Title: SIMULTANEOUS ON-SITE PRODUCTION OF HYDROGEN PEROXIDE AND NITROGEN OXIDES FROM AIR AND WATER IN A LOW POWER FLOWING LIQUID FILM PLASMA DISCHARGE FOR USE IN AGRICULTURE

Abstract: A reactor system that includes a single reactor or a plurality of parallel reactors. A method that includes injecting a mixture including liquid water and a gas, into at least one electrically-conductive inlet capillary tube of a continuously-flowing plasma reactor to generate a flowing liquid film region on one or more internal walls of the continuously-flowing plasma reactor with a gas stream flowing through the flowing liquid film region; propagating a plasma discharge along the flowing liquid film region from at least one electrically-conductive inlet capillary to an electrically-conductive outlet capillary tube at an opposing end of the continuously-flowing plasma reactor; dissociating the liquid water in the plasma discharge to form a plurality of dissociation products; producing hydrogen peroxide and nitrogen oxides from the plurality of dissociation products.
SIMULTANEOUS ON-SITE PRODUCTION OF HYDROGEN PEROXIDE AND NITROGEN OXIDES FROM AIR AND WATER IN A LOW POWER FLOWING LIQUID FILM PLASMA DISCHARGE FOR USE IN AGRICULTURE

FIELD OF THE INVENTION

The invention relates generally to the production of hydrogen peroxide and nitrogen oxides, and more specifically to the simultaneous production of hydrogen peroxide and nitrogen oxides from air and water.

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims priority to US Provisional Patent Application No. 61/953,382, filed March 14, 2014 entitled SIMULTANEOUS ON-SITE PRODUCTION OF HYDROGEN PEROXIDE AND NITROGEN OXIDES FROM AIR AND WATER IN A LOW POWER FLOWING LIQUID FILM PLASMA DISCHARGE FOR USE IN AGRICULTURE, and to US Patent Application No. 14/213,068, filed on March 14, 2014 entitled FORMATION OF ALCOHOLS AND CARBONYL COMPOUNDS FROM HEXANE AND CYCLOHEXANE WITH WATER IN A LIQUID FILM PLASMA REACTOR, which claimed priority to US Provisional Patent Application No. 61/784,149, filed March 14, 2013 entitled ORGANIC CHEMICAL SYNTHESIS USING PLASMA REACTORS WITH LIQUID ORGANIC AND LIQUID WATER, each of which is incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

Nitrate is a form of nitrogen which has high bioavailability to plant life and is one of the most common components in the fertilizers which are used in agriculture. Because of its high bioavailability, very low concentrations of nitrate fertilizers are commonly dissolved directly into irrigation systems for foliar application to provide a continuous supply of nutrients to the plants and allow more efficient absorption. Hydrogen peroxide can also be used in agriculture for
disease prevention and algae control where it too can be added directly into an irrigation system in very low concentrations. It would be desirable to facilitate the simultaneous production of hydrogen peroxide and nitrogen oxides from air and water, particularly for use in agriculture.

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BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood with reference to the following description and appended claims, and accompanying drawings where:

FIG. 1A: is a schematic diagram of a system and process according to various embodiments;

FIG. 1B: is a schematic diagram of a system and process for operating a plurality of reactors in parallel, according to various embodiments;

FIG. 1C: is a schematic diagram of a manifold useful for operating a plurality of reactors in parallel, according to various embodiments;

FIG. 2A: shows an illustration of a vertical cross section of the plasma reactor according to various embodiments;

FIG. 2B: shows a perspective view illustration of a casing according to various embodiments;

FIG. 3A-D: show illustrations cross sections of various embodiments of the plasma reactor;

FIG. 4A - C: are photographs of the plasma discharge with a) rapid shutter speed (1/1 2000 sec) b) a long exposure time (1/60 sec), c) a view showing the liquid/gas interface;

FIG. 5A-L: are charts showing sample waveform of discharges;
FIG. 6A-D: are charts showing concentration of hydrogen peroxide (a), production rate of hydrogen peroxide (b), mean discharge power (c), and energy yield (d) for various water flow rates when only argon is used as the carrier gas;

FIG. 7A-B: are charts showing the concentration and production rate of hydrogen peroxide for various water and gas flow rates when air is utilized as the carrier gas;

FIG. 8A-B: are charts showing the concentration and production rate of nitrate for various water and gas flow rates when air is utilized as the carrier gas;

FIG. 9A: is an exemplary circuit diagram of a power supply, including a power source, a pulse generator, and an ignition coil system, according to various embodiments;

FIG. 9B: is an enlarged view of the power source shown in Figure 9A;

FIG. 9C: is an enlarged view of the pulse generator shown in Figure 9A;

FIG. 9D: is an enlarged view of the ignition coil system shown in Figure 9A;

It should be understood that the various embodiments are not limited to the arrangements and instrumentality shown in the drawings.

DETAILED DESCRIPTION OF THE INVENTION

According to various embodiments both air and water are used in a single system to generate both nitrate and hydrogen peroxide simultaneously without the need for other chemical intermediates or stabilizers.
The present invention may be understood more readily by reference to the following detailed description of preferred embodiments of the invention as well as to the examples included therein. All numeric values are herein assumed to be modified by the term "about," whether or not explicitly indicated. The term "about" generally refers to a range of numbers that one of skill in the art would consider equivalent to the recited value (i.e., having the same function or result). In many instances, the term "about" may include numbers that are rounded to the nearest significant figure.

Electrical discharge plasma contacting liquid phases has been studied for a wide range of chemical, biomedical, environmental, and materials synthesis applications. The synthesis of a number of organic and inorganic compounds by gas-liquid plasma can involve glow discharge electrolysis whereby one electrode is placed inside the liquid phase and one in the gas phase. A wide range of other gas-liquid contacting schemes has been studied including falling films, aerosol sprays, and bubble injection into liquids. It has been shown that the presence of the liquid phase not only affects plasma properties such as electron energy and density, but also the chemical reactions which take place. The liquid phase can also serve as a source of additional vapor phase reactant as well as function as a reservoir to collect the generated products, protecting those products from degradation by direct electron attack in the gas phase plasma.

For chemical synthesis in gas-liquid plasma discharges the reactions that occur depend on the chemical makeup of both the liquid and the carrier gas. In the simplest case an inert gas can be used in conjunction with water in order to limit the reactive chemical species present to only hydrogen and oxygen. Under these conditions it has been shown that hydrogen peroxide can be generated by the disassociation of the water molecules in the gas phase plasma into hydroxyl radicals. Due to the limited chemistry present in this situation, neighboring hydroxyl radicals combine to form hydrogen peroxide molecules which rapidly dissolve into the liquid phase where they are protected from degradation by the plasma and can be easily collected.
When a non-inert carrier gas is used in conjunction with liquid water the reactive chemical species in the gas stream can react with the hydroxyl radicals formed from the water to generate other oxidized products. When air (O₂, N₂) is subjected to a plasma discharge NOₓ is formed after dissociation of the diatomic species present in the gas. The formed NOₓ molecules can then be oxidized into nitrate by hydroxyl radicals. Similar to hydrogen peroxide, the formed nitrate rapidly dissolves into the liquid phase where it is protected from degradation by the plasma and can be easily collected.

