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(54) PLASMA DISCHARGE SYSTEM AND METHOD OF USING THE SAME

(57) The present invention relates to a plasma discharge system and a method for operating the plasma discharge system. The system comprises a voltage source; a conductive coil electrically connected to the voltage source, the conductive coil being configured to generate a magnetic field when electric current is flowed therethrough; a first electrode structure electrically connected to the voltage source; a second electrode structure positioned apart from the first electrode structure

and being electrically connected to the voltage source so as to create a potential difference between the first and the second electrode structures such that at least one electrical discharge occurs in between the first and the second electrode structures. The conductive coil and the first and second electrode structures are positioned such that the magnetic field exerts a force on the electrical discharge. The conductive coil is electrically connected in series with the first and/or second electrode structures.

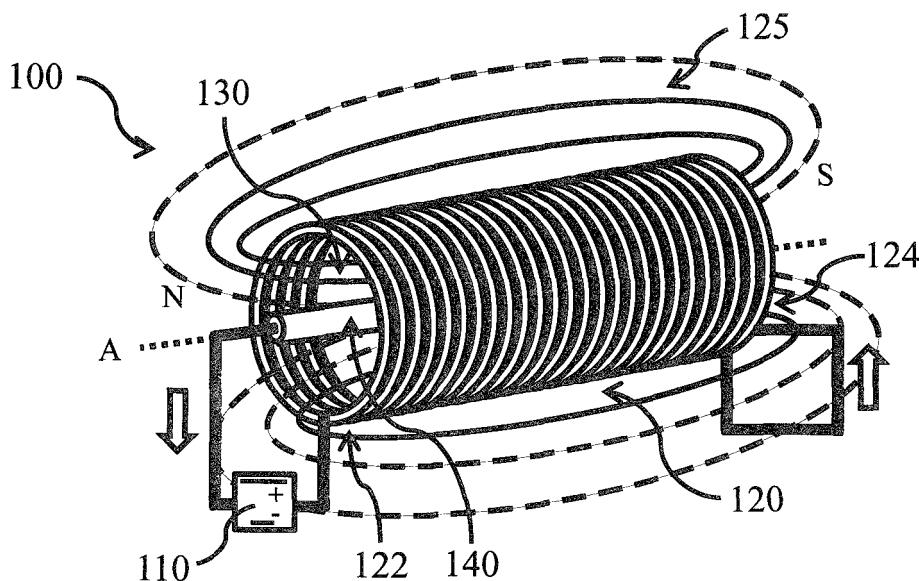


Fig. 1

Description

Background

[0001] The invention relates to a plasma discharge system and a method for operating the plasma discharge system.

[0002] An electrical discharge can form between two electrodes when the resistance of the air or other medium in between the electrodes is overcome by a great enough potential difference between the electrodes. Said electrical discharge can be set into motion through the influence of a magnetic field and by repeatedly passing through a specific area can form a type of "plasma layer".

[0003] WO 2017/021194 A1, incorporated herein by reference in its entirety, describes methods and devices for producing plasma. The apparatus for producing plasma requires at least a first electrode and a second electrode with a potential difference existing between them. The potential difference produces a discharge path between said electrodes in a discharge region between them. A magnetic field device is arranged such that a magnetic field vector is oriented at an angle to the discharge path. The magnetic field sets the discharge path into motion within the discharge region.

[0004] Generation and maintenance of the plasma layer requires control over the electrical discharge as well as the magnetic field.

[0005] It is therefore an object of the present invention to provide a plasma discharge system which is particularly suited for controlling the electrical discharge and magnetic field.

[0006] It is a further object of the present invention to provide a plasma discharge system which is simple and economical to manufacture.

Summary

[0007] This object is achieved with the features of the independent claims. Dependent claims refer to preferred aspects of the invention.

[0008] As discussed herein, the term "plasma" refers to an ionized gas comprising positive ions and free electrons. A plasma apparatus is understood to be an apparatus capable of producing plasma. The terms "plasma discharge" and "electrical discharge" may be used interchangeably.

