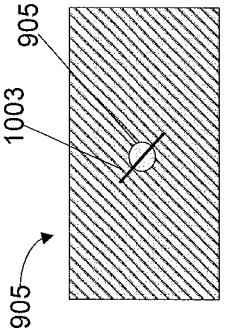


FIG. 10C

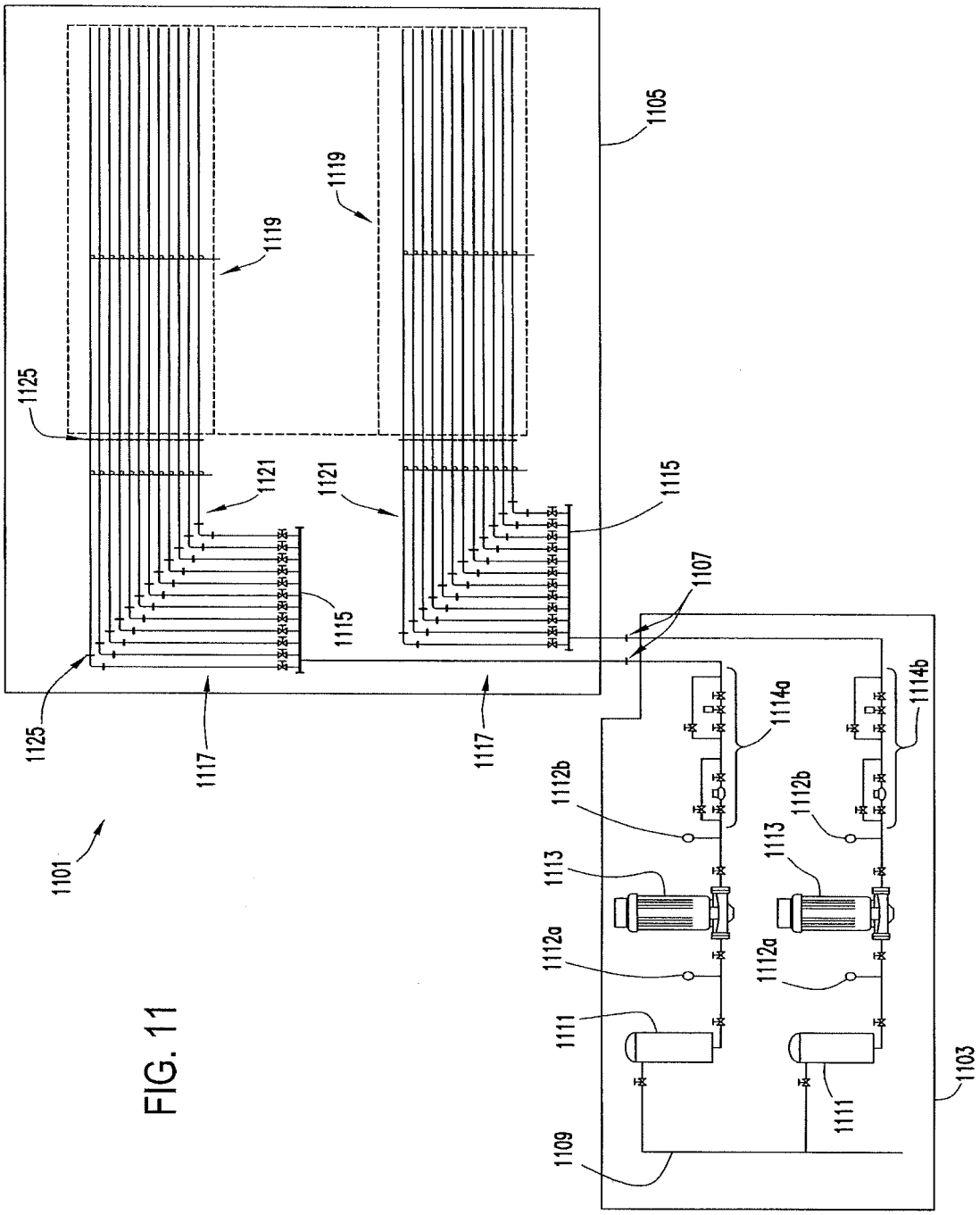
1101
1103
1105
1107
1109
1111
1112a
1112b
1113
1114a
1114b
1115
1117
1119
1121
1125