Various embodiments relate to a system which can be used on a farm to generate both nitrate and hydrogen peroxide on-site to be introduced directly into an irrigation system where the only chemical feeds required are air and water. Further, by manipulating the flow rates of these reactants into the system the relative concentrations of the generated products can be varied to fit the requirements of specific applications. For applications which require higher hydrogen peroxide concentrations argon gas could be supplemented into the gas phase in order to increase generation.

Various embodiments relate to a method that includes injecting a mixture comprising liquid water and a gas, into at least one electrically-conductive inlet capillary tube of a continuously-flowing plasma reactor to generate a flowing liquid film region on one or more internal walls of the continuously-flowing plasma reactor with a gas stream flowing through the flowing liquid film region; propagating a plasma discharge along the flowing liquid film region from at least one electrically-conductive inlet capillary to an electrically-conductive outlet capillary tube at an opposing end of the continuously-flowing plasma reactor; dissociating the liquid water in the plasma discharge to form a plurality of dissociation products; producing hydrogen peroxide and nitrogen oxides (NO, NO₂, NO₃) from the plurality of dissociation products; dissolving the hydrogen peroxide and the nitrogen oxides into the flowing liquid film region; and recovering at least a portion of the hydrogen peroxide and the nitrogen oxides from the electrically conductive outlet capillary. The nitrogen oxides and the hydrogen peroxide dissolved into the flowing liquid film region may be protected
from degradation as the hydrogen peroxide and the nitrogen oxides flow through the flowing liquid film region and exit the continuously-flowing plasma reactor via the electrically conductive outlet capillary. The mixture may be injected into a plurality of electrically-conductive inlet capillary tubes. The flowing liquid film region may have an annular shape. The plasma discharge may have a nominal frequency of 500 Hz. The plasma discharge may have a frequency of from about 100 to 10,000 Hz. The liquid water may have a temperature of from greater than 0 to less than 100 degrees Celsius and the reactor may have a pressure of from approximately 0.1 to 2 bar. The liquid water may have a conductivity of near 1 microSiemens/cm to 500 microSiemens/cm. The gas may be air. The at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary may include an electrically conductive material. The electrically conductive material may include stainless steel, nickel alloys, chromium alloys, titanium alloys, molybdenum alloys, copper alloys, gold alloys, platinum alloys, zinc alloys, zirconium alloys, and combinations thereof.

Some embodiments relate to a reactor system that includes a single reactor. Other embodiments relate to a reactor system that may include a casing having a plurality of internal cavities; and a plurality of reactor assemblies arranged in parallel, wherein each of the plurality of reactor assemblies includes: at least one electrically-conductive inlet capillary having an inlet capillary body extending between a fluid-receiving tip and a fluid-injecting tip, wherein the fluid-receiving tip is positioned outside one of the plurality of internal cavities, and wherein the fluid-injecting tip is positioned inside one of the plurality of internal cavities; at least one electrically-conductive outlet capillary having an outlet capillary body extending between a fluid-collecting tip and a fluid-ejecting tip, wherein the fluid-collecting tip is positioned inside one of the plurality of internal cavities, and wherein the fluid-ejecting tip is positioned outside one of the plurality of internal cavities, wherein the fluid injecting tip is disposed relative to the fluid collecting tip to generate a flowing liquid film region on an internal wall of one of the plurality of internal cavities and a gas stream flowing through the flowing liquid film region, when a fluid is injected into the internal cavity via the at
least one electrically conductive inlet capillary, and wherein the fluid injecting tip is disposed relative to the fluid collecting tip to propagate a plasma discharge along the flowing liquid film region between the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary. The fluid injecting tip may be aligned with the fluid collecting tip. A gap may separate the fluid-injecting tip and the fluid-collecting tip. The gap may have a length, and a ratio of the voltage to the length may be at least about 2.5x10^5 V/m. The reactor system may also include a power source, supplying a voltage across the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary. The power source may be adapted to provide a pulsed current between the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary. The power source may be adapted to provide a D.C. current between the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary. The power source may be adapted to provide an A.C. current between the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary.

Figure 1A shows a schematic diagram of a system and process 100 according to various embodiments. A high pressure carrier gas may be added to the mixing zone 103 from a high pressure storage container 106 via a pressure regulator 105. The flow rate of the high pressure carrier gas may be measured by a rotameter 104. Simultaneously, deionized (DI) water 102 can be pumped via a pump 101, such as a high-pressure pulse injection pump, into the mixing zone 103. The mixing zone 103 may be any suitable structure. For example, the mixing zone 103 may simply be a tee joint, such as a nylon Swagelok tee joint. After mixing in the mixing zone 103, all of the contents of the mixing zone may be passed to, added to, or injected to a reactor 109. The reactor 109 is illustrated in greater detail in Figure 2A. Generally speaking, however, when added to the reactor 109, the contents of the mixing zone 103 can generate a flowing liquid film region on one or more internal walls of the reactor 109 with a gas stream flowing through the flowing liquid film region. A power source may supply a
voltage across at least one electrically-conductive inlet capillary and at least one electrically-conductive outlet capillary of the reactor. A high voltage (HV) probe 108 can be used to measure the voltage applied to the reactor. At the outlet of the reactor a shunt 110 can be used to measure the electrical current and thereby in combination with the voltage determine the power delivered to the reactor. A plasma discharge may be propagated along the flowing liquid film region from at least one electrically-conductive inlet capillary to an electrically-conductive outlet capillary tube at an opposing end of the continuously-flowing plasma reactor 109. The reactor 109 may, therefore, include a plasma discharge region 112. According to certain preferred embodiments, the plasma discharge region 112 may be bounded by a casing 113. The casing may be optically transparent to allow emission spectroscopy and/or high speed imaging to be performed on the plasma discharge region 112 of the reactor 109 via an imaging apparatus 114. For example, a chemical analysis of the contents of the reactor 109 can be performed using atomic emission spectroscopy (AES), which measures the intensity of light emitted from a flame, plasma, arc, or spark at a particular wavelength to determine the quantity of an element in a sample. As a result of the plasma discharge, the liquid water in the plasma discharge may be dissociated to form a plurality of dissociation products. Hydrogen peroxide and nitrogen oxides (NO, NO₂, NO₃) may be produced from the plurality of dissociation products. The hydrogen peroxide and the nitrogen oxides may be dissolved into the flowing liquid film region. At least a portion of the hydrogen peroxide and the nitrogen oxides may be recovered from the electrically conductive outlet capillary. For example, a liquid effluent trap 111 may be used to collect the liquid exiting the reactor for use and/or subsequent chemical analysis via a gas effluent exit 115.

Figure 1B illustrates an embodiment of the system and process 118 wherein a plurality of reactors 109 are connected in parallel. All details of the system and process can be the same as those illustrated in Figure 1A, except as otherwise noted. Any number of reactors 109 may be operated in parallel, although only two reactors 109 are so illustrated. In parallel operation, the high
pressure storage container 106 may supply the high pressure carrier gas to a
gas splitting region 119, which may divert the high pressure carrier gas stream to
a plurality of mixing zones 103. Similarly, the pump 101 may supply the
deionized water 102 to a water splitting region 120, which may divert the
deonized water 102 to the plurality of mixing zones 103. Just as in the
embodiment illustrated in Figure 1A, the after mixing in each of the plurality of
mixing zones 103, the contents of each mixing zone may be passed to, added to,
or injected to one of the plurality of reactors 109. The liquid, comprising the
reaction products, as described with respect to Figure 1A, may be discharged
from each of the plurality of reactors 109 at an approximately equal flow rate.