[0009] The invention relates to a plasma discharge system comprising a voltage source, a conductive coil electrically connected to the voltage source and being configured to generate a magnetic field when an electric current is flowed therethrough, a first electrode structure electrically connected to the voltage source, and a second electrode structure positioned apart from the first electrode structure, the second electrode structure being electrically connected to the voltage source so as to create a potential difference between the first and second electrode structures such that at least one electrical dis-

charge occurs in between the first and the second electrode structures, wherein the conductive coil, the first electrode structure and the second electrode structure are positioned such that the magnetic field exerts a force on the electrical discharge, and wherein the conductive coil is electrically connected in series with the first and/or the second electrode structure. Preferably, the magnetic field exerts a force on the electrical discharge such that the discharge is set into motion, more preferably such that it rotates.

[0010] The conductive coil, as provided in the present invention is a type of electromagnet, commonly known as a solenoid. When current flows through the conductive coil, a magnetic field is generated in the vicinity of the conductive coil. This magnetic field can be used to propel the electrical discharge. Connecting the conductive coil electrically to the first and/or the second electrode structures allows for the conductive coil and the electrical discharge to then be connected in series.

[0011] The speed with which the electrical discharge is propelled by the magnetic field is dependent on the strength of the current in the electrical discharge and the strength of the magnetic field as generated by the current in the conductive coil. As these features are arranged in series, the current flowing through both the electrical discharge and the conductive coil is the same. Thus by increasing the current through the electrical circuit, the speed of migration of the electrical discharge is duly increased.

[0012] Preferably, the conductive coil has a coil resistance which limits the maximum current of the plasma discharge system. As the coil resistance tends to pose the greatest resistance in the series circuit, the coil resistance can be the dominant factor in determining current strength. The serial connection of the coil with the first and/or the second electrode structure thus provides a simple and economical manner of adjusting the current strength via the coil.

[0013] Preferably, the first electrode structure and/or the second electrode structure are positioned radially inside the conductive coil. Although a conductive coil creates a magnetic field both within the coil and outside of the coil, the greatest magnetic flux and the magnetic field lines closest to parallel can be present through the center of the coil. Such arrangement of the first electrode structure and/or the second electrode structure thus allows for an efficient use of the magnetic flux.

[0014] Preferably, the first electrode structure and/or the second electrode structure are centered about a longitudinal axis, with the first electrode structure extending at least partially around the second electrode structure. More preferably, the first electrode structure comprises a cylinder electrode centered about the longitudinal axis and/or the second electrode structure comprises a wire or pin electrode aligned along the longitudinal axis. More preferably the second electrode structure further comprises a cylinder electrode centered about the longitudinal axis and spaced apart from the first electrode struc-

ture. Such electrode shapes conform to the geometry of the conductive coil and may provide the greatest utilization of the magnetic field within the center of the conductive coil.

[0015] Preferably, the voltage source, the conductive coil, the first electrode structure, the electrical discharge, and the second electrode structure form a circuit. While this need not be the case, providing said elements within a single circuit can allow for the greatest degree of control over the current and may simplify the operation and construction of the plasma discharge apparatus. The conductive coil may be formed by using one or more wires having any type of cross section, e.g. round, square, oval or rectangular. Without wanting to be bound by theory, it is believed that a flat wire, wherein the flat wire has a width to height ratio greater than 1, more preferably with a width to height ratio greater than 5, and even more preferably with a width to height ratio greater than 9 may provide advantages in the context of the invention. Such wire may have, for example, a rectangular or oval cross section. The resistance of the conductive coil has an inverse relationship with the cross sectional area of the conductive wire forming the coil. Thus, by increasing the cross sectional area of the wires, lower resistance values for the conductive coil can be obtained.

[0016] The plasma discharge system can comprise low resistance conductive wires. Preferably, the low resistance conductive wires comprise copper and/or silver. Lowering resistance of the conductive wires aids in lowering the overall resistance of the conductive coil.

[0017] Preferably, the magnetic field has a magnetic field strength of at least 0.1 Tesla, at least 0.2 Tesla or at least 0.3 Tesla. More preferably, the magnetic field has a magnetic field strength of between 0.1 Tesla and 10 Tesla, more preferably between 0.2 Tesla and 2 Tesla, and even more preferably between 0.3 Tesla and 1.0 Tesla. Such magnetic field strength values may be sufficient to propel the electrical discharge with sufficient speed within the discharge area.