FIG. 11

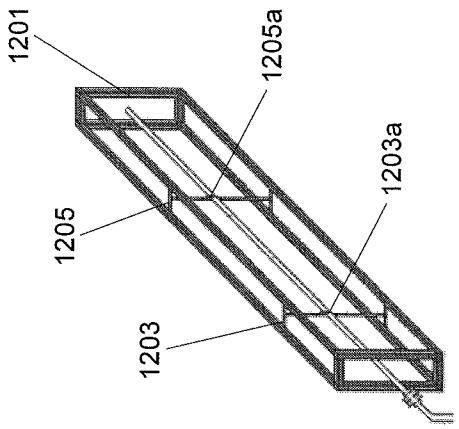


FIG. 12A

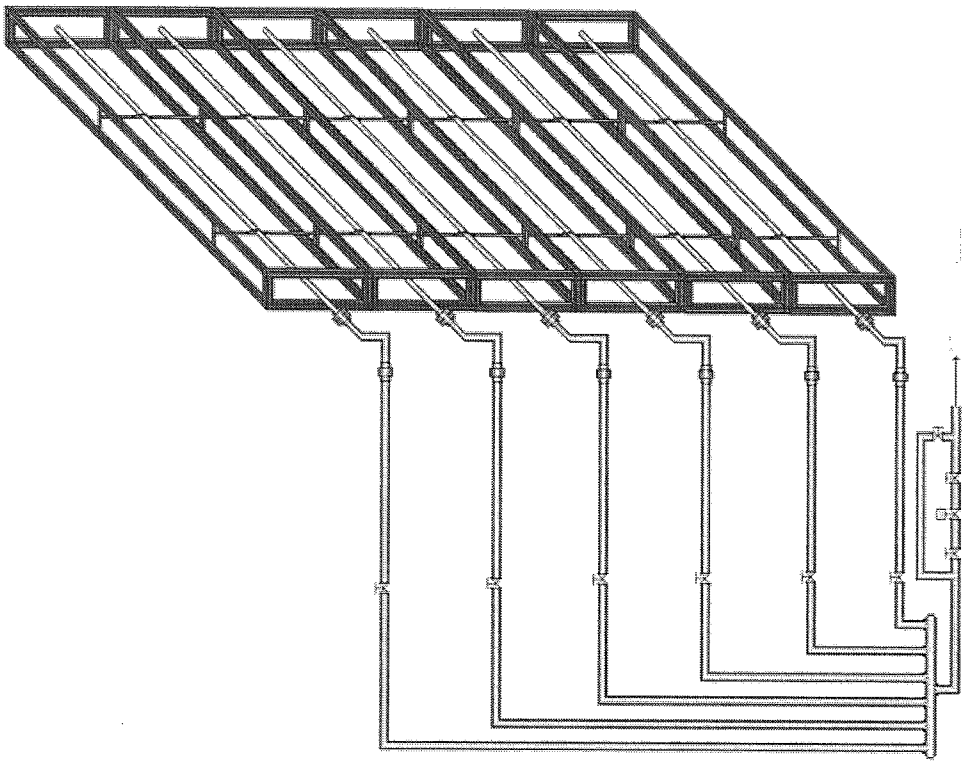

FIG. 12B

| EASTERN BITUMINOUS ULTIMATE ANALYSIS | | | |
|---|---|---|---|
| Carbon | 69.9% | Hydrogen | 4.7% |
| Oxygen | 6.4% | Nitrogen | 1.2% |
| Sulfur | 2.2% | Ash | 13.2% |
| Moisture | 2.4% | Heating Value | 12,644 Btu/lb |