Figure 1C illustrates a manifold 121 useful in various embodiments
wherein a plurality of reactors 109 are connected in parallel. The manifold 121
includes one or more gas inlets 124 and one or more water inlets 123. The one
or more gas inlets 124 and the one or more can supply gas and water,
respectively, to a plurality of mixing zones 125. Each of the mixing zones 125
may include an outlet 122 for discharging a water/gas mixture to a respective one
of the plurality of reactors 109. The manifold 121 may be made from any suitable
material. A preferable material is plastic. The manifold 121 may be
manufactured by any suitable means, including but not limited to welding, gluing,
or 3D printing. As illustrated in Figure 1C, the manifold 121 can include a
plurality of tubular components. The tubular components may be of any suitable
size. According to certain embodiments, however, the tubular components may
have a wall thickness of about 1/16 inch and an internal diameter of about 1/8 inch.

Figure 2A shows an illustration of a vertical cross section of a single
plasma reactor 109, enclosed in a casing 204. The casing 204 may be
cylindrical, or any suitable shape. For example, in Figure 2B, a slab-shaped
casing 204 is illustrated. The slab-shaped casing includes a plurality of
throughholes 218 into which the other components of the reactor 109 may be
fitted. The slab-shaped casing 204 is particularly useful for operating a plurality
of plasma reactors 109.
The specific features of any given plasma reactor 109, are illustrated in greater detail in Figure 2A. Various embodiments of the reactor 109 provide simple construction from pre-fabricated materials. An added benefit to such embodiments is that they can be considered "disposable."

The reactor 109 can include a body portion 217 having one or more internal walls 213, 214 that define an internal cavity 215. For a tubular geometry internal walls 213 and 214 may be the same wall. According to various embodiments, and as shown in Figure 2, the body portion 217 may be cylindrical. Other geometric shapes are possible.

The reactor 109 can include at least one electrically-conductive inlet capillary 201 having an inlet capillary body 207 extending between a fluid-receiving tip 208 and a fluid-injecting tip 209. The fluid-receiving tip 208 is positioned outside the internal cavity 215, and the fluid-injecting tip 209 is positioned inside the internal cavity 215.

The reactor can include at least one electrically-conductive outlet capillary 205 having an outlet capillary body 210 extending between a fluid-collecting tip 211 and a fluid-ejecting tip 212. The fluid-collecting tip 211 is positioned inside the internal cavity 215, and the fluid-ejecting tip 212 is positioned outside the internal cavity 215.

The electrically-conductive inlet capillary 201 and the electrically-conductive outlet capillary 205 can be made of any electrically conductive material, for example, according to one particularly preferred embodiment the electrically-conductive inlet capillary 201 and the electrically-conductive outlet capillary 205 can be made of 316 stainless steel capillary tubing with an outer diameter (O.D.) of 1.59 mm. Other electrically-conductive materials, as described herein can also be employed. The capillaries can also be any shape, but are preferably cylindrical.

The fluid injecting tip 209 can be disposed relative to the fluid collecting tip 211 to generate a flowing liquid film region 203 on the one or more internal walls 213, 214 and a gas stream or a gas flow region 202 flowing through the flowing liquid film region 203, when a fluid is injected into the internal cavity 215 via the
at least one electrically conductive inlet capillary 201. The fluid injecting tip 209 can be disposed relative to the fluid collecting tip 211 to propagate a plasma discharge along the flowing liquid film region 203 between the at least one electrically-conductive inlet capillary 201 and the at least one electrically-conductive outlet capillary 205. According to various embodiments, the fluid injecting tip 209 can be aligned with the fluid collecting tip 211.

According to particularly preferred embodiments, the internal walls 213, 214 can be defined by the inner walls of the casing 204. As discussed above, the casing 204 can take a variety of geometrical forms. The casing 204 can also be made of a variety of materials, including but not limited to glass materials, plastic materials, and crystalline materials. Some exemplary material include glass, polytetrafluoroethylene, polyethylene terephthalate, and fused quartz. Fused quartz or fused silica is glass consisting of silica in amorphous (non-crystalline) form.

Fused silica is particularly preferred, at least in part, because it provides a wide transparency range, a low electrical conductivity, a high melting point, a high thermal conductivity, and a low thermal expansion coefficient. Generally, the higher the thermal expansion coefficient and the lower the thermal conductivity, the more sensitive the substance is to quick changes in temperature. The extremely low coefficient of thermal expansion of fused quartz, i.e., about 5.5x10^{-7}/°C (20-320 °C), accounts, at least in part, for its remarkable ability to undergo large, rapid temperature changes without cracking.

According to certain embodiments, the casing 204 may be a substantially optically transparent material. Differing degrees of optical transparency are possible. As used herein, "optically transparent" refers to a material or layer that transmits rays of visible light in such a way that the human eye may see through the material distinctly. One definition of optically transparent is a maximum of 50% attenuation at a wavelength of 550 nm (green light) for a material or layer, e.g., a layer 1 μm thick. Another definition can be based on the Strehl Ratio, which ranges from 0 to 1, with 1 being a perfectly transparent material. Exemplary optically transparent materials can have a Strehl Ratio ≥ 0.5, or a
Strehl Ratio $\geq 0.6$, or a Strehl Ratio $\geq 0.7$, or a Strehl Ratio $\geq 0.8$, or a Strehl Ratio $\geq 0.9$, or a Strehl Ratio $\geq 0.95$, or a Strehl Ratio $\geq 0.975$, or a Strehl Ratio $\geq 0.99$.

The casing 204 may have an electrical conductivity within a range having a lower limit and/or an upper limit. The range can include or exclude the lower limit and/or the upper limit. The lower limit and/or upper limit can be selected from about $10^{-11}$, about $10^{-12}$, about $10^{-13}$, about $10^{-14}$, about $10^{-15}$, about $10^{-16}$, about $10^{-17}$, about $10^{-18}$, about $10^{-19}$, about $10^{-20}$, about $10^{-21}$, about $10^{-22}$, about $10^{-23}$, about $10^{-24}$, and about $10^{-25}$ Siemens/meter. For example, according to certain preferred embodiments, the casing 204 may have an electrical conductivity in a range of from about $10^{-11}$ to about $10^{-25}$ Siemens/meter. Other materials having similar electrical conductivities may also be employed. A casing 204 comprising glass may have an electrical conductivity in a range of from about 10-11 to about $10^{-16}$ S/m. A casing 204 comprising polytetrafluorethylene may have an electrical conductivity in a range of from about $10^{-23}$ to about $10^{-25}$ Siemens/meter. A casing 204 comprising polyethylene terephthalate will generally have an electrical conductivity on the order of $10^{-21}$ Siemens/meter.