[0018] Preferably, the plasma discharge system further comprises a discharge gap between the first and second electrode structures. The discharge gap can comprise a gap resistance that depends at least in part on a width of the discharge gap and/or the potential difference. The gap resistance may be at least 1 kOhm, at least 10 kOhm or at least 15 kOhm. The gap resistance may be 100 kOhm or less, more preferably 50 kOhm or less and even more preferably 25 kOhm or less. Preferably, the gap resistance is between 1 kOhm and 100 kOhm. More preferably the gap resistance is between 10 kOhm and 50 kOhm. Even more preferably the gap resistance is between 15 kOhm and 25 kOhm. Said resistance values are determined by the gap width and the properties of the medium between the first and second electrode structures. Without wanting to be bound by theory, it is believed that said resistance values promote a sustainable electrical discharge with a high current. The plasma discharge system can further comprise a dis-

charge gap with a gap resistance between the first and second electrode structures. The gap resistance depends at least in part on a width of the discharge gap, the width may be 10 cm or less, preferably 8 cm or less, or more preferably 5 cm or less or 3 cm or less. Small gap widths reduce the resistance of the electrical discharge.

[0019] Preferably, the electrical discharge comprises a current greater than 20 mA, more preferably greater than 50 mA, and even more preferably greater than 100 mA. Said current values may be helpful for achieving the desired magnetic field strength within the conductive coil.

[0020] Preferably, the conductive coil has a resistance of at least 1 kOhm, at least 10 kOhm, or at least 15 kOhm. Preferably, the conductive coil has a resistance of 100 kOhm or less, more preferably 50 kOhm or less, and even more preferably 25 kOhm or less. For example, the conductive coil may have a resistance of between 1 kOhm and 100 kOhm, more preferably between 10 kOhm and 50 kOhm, and even more preferably between 15 kOhm and 25 kOhm. Resistance values within the conductive coil may be the dominant resistance present within the plasma discharge apparatus. Resistance values within these ranges can ensure that large enough current values are reached both within the electrical discharge and through the conductive coil.

[0021] The conductive coil may have a number of turns, wherein the magnetic field strength of the magnetic field and a coil resistance of the conductive coil partially depend on the number of turns. Reducing the number of turns may decrease resistance within the coil, but also may decrease the strength of the magnetic field within the conductive coil. Preferably, the coil comprises at least 1×10^4 turns, more preferably at least 1×10^5 turns, even more preferably at least 2×10^5 turns. Preferably, the coil comprises less than 1×10^7 turns, more preferably less than 1×10^6 turns, even more preferably less than 5×10^5 turns. The coil may have at least 1×10^5 turns/m, more preferably at least 1×10^6 turns/m, even more preferably at least 5×10^6 turns/m.

[0022] Preferably the voltage source is configured to supply a voltage of at least 1 kV, more preferably at least 2 kV, and even more preferably at least 4 kV. Said voltage (potential difference) values may be sufficient to drive a large enough current through the plasma discharge apparatus such that an electrical discharge is initiated and the magnetic field strength drives the electrical discharge at sufficient speed within the discharge area.

[0023] Preferably the plasma discharge system is suitable for operations at a temperature of 350 °C or higher, more preferably at a temperature of 900 °C or higher, and even more preferably at a temperature of 1500 °C or higher. A plasma discharge system suited for higher operation temperatures allows for contact with heated gases or exhaust without detriment to the plasma discharge system.

[0024] The coil may have an inner diameter of at least 2 cm, preferably at least 3 cm. Furthermore, the coil may

have an inner diameter of less than 30 cm, preferably less than 15 cm, more preferably less than 10 cm, even more preferably less than 7 cm.

[0025] The plasma discharge system may be configured to receive a flow of exhaust particles between the first and second electrode structures such that a portion of the exhaust particles is excited, disassociated, and/or ionized through contact with the electrical discharge. By contacting these particles with the electrical discharge (plasma discharge) the exhaust particles can be reduced to less harmful components and thereby rendered less environmentally damaging and/or toxic.