FIG. 13A

| Operating Conditions (8/14/2012) | | |
|---|---|---|
| | Inlet | Outlet |
| Gas Temp | 257°F (125°C) | 89°F (32°C) |
| NOx | 43.36 ppm | 0.44 ppm |
| $SO_2$ | 216.58 ppm | 0.00 ppm |
| $CO_2$ | 13,865 ppm | 3,352 ppm |

FIG. 13B

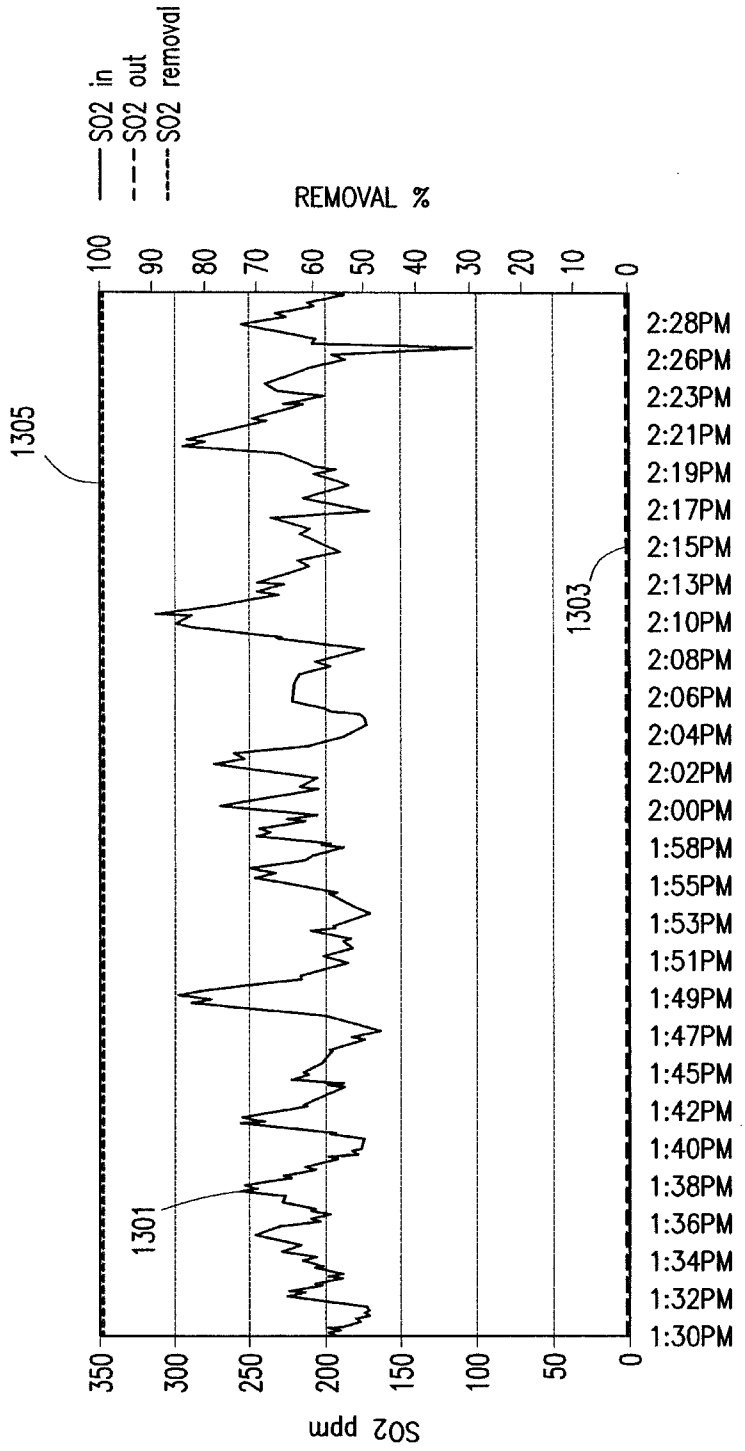
SO2 in
SO2 out
SO2 removal
REMOVAL %
100
90
80
70
60
50
40
30
20
10
0
2:28PM
2:26PM
2:23PM
2:21PM
2:19PM
2:17PM
2:15PM
2:13PM
2:10PM
2:08PM
2:06PM
2:04PM
2:02PM
2:00PM
1:58PM
1:55PM
1:53PM
1:51PM
1:49PM
1:47PM
1:45PM
1:42PM
1:40PM
1:38PM
1:36PM
1:34PM
1:32PM
1:30PM
1305
1303
1301
350
300
250
200
150
100
50
0
SO2 ppm