The casing 204 may have a melting point within a range having a lower limit and/or an upper limit. The range can include or exclude the lower limit and/or the upper limit. The lower limit and/or upper limit can be selected from about 300, 325, 350, 375, 400, 425, 450, 475, 500, 525, 550, 575, 600, 625, 650, 675, 700, 725, 750, 775, 800, 825, 850, 875, 900, 925, 950, 975, 1000, 1025, 1050, 1075, 1100, 1125, 1150, 1175, 1200, 1225, 1250, 1275, 1300, 1325, 1350, 1375, 1400, 1425, 1450, 1475, 1500, 1525, 1550, 1575, and 1600 degrees Celsius. For example, according to certain preferred embodiments, the casing 204 may have a melting point in a range of from about 300 degrees Celsius to over 1600 degrees Celsius. Other materials having similar melting points may also be employed. A casing comprising polytetrafluorethylene, for example, may have a melting point of about 327 degrees Celsius. A casing comprising glass may have a melting point of about 1500 degrees Celsius. A casing comprising fused quartz may have a melting point of about 1600 degrees Celsius.
The casing 204 may have a thermal conductivity within a range having a lower limit and/or an upper limit. The range can include or exclude the lower limit and/or the upper limit. The lower limit and/or upper limit can be selected from about 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7, 2.8, 2.9, 3, 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9, and 5 W/m-K. For example, according to certain preferred embodiments, the casing 204 may have a thermal conductivity of from about 0.1 to about 5.0 W/m-K. Other materials with similar thermal conductivities may be employed. A casing comprising glass may have a thermal conductivity of from about 0.5 to about 1.0 W/m-K. A casing comprising fused quartz may have a thermal conductivity of about 1.3 W/m-K.

The casing 204 may have a thermal expansion coefficient within a range having a lower limit and/or an upper limit. The range can include or exclude the lower limit and/or the upper limit. The lower limit and/or upper limit can be selected from about 10^{-7}, about 10^{-6}, and about 10^{-5} per degree Celsius. For example, according to certain preferred embodiments, the casing 204 may have a thermal expansion coefficient of from about 10^{-7} to about 10^{-5} per degree Celsius. Other materials having similar thermal expansion coefficients may be employed. A casing comprising fused quartz may have a thermal expansion coefficient of about 5.5x10^{-7} per degree Celsius. A casing comprising polytetrafluoroethylene may have a thermal expansion coefficient of about 1.35x10^{-5} per degree Celsius.

As illustrated in Figure 1A, the casing 204 may be a piece of fused quartz tubing with an I.D. of 3.0 mm (AdValue Technology), which can serve as a viewing port for emission spectroscopy and high speed imaging. According to other particularly preferred embodiments, the electrically-conductive inlet capillary 201 and the electrically-conductive outlet capillary 205 can be incased by fused quartz tubing spacers 206 with an I.D. of 1.6 mm (AdValue Technology); the tubing 206 can be positioned such that the ends of the stainless steel and quartz tube spacers are flush at the entrance and exit of the discharge region, i.e. the internal cavity 215. These inlet and outlet assemblies comprising
the electrically-conductive inlet capillary 201 and the electrically-conductive outlet capillary 205 incased by fused quartz tubing spacers 206 can then inserted into either end of the tubing 204.

The fluid injecting tip 209 and the fluid collecting tip 211 (or when employed, the respective ends of the inlet and outlet assemblies) can be positioned such that a gap 216 having a length. The gap 216 can have a length within a range having a lower limit and/or an upper limit. The range can include or exclude the lower limit and/or the upper limit. The lower limit and/or upper limit can be selected from 0.1 , 0.2 , 0.3 , 0.4 , 0.5 , 0.6 , 0.7 , 0.8 , 0.9 , 1 , 1.1 , 1.2 , 1.3 , 1.4 , 1.5 , 1.6 , 1.7 , 1.8 , 1.9 , 2 , 2.1 , 2.2 , 2.3 , 2.4 , 2.5 , 2.6 , 2.7 , 2.8 , 2.9 , 3 , 3.1 , 3.2 , 3.3 , 3.4 , 3.5 , 3.6 , 3.7 , 3.8 , 3.9 , 4 , 4.1 , 4.2 , 4.3 , 4.4 , 4.5 , 4.6 , 4.7 , 4.8 , 4.9 , 5 , 5.1 , 5.2 , 5.3 , 5.4 , 5.5 , 5.6 , 5.7 , 5.8 , 5.9 , 6 , 6.1 , 6.2 , 6.3 , 6.4 , 6.5 , 6.6 , 6.7 , 6.8 , 6.9 , 7 , 7.1 , 7.2 , 7.3 , 7.4 , 7.5 , 7.6 , 7.7 , 7.8 , 7.9 , 8 , 8.1 , 8.2 , 8.3 , 8.4 , 8.5 , 8.6 , 8.7 , 8.8 , 8.9 , 9 , 9.1 , 9.2 , 9.3 , 9.4 , 9.5 , 9.6 , 9.7 , 9.8 , 9.9 , 10 , 10.1 , 10.2 , 10.3 , 10.4 , 10.5 , 10.6 , 10.7 , 10.8 , 10.9 , 11 , 11.1 , 11.2 , 11.3 , 11.4 , 11.5 , 11.6 , 11.7 , 11.8 , 11.9 , 12 , 12.1 , 12.2 , 12.3 , 12.4 , 12.5 , 12.6 , 12.7 , 12.8 , 12.9 , 13 , 13.1 , 13.2 , 13.3 , 13.4 , 13.5 , 13.6 , 13.7 , 13.8 , 13.9 , 14 , 14.1 , 14.2 , 14.3 , 14.4 , 14.5 , 14.6 , 14.7 , 14.8 , 14.9 , 15 , 15.1 , 15.2 , 15.3 , 15.4 , 15.5 , 15.6 , 15.7 , 15.8 , 15.9 , 16 , 16.1 , 16.2 , 16.3 , 16.4 , 16.5 , 16.6 , 16.7 , 16.8 , 16.9 , 17 , 17.1 , 17.2 , 17.3 , 17.4 , 17.5 , 17.6 , 17.7 , 17.8 , 17.9 , 18 , 18.1 , 18.2 , 18.3 , 18.4 , 18.5 , 18.6 , 18.7 , 18.8 , 18.9 , 19 , 19.1 , 19.2 , 19.3 , 19.4 , 19.5 , 19.6 , 19.7 , 19.8 , 19.9 , 20 , 20.1 , 20.2 , 20.3 , 20.4 , 20.5 , 20.6 , 20.7 , 20.8 , 20.9 , 21 , 21.1 , 21.2 , 21.3 , 21.4 , 21.5 , 21.6 , 21.7 , 21.8 , 21.9 , 22 , 22.1 , 22.2 , 22.3 , 22.4 , 22.5 , 22.6 , 22.7 , 22.8 , 22.9 , 23 , 23.1 , 23.2 , 23.3 , 23.4 , 23.5 , 23.6 , 23.7 , 23.8 , 23.9 , 24 , 24.1 , 24.2 , 24.3 , 24.4 , 24.5 , 24.6 , 24.7 , 24.8 , 24.9 , and 25 mm. For example, according to certain preferred embodiments, the gap 216 can have a length of about 4 mm.

The system may also include a power source 116, supplying a voltage across the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary. The power source 116 may be adapted to provide a pulsed current, a D.C. current, and/or an A.C. current between the at least one electrically-conductive inlet capillary 201 and the at least one
electrically-conductive outlet capillary 205. As illustrated in Figure 2A, the power source 116 is electrically connected to the at least one electrically-conductive inlet capillary 201, while the at least one electrically-conductive outlet capillary 205 is grounded. The opposite arrangement is also possible, wherein the power source 116 is electrically connected to the at least one electrically-conductive outlet capillary 205, while the at least one electrically-conductive inlet capillary 201 is grounded. A wide variety of other configurations are conceivable, whereby the power source 116 can be adapted to provide a pulsed current, a D.C. current, and/or an A.C. current between the at least one electrically-conductive inlet capillary 201 and the at least one electrically-conductive outlet capillary 205.