[0026] According to a second aspect the invention relates to a method for operating a plasma discharge system, wherein the method comprises at least the following steps: providing a voltage source, a conductive coil, a first electrode structure, and a second electrode structure; electrically connecting the voltage source to the conductive coil, the first electrode structure, and the second electrode structure, wherein the conductive coil is connected in series with the first and/or the second electrode structure; operating the voltage source to generate an electrical discharge between the first and the second electrode structures to induce a magnetic field around the conductive coil, wherein the magnetic field is oriented so as to exert a force on the electrical discharge. The plasma discharge system may comprise any of the features described for the plasma discharge system according to the first aspect of the invention above.

[0027] Preferably the method further comprises the steps of positioning the first and/or second electrode structure radially inside of the conductive coil.

[0028] Preferably the method further comprises the step of flowing exhaust particles between the first and second electrode structures such that a portion of the exhaust particles is excited, disassociated, and /or ionized through contact with the electrical discharge.

[0029] As optionally applicable to all aspects described herein, the voltage source may be configured to provide a pulsed electrical current. The pulsed electrical current may have a period between 10 and 1000 milliseconds, preferably between 100 and 500 milliseconds, and/or a period of at least 10 milliseconds, at least 50 milliseconds, or at least 100 milliseconds. Alternatively or additionally, the voltage source may provide a pulsed electrical current having a duty cycle of at most 0.7 or at most 0.5. For example, the duty cycle may be between 0.7 and 0.05, preferably between 0.5 and 0.1.

Brief Description of the Drawings

[0030] The invention will be explained in more detail in the following text with reference to preferred exemplary embodiments which are illustrated in the appended drawings, in which:

Fig. 1 schematically shows a perspective view of a configuration of a plasma discharge system;

Fig. 2 schematically shows a cross-section of the plasma discharge system of Fig. 1.

Detailed Description

[0031] Fig. 1 depicts a plasma discharge system 100 according to the present invention. The plasma discharge system 100 includes a voltage source 110, a conductive coil 120, a first electrode structure 130, and a second electrode structure 140.

[0032] The voltage source 110, may be any type of voltage source, such as a battery or an electrical outlet. The voltage source 110 may comprise further electrical components (not shown), for example components to regulate the voltage and/or current output by the voltage source 110. The voltage source 110 drives a current through the system 100 and is electrically connected with the conductive coil 120, the first electrode structure 130, and the second electrode structure 140. Specifically, the conductive coil 120 is connected in series with the first and/or second electrode structures 130, 140.

[0033] One example of this system 100 is illustrated in Fig. 1, wherein the direction of flow of the current originating at the voltage source 110 is indicated by the white arrows. The current may first flow into the first end 122 of the conductive coil 120. The current travels the length of the coil 120 and then emerges from the second end 124 of the conductive coil 120, the current may then flow into the first electrode structure 130 which is placed radially within the conductive coil 120. With a great enough voltage supplied by the voltage source 110, the potential difference between the first electrode structure 130 and the second electrode structure 140 is great enough to overcome the resistance of the medium in between. Thus, the medium between the first and second electrode structures 130, 140 experiences dielectric breakdown and an electrical discharge 135 bridges the gap between the first electrode structure 130 and the second electrode structure 140. After passing through the second electrode structure 140, the electrical current travels along the electrical connection back to the voltage source 110, thereby forming a closed current loop. In this way the voltage source 110, the conductive coil 120, the first electrode structure 130, and the second electrode structure 140 may form a circuit. Naturally, the direction of the current may also be reversed and still achieve the same functioning principles. Moreover, the skilled person will recognize that the invention is not limited to this particular serial connection, but the order of the above-mentioned elements in the circuit may be changed.

[0034] The coil 120 is electrically conductive and can also be referred to as a solenoid. The conductive coil 120 defines a longitudinal axis A of the plasma discharge system 100 through the center of the coil 120. Due to the shape, the conductive coil 120 creates a magnetic field 125 extending around the coil 120 and through the center of the coil 120 when an electrical current is flowed there-through. The magnetic field 125 may be substantially par-

allel to the longitudinal axis A in the center of the coil 120 and is directional. For example, if the electrical current flows from the first end 122 to the second end 124 of the conductive coil 120 in a counterclockwise direction (when viewed from the first end 122 side), then the magnetic north pole of the magnetic field 125 would be proximal to the first end 122 of the conductive coil 120. If the conductive coil 120 were wound in a clockwise direction (when viewed from the first end 122 side), then the magnetic north pole N would be on the second end side 124. If the direction of the electrical current were reversed, the magnetic poles of the magnetic field 125 would be similarly reversed.