FIG. 13C

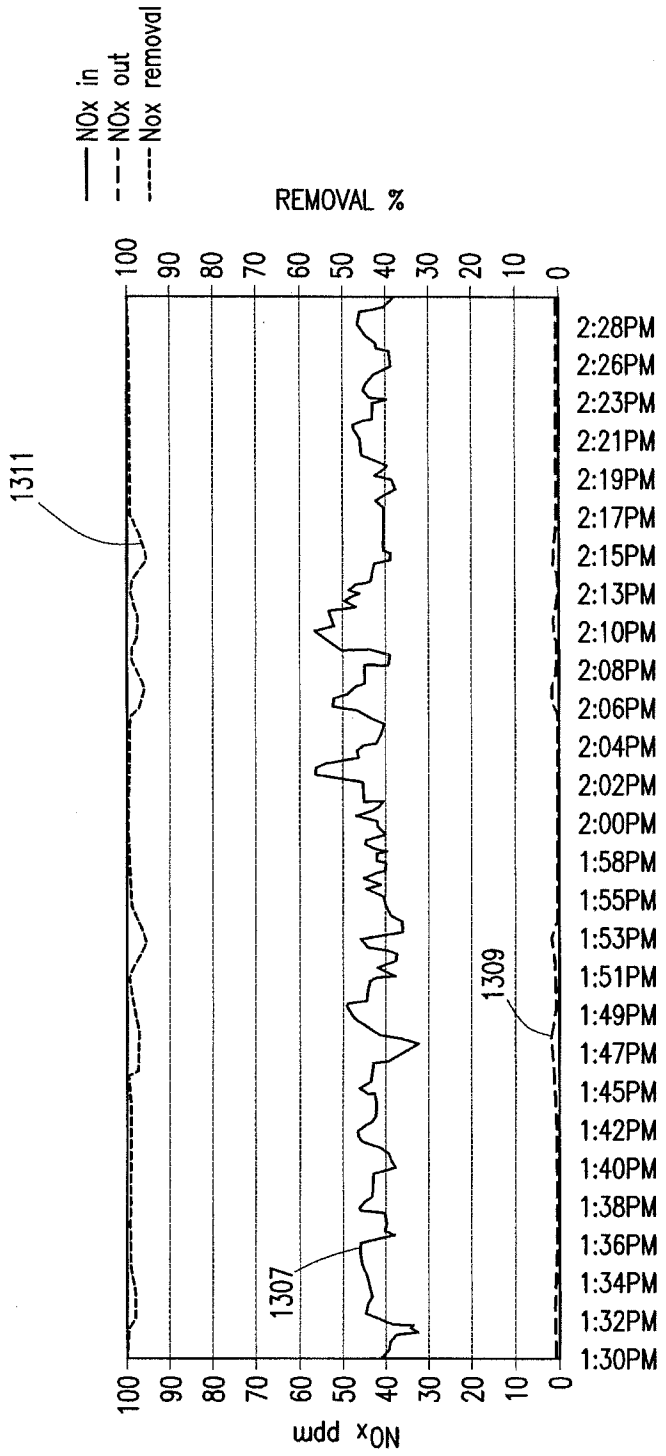
NOx in
NOx out
Nox removal
REMOVAL %
100
90
80
70
60
50
40
30
20
10
0
2:28PM
2:26PM
2:23PM
2:21PM
2:19PM
2:17PM
2:15PM
2:13PM
2:10PM
2:08PM
2:06PM
2:04PM
2:02PM
2:00PM
1:58PM
1:55PM
1:53PM
1:51PM
1:49PM
1:47PM
1:45PM
1:42PM
1:40PM
1:38PM
1:36PM
1:34PM
1:32PM
1:30PM
1311
1307
1309
ppm NOx