A gap 216 separates the at least one electrically-conductive inlet capillary 201 and the at least one electrically-conductive outlet capillary 205. A ratio of the voltage supplied, i.e., the input voltage, by the power source 116 to the length of the gap 216 can be within a range having a lower limit and/or an upper limit. The range can include or exclude the lower limit and/or the upper limit. The input voltage should be sufficient to generate an electric field sufficient to produce the electrical breakdown and discharge plasma formation. The lower limit and/or upper limit can be selected from 2.5x10^5 V/m, 3x10^5, 4x10^5, 5x10^5, 6x10^5, 7x10^5, 8x10^5, 9x10^5 V/m, 1x10^6 V/m, 1.5x10^6 V/m, 2x10^6 V/m, 2.5x10^6 V/m, 3x10^6 V/m, and 3.5x10^6 V/m. For example, the gap 216 can have a length, and a ratio of the voltage to the length can be at least about 2.5x10^5 V/m or about 5x10^5 V/m.

According to certain embodiments, a combination of a gap of from about 1 to about 10 mm and an input voltage ranging from about 8 to about 20 V, can provide an average discharge voltage of about 500 V with peaks of from 1 to 3 kV. A transformer in the power supply (ignition coil) may transform the input voltage to the power supply to a much higher voltage in order to generate the electric fields mentioned above. These characteristics are exemplified in Figure 5A. Varying the input voltage between 8 and 15 V, supplied to such embodiments, did not have a significant impact on the average discharge
voltage, but did increase the current and total power. This is because of the properties of the ignition coil - increasing the input voltage increases the energy to the coil but does not change the output voltage of the ignition coil to generate the high electric fields needed to create the plasma by electrical breakdown. An average discharge voltage of about 2 kV in a gap of about 4 mm would provide 5 kV/cm as an electric field to create the discharge. Normally in air or pure gas without the liquid water stream, breakdown voltages range between 25 to 35 kV/cm and this can decrease with humidity, but not to the level obtained with a liquid stream contact.

Again, the power source 116 may be adapted to provide a pulsed current, a D.C. current, and/or an A.C. current between the at least one electrically-conductive inlet capillary 201 and the at least one electrically-conductive outlet capillary 205.

The pulsed current may have a frequency within a range having a lower limit and/or an upper limit. The range can include or exclude the lower limit and/or the upper limit. The lower limit and/or upper limit can be selected from about 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, 360, 370, 380, 390, 400, 410, 420, 430, 440, 450, 460, 470, 480, 490, 500, 510, 520, 530, 540, 550, 560, 570, 580, 590, 600, 610, 620, 630, 640, 650, 660, 670, 680, 690, 700, 710, 720, 730, 740, 750, 760, 770, 780, 790, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, and 2000 Hz. For example, according to certain preferred embodiments, the pulsed current may have a frequency in a range of from about 1 Hz to about 2000 Hz. A preferred subrange is from about 100 to about 800 Hz.

The pulse may have a width of from about 0.1 ms to about 1.0 ms.

According to various embodiments the voltage supplied by the power source 116 may be brought to a sufficient level to initiate voltage breakdown and to produce a discharge channel (arc or streamer). The discharge channel characteristics such as rate of fire and on-time may be controlled via a peripheral
board. The peripheral board may include a timer, which outputs a voltage pulse train based on its own input voltage level and reset characteristics.

The reaction within the reactor may be subject to the discharge channel or arc, which can be optimized/controlled by changing the peripheral board settings. The peripheral board is powered by a 12V power supply only because the timer used on this specific board calls for 4-18V power; any suitable voltage may be utilized. The peripheral board does not supply energy to the reaction it simply controls the on and off of the arc. The voltage pulse train output is sent to a switch built into an ignition coil. The ignition coil may have wires for power and for control of the power switch. The second power supply used in the present setup is merely the power for the arc itself. The peripheral board output may be tied to the switch control of the ignition coil. It should be emphasized, again, that the particular configuration described herein is merely exemplary and that a wide variety of other configurations are readily conceivable, whereby the power source can be adapted to provide a pulsed current, a D.C. current, and/or an A.C. current between the at least one electrically-conductive inlet capillary 201 and the at least one electrically-conductive outlet capillary 205. Based on the particular configuration of the power supply described above, a nominally 2.5x10^5 V/m electric field is applied across two conductive electrode surfaces at (2 to 6 mm) distance apart. The voltage is of a high enough potential to overcome the separation causing an electrical discharge or arc. This arcing happens while a fluid (gas and liquid) passes between the contacts. Chemical reactions occur in and near the plasma discharge or arc. The desired product output is partly dependent on the frequency and duration of the arc and the flow, composition, and rate of the input reactants. To better control this reaction the peripheral board is utilized which allows the user to control the characteristics of the pulse train that is sent to the ignition coil’s power switch. The number of reactors in a set and the number of sets used for the desired scale needed are all problem specific and can be varied as needed. The specific power supply for the larger unit will depend upon the scale required. A person having ordinary skill in the art will be readily equipped to scale the power supply, the system, and/or method
disclosed herein to any desirable level. A person having ordinary skill in the art will readily appreciate that for a given input composition, flow rate, and reactor geometry, a voltage and power sufficient to produce an electrical breakdown in the gap between the electrodes which contains the water and gas mixture may be readily determined.

According to various embodiments, the body portion 217 can be cylindrical. The cylindrical body portion 217 can have a first diameter within a range having a lower limit and/or an upper limit. The range can include or exclude the lower limit and/or the upper limit. The lower limit and/or upper limit can be selected from 0.01, 0.02, 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.1, 0.11, 0.12, 0.13, 0.14, 0.15, 0.16, 0.17, 0.18, 0.19, 0.2, 0.21, 0.22, 0.23, 0.24, 0.25, 0.26, 0.27, 0.28, 0.29, 0.3, 0.31, 0.32, 0.33, 0.34, 0.35, 0.36, 0.37, 0.38, 0.39, 0.4, 0.41, 0.42, 0.43, 0.44, 0.45, 0.46, 0.47, 0.48, 0.49, 0.5, 0.51, 0.52, 0.53, 0.54, 0.55, 0.56, 0.57, 0.58, 0.59, 0.6, 0.61, 0.62, 0.63, 0.64, 0.65, 0.66, 0.67, 0.68, 0.69, 0.7, 0.71, 0.72, 0.73, 0.74, 0.75, 0.76, 0.77, 0.78, 0.79, 0.8, 0.81, 0.82, 0.83, 0.84, 0.85, 0.86, 0.87, 0.88, 0.89, 0.9, 0.91, 0.92, 0.93, 0.94, 0.95, 0.96, 0.97, 0.98, 0.99, 1, 1.01, 1.02, 1.03, 1.04, 1.05, 1.06, 1.07, 1.08, 1.09, 1.1, 1.11, 1.12, 1.13, 1.14, 1.15, 1.16, 1.17, 1.18, 1.19, 1.2, 1.21, 1.22, 1.23, 1.24, 1.25, 1.26, 1.27, 1.28, 1.29, 1.3, 1.31, 1.32, 1.33, 1.34, 1.35, 1.36, 1.37, 1.38, 1.39, 1.4, 1.41, 1.42, 1.43, 1.44, 1.45, 1.46, 1.47, 1.48, 1.49, 1.5, 1.51, 1.52, 1.53, 1.54, 1.55, 1.56, 1.57, 1.58, 1.59, 1.6, 1.61, 1.62, 1.63, 1.64, 1.65, 1.66, 1.67, 1.68, 1.69, 1.7, 1.71, 1.72, 1.73, 1.74, 1.75, 1.76, 1.77, 1.78, 1.79, 1.8, 1.81, 1.82, 1.83, 1.84, 1.85, 1.86, 1.87, 1.88, 1.89, 1.9, 1.91, 1.92, 1.93, 1.94, 1.95, 1.96, 1.97, 1.98, 1.99, and 2 cm. For example, according to certain preferred embodiments, the cylindrical body portion 217 can have a first diameter 0.1 to 1 cm. The at least one electrically-conductive inlet capillary can have a second diameter that is less than the first diameter. The at least one electrically-conductive outlet capillary can have a third diameter that is greater than the second diameter and less than the first diameter.