[0035] Inherently, the conductive coil 120 has an electrical resistance. This coil resistance may, in many cases, be the greatest resistance within the plasma discharge system 100. As such, the coil resistance may operate as a type of regulator of the maximum current flowing through the plasma discharge system 100. The coil resistance may be within the range of 1 kOhm and 100 kOhm, preferably between 10 kOhm and 50 kOhm, and more preferably between 15 kOhm and 25 kOhm. The conductive coil 120 comprises a number of turns N. Generally, the strength of the magnetic field 125 and the coil resistance are dependent on the number of turns N.

[0036] The first electrode structure 130 and the second electrode structure 140 may be placed anywhere within the magnetic field 125, however, they are preferably provided in an area of the magnetic field wherein the magnetic field lines are substantially parallel, which may be proximate the outer surface of the coil 120 or more preferably within the coil 120.

[0037] The first electrode structure 130 may be elongated parallel to the longitudinal axis A of the conductive coil 120. Fig. 1 illustrates one example configuration of the first and second electrode structures 130, 140. In this configuration the first electrode structure 130 may be a hollow conductive cylinder or ring positioned within at least a portion of the conductive coil 120. It may be advantageous in some circumstances to center the first electrode structure 130 longitudinally within the conductive coil 120 without extending all of the way to the first end 122 or the second end 124 of the coil 120. In this way, edge effects of the magnetic field 125 may affect the first electrode structure 130 less.

[0038] The second electrode structure 140 may be a pin electrode elongated parallel to the longitudinal axis A of the conductive coil. The second electrode structure 140 may also be a cylinder electrode, but preferably with a smaller radius than the first electrode structure 130. For example, the second electrode 140 may be a hollow cylinder, similar to the first electrode structure 130, or it may be a solid cylinder electrode.

[0039] Preferably, the second electrode structure 140 is positioned radially inside of the first electrode structure 130, preferably aligned along the longitudinal axis A.

[0040] Fig. 2 shows a schematic cross-section of one configuration of the plasma discharge system 100. The

conductive coil 120 is centered about the longitudinal axis A and may be positioned radially outside of the first and second electrode structures 130, 140. The magnetic field 125 generated by the conductive coil 120 may be substantially parallel to the longitudinal axis A in the longitudinal center of the conductive coil 120, and, as shown in Fig. 2, may extend into the page. The first electrode structure 130 is preferably positioned radially inside of the conductive coil 120 and, more preferably, centered about the longitudinal axis A. Preferably, electrical insulation is provided in the space between the conductive coil 120 and the first electrodes structure 130.

[0041] The second electrode structure 140 is preferably positioned radially inside of the first electrode structure 130 and may be aligned along the longitudinal axis A. As shown in Fig. 2, during operation of the plasma discharge system 100 an electrical discharge 135 is initiated between the first electrode structure 130 and the second electrode structure 140. It may also be possible or even preferable to have more than one electrical discharge 135 operating simultaneously between the first electrode structure 130 and the second electrode structure 140. As the electrical discharge 135 is positioned within the magnetic field 125 and the magnetic field lines form an angle with regards to the electrical discharge 135, i.e. the magnetic field lines and the electrical discharge 135 are not parallel, the magnetic field 125 exerts a Lorentz force on the electrical discharge 135. Said Lorentz force is oriented in a direction perpendicular to the magnetic field 125 and roughly perpendicular to the electrical discharge 135, consequently setting the electrical discharge 135 into motion within the space between the first electrode structure 130 and the second electrode structure 140. In the example depicted in Fig. 2, the electrical discharge 135 will migrate around the longitudinal axis A either in a clockwise direction or counter-clockwise direction depending on the orientation of the magnetic field 125, as indicated by the white arrow. More specifically, the electrical discharge 135 will rotate.

[0042] In the configuration depicted in Fig. 2, the one or more electrical discharges 135 will travel clockwise around the longitudinal axis A of the plasma discharge system 100. The area between the first electrode structure 130 and the second electrode structure 140 through which the electrical discharge 135 repeatedly passes can be referred to as the discharge area. The electrical discharge 135 may also be referred to as a plasma discharge. Thus, if the electrical discharge 135 passes repeatedly through the discharge area, then the electrical discharge 135 can be thought of as creating a plasma layer within the conductive coil 120.