FIG. 13D

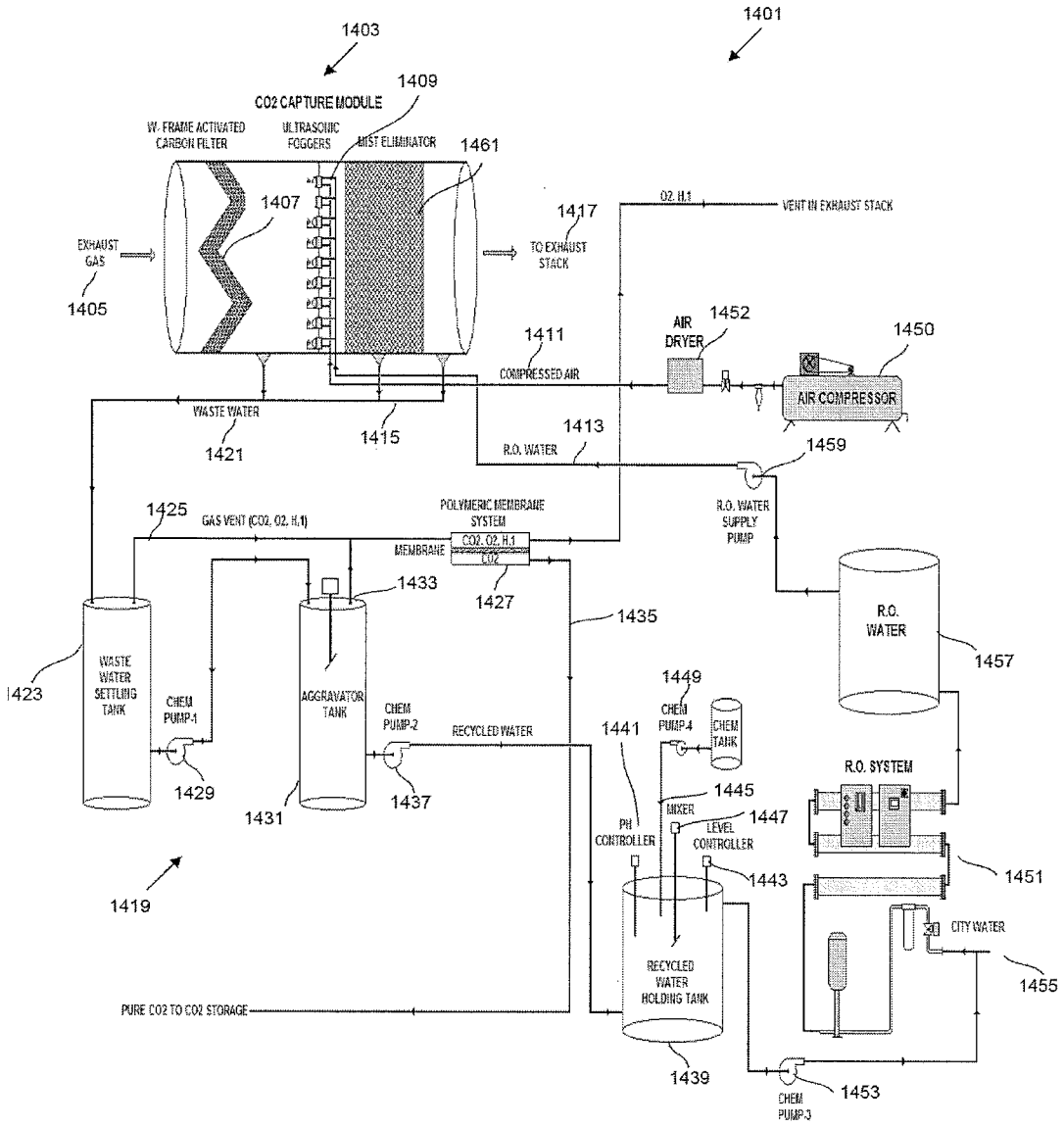
1401
1403
1409
CO2 CAPTURE MODULE
W. FRAME ACTIVATED CARBON FILTER
ULTRASONIC FOGGERS
MIST ELIMINATOR
1461
1407
EXHAUST GAS
1405
1417
TO EXHAUST STACK
O2, H.1
VENT IN EXHAUST STACK
1411
COMPRESSED AIR
AIR DRYER
1452
1450
AIR COMPRESSOR
WASTE WATER
1421
1415
1413
R.O. WATER
1459
R.O. WATER SUPPLY PUMP
1425
GAS VENT (CO2, O2, H.1)
POLYMERIC MEMBRANE SYSTEM
MEMBRANE
CO2, O2, H.1
CO2
1427
1433
1435
R.O. WATER
1457
1423
WASTE WATER SETTLING TANK
CHEM PUMP-1
1429
AGGRAVATOR TANK
CHEM PUMP-2
RECYCLED WATER
1437
1431
1449
CHEM PUMP-4
CHEM TANK
1441
R.O. SYSTEM
1445
MIXER
PH CONTROLLER
LEVEL CONTROLLER
1447
1443
1451
CITY WATER
1455
1419
RECYCLED WATER HOLDING TANK
1439
1453
CHEM PUMP-3
PURE CO2 TO CO2 STORAGE