Figure 3A shows an illustration of a radial cross section along line A-A as shown in Figure 2A of the plasma reactor 109, i.e. the discharge region,
according to various embodiments. The gas flow region 202 can be bounded by a highly turbulent gas/liquid interface 301, separating the gas flow and plasma discharge region 202 from the liquid film flow region 203. As discussed under Figure 2A, the liquid film flow region 203 flows along the casing 204, which may acts as the reactor wall.

According to various embodiments, the gas flow can be determined by the nozzle, i.e. the outlet of a capillary, diameter and the pressure. The liquid flow can be determined by the gas flow, and all other dependent properties can thereafter be determined. The maximum liquid flow can be determined by the gas flow, and all other dependent properties can thereafter be determined. The pressure of the inlet gas can be in the range of 10 to 500 pounds per square inch (psi). For an inlet gas pressure of 60 psi and a 0.01 inch inlet capillary nozzle with a 3 mm tube, the gas flow is 0.3 liters per minute and the upper liquid flow can be 4 ml/min. In addition to scaling up this process by placing many single reactors in parallel, alternative geometries could be used which utilize a single large volume chamber for the flow of water and gas in conjunction with multiple inlet and outlet nozzles into and out of the single chamber.

Figure 3B shows an illustration of a radial cross section of an exemplary configuration comprising a reactor body 302 and a plurality of electrically-conductive inlet capillaries 303. The reactor body 302 is an annular ring and has a distance D between its walls. Each of the electrically-conductive inlet capillaries 303 can have a range of influence 304 within the reactor body 302. Inside its range of influence each electrically-conductive inlet capillary can be used to form a plasma discharge. One or more electrically-conductive outlet capillaries (not shown) can be aligned with or otherwise positioned relative to the plurality of electrically-conductive inlet capillaries 303 to generate a flowing liquid film region on one or more internal walls of the reactor body 302 and a gas stream or a gas flow region flowing through the flowing liquid film region, when a fluid is injected into the internal cavity via the at least one electrically conductive inlet capillary 303. The one or more electrically-conductive outlet capillaries (not shown) can additionally or alternatively be aligned with or otherwise positioned.
relative to the plurality of electrically-conductive inlet capillaries 303 to propagate a plasma discharge along the flowing liquid film region between one or more of the plurality of electrically-conductive inlet capillaries 303 and one or more of the one or more plurality of electrically-conductive outlet capillaries. As shown, a gas liquid interface 305 can be generated between a liquid film region 307 and a gas flow region 306 passing through the liquid film region 307.

Figure 3c shows an illustration of a radial cross section of an exemplary configuration comprising a reactor body 308 and a plurality of electrically-conductive inlet capillaries 309. The reactor body 308 is an elongated box and has a distance D between its walls. Each of the electrically-conductive inlet capillaries 309 can have a range of influence 310 within the reactor body 308. Inside its range of influence each electrically-conductive inlet capillary can be used to form a plasma discharge. One or more electrically-conductive outlet capillaries (not shown) can be aligned with or otherwise positioned relative to the plurality of electrically-conductive inlet capillaries 309 to generate a flowing liquid film region on one or more internal walls of the reactor body 308 and a gas stream or a gas flow region flowing through the flowing liquid film region, when a fluid is injected into the internal cavity via the at least one electrically conductive inlet capillary 309. The one or more electrically-conductive outlet capillaries (not shown) can additionally or alternatively be aligned with or otherwise positioned relative to the plurality of electrically-conductive inlet capillaries 309 to propagate a plasma discharge along the flowing liquid film region between one or more of the plurality of electrically-conductive inlet capillaries 309 and one or more of the one or more plurality of electrically-conductive outlet capillaries. As shown, a gas liquid interface 311 can be generated between a liquid film region 312 and a gas flow region 313 passing through the liquid film region 312.

Any configuration of the reactor body can be employed. The configurations shown in Figure 2, Figure 3A, Figure 3B, and Figure 3C are merely exemplary. A variety of geometries can be employed, but a cylindrical geometry tends to maximize contact between the discharge plasma channel and the liquid, which is desirable.
Figure 3D shows a vertical cross-section of a reactor body 308 as depicted in either Figures 3B or 3C. Since the cross section would be the same for both the reactor body could have been designated with reference numeral 302. Reference numerals in the specific embodiment shown in Figure 3d correspond to those in Figure 3c. Again, since the cross section would be the same for Figure 3b, the reference numerals of Figure 3b could have been used. Figure 3d also shows a plurality of electrically-conductive outlet capillaries 314. The electrically-conductive outlet capillaries 314 are shown in alignment with the electrically-conductive inlet capillaries 309. Figure 3c also illustrates a length L of the reactor body 308.

Figure 4a, 4b, and 4c depict high speed imaging of the plasma discharge region. Figure 4a shows a single plasma channel 400 propagating between electrodes and along the gas liquid interface. Figure 4b, with a long photographic exposure, shows multiple plasma channels 400, 401, and 402 propagating between electrodes. Figure 4c shows a liquid film region 403, and a gas flow region 404, separated by a liquid/gas interface 405. A plasma discharge 406 is also shown at the liquid/gas interface 405.

Examples

Reactor and Apparatus

The examples employ a process as illustrated in Figure 1A, which shows the general process schematic of the experimental setup. The reactor 109 was the reactor illustrated in Figure 2A. High purity air and/or argon gas (Air Gas; Tallahassee, FL) at 4.14 kPa was utilized where the volumetric flow rate was measured by a rotameter (Cole Palmer; Vernon Hills, IL). The carrier gas was allowed to flow unrestricted into the reactor inlet. The gas flow rate is a function of the pressure head and the inner diameter (I.D.) of the reactor inlet nozzle.

The carrier gas then contacted a liquid stream of deionized water (pH - 5.0 ± 0.2, conductivity - 5.0 ± 1.0 µS/cm) at mixing zone 103 (1/1 6" Swagelok® nylon tee joint, Jax Fluid System Technologies; Jacksonville, FL). The deionized...
water was delivered to the system with a high pressure, pulse injection pump 101 (Optos Series, Eldex Laboratories Inc.; Napa, CA).