[0043] The distance between the first electrode structure 130 and the second electrode structure 140 is referred to herein as a discharge gap G. Among other factors, the size of the discharge gap G affects the amount of resistance posed by the material between the first electrode structure 130 and the second electrode structure 140. Consequently, it is preferred that the gap distance

G is 5 cm or less, more preferably that the gap distance is 4 cm or less, and even more preferably that the gap distance is 3 cm or less. Reducing the gap distance G reduces the resistance experienced by the electrical discharge 135, but may also effectively reduce the discharge area and the area of the plasma layer. Accordingly it is also preferred that the gap resistance be between 1 kOhm and 100 kOhm, more preferably between 10 kOhm and 50 kOhm, and even more preferably between 15 kOhm and 25 kOhm, wherein said gap resistance is determined by the medium in between the first and second electrode structures 130, 140 as well as the gap distance G. Through tuning of the gap resistance and the potential difference supplied by the voltage source 110, it is preferable to form an electrical discharge 135 which comprises a current greater than 20 mA, more preferably a current greater than 50 mA, and even more preferably greater than 100 mA.

[0044] While it is clear that the exact voltage and/or current provided by the voltage source may be determined by the requirements of the system, generally, the voltage source may be configured to provide a voltage of at least 1 kV, preferably at least 2 kV, more preferably at least 4 kV. Said potential difference may be sufficient to overcome the gap resistance. In some configurations the voltage source may be configured to provide a pulsed or intermittent potential difference. In some circumstances the plasma discharge may continue to provide an ionizing/dissociating effect within the discharge region for a time after being terminated. Thus, this plasma "afterglow" can potentially be utilized to reduce overall power requirements of the plasma apparatus and the temperature of gases flowing through the plasma apparatus could potentially be lowered. The voltage source may then be configured to provide a pulsed electrical current having a period between 10 and 1000 milliseconds, or preferably between 100 and 500 milliseconds. The voltage source may also be configured to provide a pulsed electrical current having a duty cycle between 0.7 and 0.05, preferably between 0.5 and 0.1.

[0045] Particles or molecules which pass through the plasma layer can become excited, disassociated, and/or ionized, which can be thought of as a type of purifying effect, rendering the molecules into smaller particles or alternative configurations which are less damaging to humans or the environment. Thus, the plasma discharge system 100 can be configured to allow for a flow of gas containing unwanted particles therethrough, such that the particles pass through the plasma layer. In this manner the conductive coil 120 and/or the first electrode structure 130 may act as a type of tube or passageway through which the flow of particles can be guided. The passageway may have an outer diameter of at least 2 cm, preferably at least 3 cm and/or less than 30 cm, preferably less than 15 cm.

[0046] In some configurations the unwanted particles may be the result of combustion processes. In such an instance, the gas passing through the plasma discharge

system 100 may be at high temperatures due to the combustion process. Thus, the plasma discharge system 100 may be suitable for operating at temperatures of 350 °C or higher, preferably 900 °C or higher, or more preferably at a temperature of 1500 °C or higher. Suitability for use at said temperatures may be influenced by the type of materials used including the material specifically used for the conductive coil 120.

[0047] In order to better understand the configuration of the plasma discharge system 100 as described herein, an analytical consideration of the plasma discharge system 100 is also provided herewith, without wanting to be bound by theory.

[0048] The plasma discharge system 100 preferably produces a plasma layer created by the repeated passage of the electrical discharge 135. In order to increase the speed of progression of the electrical discharge 135, the magnitude of the Lorentz force may be controlled, the Lorentz force per unit length is given by:

$$F = I_D \times B$$

where I_D is the current in Ampere through the electrical discharge and B is the strength of the magnetic field in Tesla. Further, the magnetic field produced by a conductive coil can be derived from the equation:

$$B = \mu_0 N I_C / \ell$$

where I_C is the current running through the conductive coil in Ampere, μ_0 is the permeability of free space, N is the number of turns, and ℓ is the longitudinal length of the conductive coil in meters.