FIG. 14

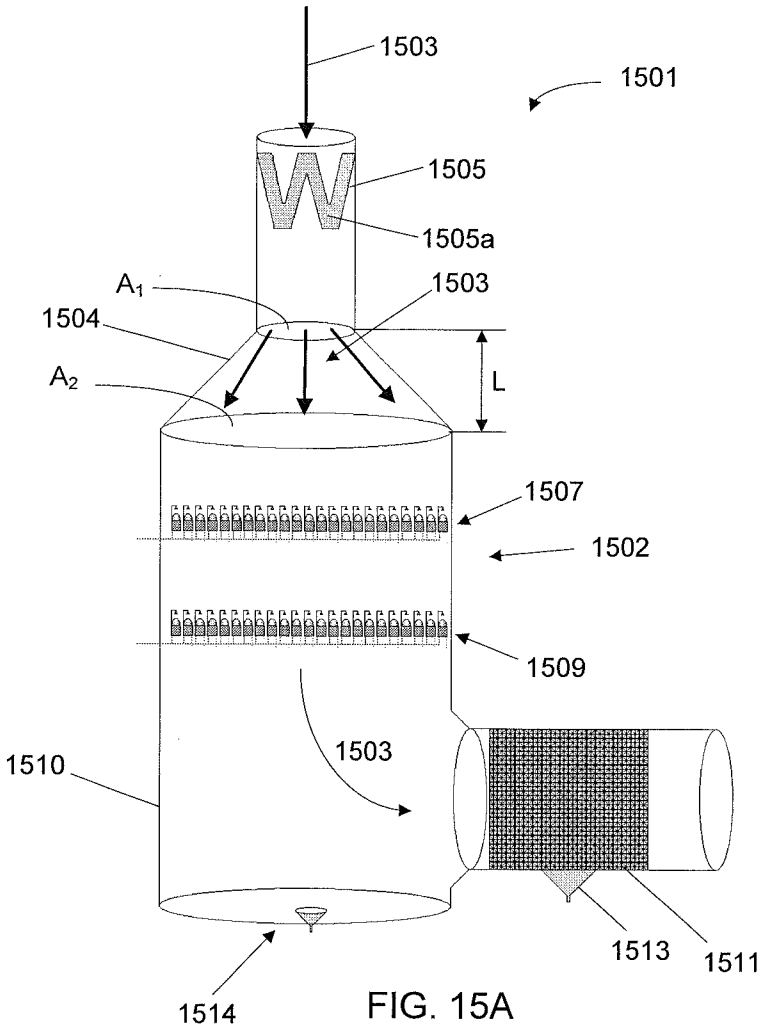


FIG. 15A

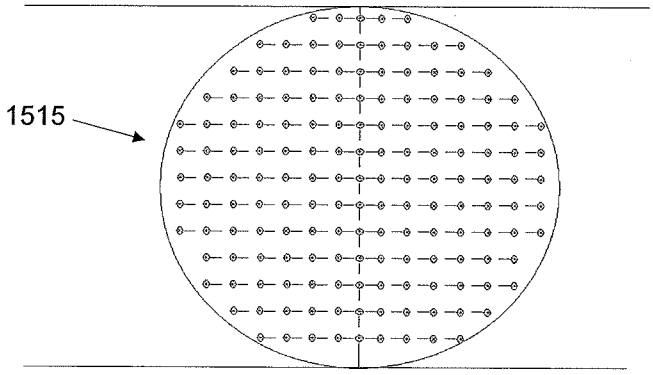


FIG. 15B