High pressure mixing occurred between these three components mixing zone 103, after which the mixture flowed through the inlet nozzle of the reactor 109 and into the plasma discharge region 112 where chemical reactions were induced. After exiting the discharge region 112, the liquid phase of the effluent was directly collected in a vessel.

The reactor according to this Example was constructed from pre-fabricated round tubing giving it a cylindrical geometry. Figure 2A shows a vertical cross section diagram of the reactor. Because of its simple construction from pre-fabricated materials, an added benefit to this reactor design is that it can be considered "disposable." The inlet and outlet parts of the reactor were made of 316 stainless steel capillary tubing with an outer diameter (O.D.) of 1.59 mm (Supeico; Bellefonte, PA) and are incased by fused quartz tubing spacers with an inner diameter (I.D.) of 1.6 mm (AdValue Technology; Tucson, AZ); the tubing was positioned such that the ends of the stainless steel and quartz tube spacers were flush at the entrance and exit of the discharge region. The inlet and outlet assemblies were then inserted into either end of a casing, i.e., an additional piece of fused quartz tubing with an I.D. of 3.0 mm (AdValue Technology; Tucson, AZ) which served as the reactor wall and viewing port for emission spectroscopy and high speed imaging 114. The inlet and outlet assemblies were positioned such that a 4 mm gap existed between the entrance and exit of the discharge region. A horizontal cross section of the discharge region is shown in Figure 3A.

A key aspect of this reactor system is the flow pattern generated inside the reactor volume. Because the inlet capillary tube had an internal diameter smaller than that of the discharge region, a well-mixed radial spray was generated as the high pressure mixture exited the inlet nozzle and entered the reactor volume. This spray then rapidly contacted the reactor wall creating a liquid film which flowed along the reactor wall coupled with a high velocity gas flow region in the radial center of the reactor.
High speed imaging was performed with a VW-9000 series high speed microscope system with a VH-OOR 0-50x lens (Keyence; Itasca, IL) to confirm the existence and analyze the previously mentioned flow regions. Figure 4A is a photograph of the reaction plasma zone region taken with a rapid shutter speed (1/1 2000 sec) and captures not only a single filamentous plasma channel, but also the wave-like pattern of water flow on the walls of the reactor. Figure 4B depicts a long exposure time (1/60 sec) and captures the many filamentous plasma channels produced during this time period. Both photos (Figure 4A and 4B) indicate that the discharge takes place along the gas-liquid interface and not within the liquid film flow region or in the middle of the gas stream; the majority of the plasma streamers appear to travel along the highly turbulent gas liquid interface.

An additional key aspect of this reactor design was that the stainless steel capillary tubing which acted as the entrance and exit to the reactor volume also function as the anode and cathode which generate the plasma discharge. This configuration provides maximum contact of the reactants with the plasma by minimizing by-pass regions where the gas-liquid flow does not contact the plasma. In the specific setup, the high voltage lead was attached to the inlet nozzle of the reactor while the outlet capillary was grounded, as shown in Figure 1A.

The power supply 116 (DC 1740B BK Precision; Yorba Linda, CA) was driven by a pulse generator (2 MHz 401 QA BK Precision; Yorba Linda, CA) to provide pulsed 12 V direct current to an automobile ignition coil (VW-AG, ERA Germany). A high voltage diode was placed between the ignition coil and the reactor to protect the coil from unwanted upstream voltage surges back to the ignition coil from the reactor. The pulse frequency and duty cycle was held constant for all experiments at 500 Hz and 40%.

Additional tests were also performed, and similar results were obtained, using the same reactor configuration, but with a power supply 900 as illustrated in Figure 9. The power supply 900 is only provided for exemplary purposes and is only one possible configuration. Indeed, since similar results were obtained,
power supply 900 demonstrates that any suitable power supply may be employed. The power supply 900 included a 12 V DC power source 901, a pulse generator 902 operating at a frequency of from 100 Hz to 1kHz at 10 to 50% DC; and an ignition coil system 903.

A constant DC power supply can also be used to sustain a discharge between the anode and cathode. In this situation the highly turbulent gas liquid interface is used to vary the spatial position of the generated plasma arc.

Sample current, voltage, and power waveforms when a pulsed power supply is utilized are shown in Figures 5A - L. Figure 5A shows the very rapid raise in voltage and figure 5B shows the current pulse over about 0.5 ms with an approximate triangular shaped decay. Power is determined by the product of voltage and current as in Figure 5C. Figures 5D though 5I are magnifications of the pulses showing more detail of the first pulse in Figure 5A. Figure 5J, Figure 5K, and Figure 5L show the voltage, current, and power wave forms, respectively, for the case of the air carrier gas at 0.5 l/min with deionized water (introduced conductivity 2.22 microSiemens/cm and initial pH 4.46) flowing at 0.75 ml/min. Because of the higher water conductivity (outlet conductivity 245 microSiemens/cm) formed by the nitrogen oxides the pulses are smoother, with less oscillation following the initial peak in the pulse as shown in the argon case.

The pulse width is smaller with the air than argon, approximately 0.2 ms in air compared to the 0.5 ms pulse in argon with less variability between pulses in air. The maximum voltage is approximately 6.5 to 7 kV in air and it is more consistent between pulses. Other pulse shapes are possible, but the exact shape depends not only on the power supply but also the reactor and the properties (conductivity) of the gas and liquid inside the reactor. The voltage, current, and power waveforms of the discharge were measured with a Tektronix DPO 3014 oscilloscope (Tektronix Inc.; Beaverton, OR). The sampling rate of the oscilloscope was 10^4 points for the 100 ms acquisition window. The discharge voltage was measured with a high-voltage probe (P6015 Tektronix; Beaverton, OR) connected to the lead electrode. The current was measured with a 100 Ω shunt to the ground in the secondary of the ignition coil. The math function of the
oscilloscope was used to generate the calculated power pulses. Averages of three power measurements for each trial were taken to reduce the error of the measurement and exported to a spreadsheet where the magnitude of the individual data points were averaged to provide a mean power for the time period of the acquisition window. The instantaneous power was calculated by multiplication of the individual data points in the current and voltage waveforms. The mean discharge power was determined by averaging the instantaneous power across the time period of acquisition window. It should be noted that the power reported in this study was the "power delivered to the discharge" and that the overall efficiency also depends upon the power and efficiency of the transformer.

Chemical analysis

The concentration of hydrogen peroxide formed in the liquid fractions was measured using a colorimetric test with a UV-Vis spectrophotometer (Perkin-Elmer, Lambda 35; Waltham, MA) where 2 ml liquid samples were taken and mixed with 1 ml of a titanium oxysulfate-sulfuric acid complex.[86] The absorbance of the formed yellow complex was measured at a 410 nm wavelength and converted to hydrogen peroxide concentration by a calibration curve generated with stock solutions of hydrogen peroxide where concentration was confirmed by titration with 0.1 N potassium permanganate.

The concentration of nitrate formed was measured by ion chromatography. A calibration curve was generated with standard solutions of known nitrate concentration.