[0049] When connected in series, this results in $I_D = I_C = I$. Thus the magnitude of the Lorentz force depends on the strength of the current flowing through the circuit:

$$F = \mu_0 N I^2 / \ell.$$

[0050] If a voltage source supplies a pre-determined potential difference to the circuit, then according to Ohm's law, only the total resistance of the circuit determines the strength of the current. To increase the strength of the current, the resistance of the total circuit must consequently be reduced. As discussed previously, the resistance of the circuit depends primarily upon the resistance of the conductive coil, wherein the resistance R of the conductive coil in Ohms can be described with the following equation:

$$R = \rho \ell_w / a$$

where ρ is the resistivity of the wire in ohm-meter, a is the cross sectional area of the wire in m^2 , ℓ_w is the total

length of the wire in meters. Preferably, the conductive coil 120 has a resistance of between 1 kOhm and 100 kOhm, more preferably between 10 kOhm and 50 kOhm, and even more preferably between 15 kOhm and 25 kOhm.

[0051] When considering the conductive coil 120, the magnetic induction of a solenoid is defined as

$$L = \mu_0 N^2 A / \ell$$

where L is inductance measured in Henries, μ_0 is the permeability of free space, N is the number of turns, A is the discharge area in m^2 , and ℓ is the longitudinal length of the conductive coil.

[0052] Preferably, the coil 120 is configured to supply a magnetic field 125 comprising a magnetic field strength of between 0.1 Tesla and 10 Tesla, more preferably between 0.2 Tesla and 2.0 Tesla, and even more preferably between 0.3 Tesla and 1.0 Tesla.

[0053] Given the above considerations, if a field strength of 1 Tesla is desired in air ($\mu_0 = 4\pi \times 10^{-7}$) with a current of 0.1 A, then a total of $n = 7.96 \times 10^6$ turns/m is required. For a conductive coil 120 with a longitudinal length of $\ell = 3$ cm, this would then require a total of $N = n\ell = 2.39 \times 10^5$ turns. The number of layers N_L of a conductive coil is typically $N_L = Nd/\ell$, where d is the wire diameter.

[0054] One advantageous configuration of the conductive coil 120 is to form the conductive coil 120 using flat wires, i.e. wires which do not have a circular cross-section, but instead have a certain width to height ratio. This width/height ratio is preferably greater than 1, more preferably greater than 5, and even more preferably greater than 9. Such a flat wire may provide a increased cross-sectional wire area while avoiding or reducing an increase in the mean winding radius of the coil. Another way to lower the resistance of the conductive coil 120 is by using a low resistance material. One possible low resistance material is silver, which has a resistivity of $\rho \sim 1.55 \times 10^{-8}$ ohm-meters.

[0055] One preferred configuration of the plasma discharge system 100 is to provide a magnetic field in the range of 0.1 to 0.5 Tesla, more preferably 0.2 to 0.4 Tesla. Given the above equations, this would yield a resistance of around 23.6 kOhm.

[0056] When the plasma discharge apparatus 100 as described herein is operated, the method includes providing a voltage source 110, a conductive coil 120, a first electrode structure 130, and a second electrode structure 140. The voltage source would be connected to the conductive coil 120, the first electrode structure 130, and the second electrode structure 140, while connecting them in a way so that conductive coil is arranged in series with the first and/or second electrode structure. After connections have been provided, the voltage source 110 can be operated to generate an electrical discharge 135 and to simultaneously induce a magnetic field proximate the

conductive coil 120. The magnetic field 125 will then exert forces on the electrical discharge 135. During the method for operating the plasma discharge system 100 it may be preferable to position the first and/or second electrode radially inside the conductive coil 120. Preferably, the first and/or second electrodes are positioned within the magnetic field 125 created by the conductive coil 120, in a location where the magnetic field lines are substantially parallel. After initiating the plasma discharge apparatus 100 particles may then be flowed through the apparatus 100 in the discharge region in between the first electrode structure 130 and the second electrode structure 140. Said particles, upon passing through the plasma layer, may become excited, disassociated and/or ionized.

[0057] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and non-restrictive; the invention is thus not limited to the disclosed embodiments. Variations to the disclosed embodiments can be understood and effected by those skilled in the art and practicing the described invention, from a study of the drawings, the disclosure, and the appended claims. In the aspects and claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality and may mean "at least one".