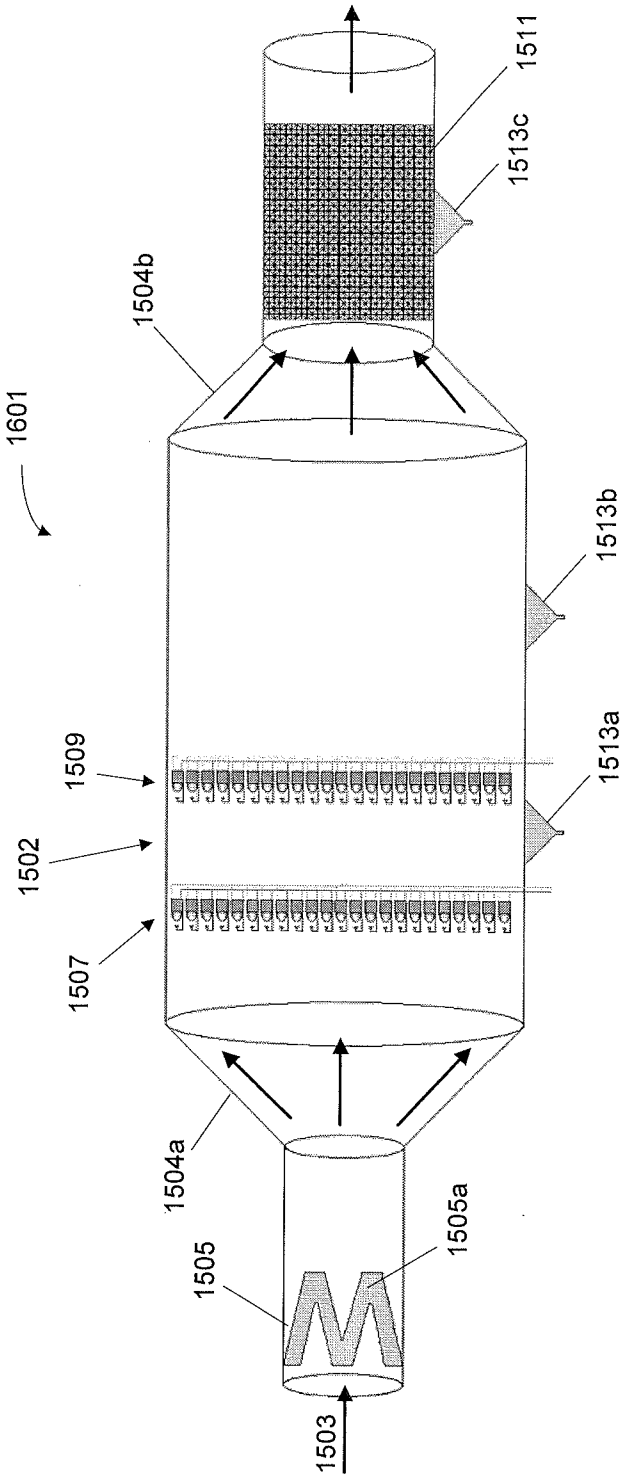
1601
1511
1513c
1504b
1513b
1509
1513a
1502
1507
1504a
1505a
1505
1503