Figure 6 depicts the concentration, production rate, and energy yield for hydrogen peroxide generation as well as discharge power for the various water flow rates when only argon is used as the carrier gas. The concentration portion of this figure clearly shows an increase in hydrogen peroxide concentration as the water flow rate was decreased. When the production rate of hydrogen peroxide was calculated from multiplication of these concentrations by their corresponding water flow rate it can be seen to be relatively stable around 0.07
µιλιοτ/s across the range of water flow rates tested. From this figure the
discharge power can also be seen to be fairly stable around 0.25 W across the
range of flow rates. Because there is relatively no change in discharge power or
production rate as a function of water flow rate, when the production rate is
divided by the power to arrive at an energy yield, the values similarly show little
variation with flow rate with an average at 33 g/kWh.

Figure 7 shows the concentration and production rate of hydrogen
peroxide generated when only air is used as the carrier gas. Clearly the amount
of hydrogen peroxide generated significantly decreases when air utilized due to
the presence of additional reactive chemical species which can react with the
formed hydroxyl radicals. It should be noted however that the production rate of
hydrogen peroxide significantly increases when the flow rates of air and water
are reduced.

Figure 8 depicts the formation of nitrate for various water flow rates when
air is used as the carrier gas. This figure shows that the concentration of nitrate
increases when the water flow rate is decreased. However, the production rate
of nitrate production rate does not significantly decrease when the water flow is
decreased indicating that dilution effects are the likely cause of the decrease in
concentration at the higher water flow rates.

Although the present invention has been described in considerable detail
with reference to certain preferred versions thereof, other versions are possible.
Therefore, the spirit and scope of the appended claims should not be limited to
the description of the preferred versions contained herein. All the features
disclosed in this specification (including any accompanying claims, abstract, and
drawings) may be replaced by alternative features serving the same, equivalent
or similar purpose, unless expressly stated otherwise. Thus, unless expressly
stated otherwise, each feature disclosed is one example only of a generic series
of equivalent or similar features.
CLAIMS
What is claimed is:

1. A method comprising:

   injecting a mixture comprising liquid water and a gas,
   into at least one electrically-conductive inlet capillary tube of a continuously-flowing plasma reactor to generate a flowing liquid film region on one or more internal walls of the continuously-flowing plasma reactor with a gas stream flowing through the flowing liquid film region;

   propagating a plasma discharge along the flowing liquid film region from at least one electrically-conductive inlet capillary to an electrically-conductive outlet capillary tube at an opposing end of the continuously-flowing plasma reactor;

   dissociating the liquid water in the plasma discharge to form a plurality of dissociation products;

   producing hydrogen peroxide and nitrogen oxides from the plurality of dissociation products;

   dissolving the hydrogen peroxide and the nitrogen oxides into the flowing liquid film region; and

   recovering at least a portion of the hydrogen peroxide and the nitrogen oxides from the electrically conductive outlet capillary.

2. The method according to Claim 1, wherein the nitrogen oxides and the hydrogen peroxide dissolved into the flowing liquid film region are protected from degradation as the hydrogen peroxide and the nitrogen oxides flow through the flowing liquid film region and exit the continuously-flowing plasma reactor via the electrically conductive outlet capillary.
3. The method according to Claim 1, wherein the liquid water has a temperature of from greater than 0 to less than 100 degrees Celsius, and wherein the reactor has a pressure of from approximately 0.1 to 2 bar.

4. The method according to Claim 1, wherein the liquid water has a conductivity of near 1 microSiemens/cm to 500 microSiemens/cm.

5. The method according to Claim 1, wherein the gas is air.

6. The method according to Claim 1, wherein the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary comprise an electrically conductive material.

7. The method according to Claim 1, wherein the electrically conductive material comprises one selected from the group consisting of stainless steel, nickel alloys, chromium alloys, titanium alloys, molybdenum alloys, copper alloys, gold alloys, platinum alloys, zinc alloys, zirconium alloys, and combinations thereof.

8. The method according to Claim 1, wherein the mixture is injected into a plurality of electrically-conductive inlet capillary tubes.

9. The method according to Claim 1, wherein the flowing liquid film region has an annular shape.

10. The method according to Claim 1, wherein the plasma discharge has a nominal frequency of 500 Hz.

11. The method according to Claim 10, wherein plasma discharge has a frequency of from about 100 to 10,000 Hz.

12. A reactor system comprising:

   a casing having a plurality of internal cavities; and

   a plurality of reactor assemblies arranged in parallel, wherein each of the plurality of reactor assemblies comprises:
at least one electrically-conductive inlet capillary having an inlet capillary body extending between a fluid-receiving tip and a fluid-injecting tip, wherein the fluid-receiving tip is positioned outside one of the plurality of internal cavities, and wherein the fluid-injecting tip is positioned inside one of the plurality of internal cavities;

at least one electrically-conductive outlet capillary having an outlet capillary body extending between a fluid-collecting tip and a fluid-ejecting tip, wherein the fluid-collecting tip is positioned inside one of the plurality of internal cavities, and wherein the fluid-ejecting tip is positioned outside one of the plurality of internal cavities,

wherein the fluid injecting tip is disposed relative to the fluid collecting tip to generate a flowing liquid film region on an internal wall of one of the plurality of internal cavities and a gas stream flowing through the flowing liquid film region, when a fluid is injected into the internal cavity via the at least one electrically-conductive inlet capillary, and

wherein the fluid injecting tip is disposed relative to the fluid collecting tip to propagate a plasma discharge along the flowing liquid film region between the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary.

13. The reactor system according to Claim 12, further comprising a power source, supplying a voltage across the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary,

14. The reactor system according to Claim 12, wherein the fluid injecting tip is aligned with the fluid collecting tip.

15. The reactor according to Claim 12, wherein the power source is adapted to provide a pulsed current between the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary.
16. The reactor system according to Claim 12, wherein the power source is adapted to provide a D.C. current between the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary.

17. The reactor system according to Claim 12, wherein the power source is adapted to provide an A.C. current between the at least one electrically-conductive inlet capillary and the at least one electrically-conductive outlet capillary.

18. The reactor system according to Claim 12, wherein a gap separates the fluid-injecting tip and the fluid-collecting tip, wherein the gap has a length, and wherein a ratio of the voltage to the length is at least about 2.5x10^5 V/m.

19. The reactor system according to Claim 12, wherein the casing is optically transparent and wherein the reactor system further comprises an imaging apparatus disposed adjacent to the casing and adapted to capture imaging information of the flowing liquid film region.

20. The reactor system according to Claim 12, wherein the casing comprises fused quartz.
Air carrier gas

**Fig. 8A**

**Fig. 8B**
Pulse Generator
F = 100 Hz to 1 kHz
DC = 10 to 50%

FIG. 9C
FIG. 9D
**INTERNATIONAL SEARCH REPORT**

**A. CLASSIFICATION OF SUBJECT MATTER**

**IPCC** - C01 B 15/027 (201 5.01)

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

- IPC(8) - B01 J 12/00, 19/00, C01B 15/027, 21/20 (2015.01)
- CPC - B01 J 12/00, 12/002, 19/000, 19/088; C01B 15/027, 21/20, 21/203 (2015.04) (keyword delimited)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>Y</td>
<td>US 8,444,924 B2 (BURLICA et al) 21 May 2013 (21.05.2013) entire document</td>
<td>1-1 1, 19, 20</td>
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**Date of the actual completion of the international search**

12 May 2015

**Date of mailing of the international search report**

09 June 2015

**Authorized officer:**

Blaine R. Copenheaver

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