FIG. 16

| Time | $CO_2$ | | | Temp | | Flow | Foggers | | Oxygen |
|---|---|---|---|---|---|---|---|---|---|
| | in | out | Temp (Just After Waste Heat Boiler) | In (just before first fogging stage) | Out (just before venting to atmosphere) | | 1st Stage | 2nd Stage | |
| | (ppmvd) | (ppmvd) | (°F) | (°F) | (°F) | (lb/hr) | (gpm) | (gpm) | (%) |
| | | | | | | | | | |
| 11:00 AM | 4,755 | 780 | 309 | 252 | 53.0 | 28,086 | 1.43 | 1.45 | 20.3 |
| 11:10 AM | 4,260 | 881 | 311 | 234 | 54.0 | 27,624 | 1.43 | 1.45 | 20.3 |
| 11:30 AM | 4,556 | 810 | 317 | 236 | 53.0 | 25,296 | 1.90 | 1.92 | 20.3 |
| 11:45 AM | 4,537 | 702 | 318 | 239 | 53.0 | 27,000 | 1.39 | 1.53 | 20.3 |
| 12:00 PM | 5,380 | 880 | 317 | 262 | 54.6 | 31,000 | 1.42 | 1.54 | 20.3 |
| 12:25 PM | 5,732 | 739 | 317 | 274 | 56.7 | 28,277 | 1.26 | 1.28 | 20.3 |
| 12:45 PM | 5,478 | 827 | 316 | 271 | 57.1 | 29,900 | 1.26 | 1.27 | 20.2 |
| 1:02 PM | 5,601 | 917 | 318 | 226 | 55.6 | 23,000 | 1.24 | 1.27 | 20.2 |
| Time Average | 5,037 | 817 | 315 | 249 | 54.6 | 27,523 | 1.42 | 1.46 | 20.3 |
| | | | | | | | | | |
| Flow | 27,523 | lb/hr | Temp | 249 | (°F) | | | | |
| Density | 0.0649 | $lb/ft^3$ | Flow | 7,070 | acfm | | | | |
| | | | | | | | | | |
| $CO_2$ Removed | 29.84 | $ft^3/min$ | Density | 0.0890 | $lb/ft^3$ | | | | |
| $CO_2$ Removed | 159.3 | lb/hr | Spray Flow | 2.88 | gpm | | | | |
| | | | | | | | | | |
| Wastewater | 2.63 | gpm | | 1,315 | lb/hr | | | | |
| $CO_2$ concen. | 0.1211 | lb/lb of water | | | | | | | |

FIG. 17

**INTERNATIONAL SEARCH REPORT**

International application No.
**PCT/US2014/051500**

**A. CLASSIFICATION OF SUBJECT MATTER**

**B01D 53/02(2006.01)i, B01D 53/62(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
B01D 53/02; C01B 31/20; C01F 11/18; B01D 53/62; B01D 53/14

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: carbon dioxide, water mist, activated carbon

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
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| A | | 4-20 |
| Y | JP 2011-529848 A (PRAXAIR TECHNOLOGY INC.) 15 December 2011<br>See paragraph [0036-0038] | 1-3 |

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
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"E" earlier application or patent but published on or after the international filing date
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"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 11 November 2014 (11.11.2014) | **12 November 2014 (12.11.2014)** |


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**INTERNATIONAL SEARCH REPORT**

Information on patent family members

International application No.
**PCT/US2014/051500**

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