[0058] The following are preferred aspects of the invention:

1. A plasma discharge system, the system comprising:

a voltage source;

a conductive coil electrically connected to the voltage source, the conductive coil being configured to generate a magnetic field when an electric current is flowed therethrough;

a first electrode structure electrically connected to the voltage source;

a second electrode structure positioned apart from the first electrode structure, the second electrode structure being electrically connected to the voltage source so as to create a potential difference between the first and second electrode structures such that at least one electrical discharge occurs in between the first and the second electrode structures;

wherein the conductive coil, the first electrode structure and the second electrode structure are positioned such that the magnetic field exerts a force on the electrical discharge, and wherein the conductive coil is electrically connected in series with the first and/or the second electrode structures.

2. The plasma discharge system of aspect 1, wherein the conductive coil has a coil resistance, the coil resistance limiting a maximum current of the plasma discharge system.

3. The plasma discharge system of aspect 1 or aspect 2, wherein the first electrode structure and/or the second electrode structure are positioned radially inside the conductive coil.

4. The plasma discharge system of any one of the previous aspects, wherein the first electrode structure comprises a cylinder electrode centered about a longitudinal axis and the second electrode structure comprises a wire or pin electrode aligned along the longitudinal axis, preferably wherein the second electrode structure further comprises a cylinder electrode centered about the longitudinal axis and spaced apart from the first electrode structure.

5. The plasma discharge system of any one of the previous aspects, wherein the voltage source, the conductive coil, the first electrode structure, the electrical discharge, and the second electrode structure form a circuit.

6. The plasma discharge system of any one of the previous aspects, wherein the conductive coil is comprised of flat wire, wherein the flat wire has a width to height ratio greater than 1, preferably with a width to height ratio greater than 5, and more preferably with a width to height ratio greater than 9.

7. The plasma discharge system of any one of the previous aspects, wherein the plasma discharge system comprises low resistance conductive wires, preferably wherein the low resistance conductive wires comprise copper and/or silver.

8. The plasma discharge system of any one of the previous aspects, wherein the magnetic field has a magnetic field strength of between 0.1 Tesla and 10 Tesla, preferably between 0.2 Tesla and 2 Tesla, more preferably between 0.3 Tesla and 1.0 Tesla.

9. The plasma discharge system of any one of the previous aspects, the plasma discharge system further comprising a discharge gap between the first and second electrode structures, wherein the discharge gap comprises a gap resistance that depends at least in part on a width of the discharge gap and/or the potential difference, the gap resistance being between 1 kOhm and 100 kOhm, preferably between 10 kOhm and 50 kOhm, more preferably between 15 kOhm and 25 kOhm.

10. The plasma discharge system of any one of the previous aspects, the plasma discharge system fur-

ther comprising a discharge gap with a gap resistance between the first and second electrode structures, wherein the gap resistance depends at least in part on a width of the discharge gap, wherein the gap width is 10 cm or less, preferably wherein the gap width is 8 cm or less, preferably wherein the gap width is 5 cm or less.

11. The plasma discharge system of any one of the previous aspects, wherein the electrical discharge comprises a current greater than 20 mA, preferably greater than 50 mA, and more preferably greater than 100 mA.

12. The plasma discharge system of any one of the previous aspects, wherein the conductive coil has a resistance of between 1 kOhm and 100 kOhm, preferably between 10 kOhm and 50 kOhm, more preferably between 15 kOhm and 25 kOhm.

13. The plasma discharge system of any one of the previous aspects, wherein the conductive coil has a number of turns, wherein a magnetic field strength of the magnetic field and a coil resistance of the conductive coil partially depend on the number of turns.

14. The plasma discharge system of any one of the previous aspects, wherein the voltage source is configured to supply a voltage of at least 1 kV, preferably at least 2 kV, more preferably at least 4 kV.

15. The plasma discharge system of any one of the previous aspects, wherein the voltage source is configured to provide a pulsed electrical current, wherein the pulsed electrical current preferably has

a period between 10 and 1000 milliseconds, preferably between 100 and 500 milliseconds; and/or

a period of at least 10 milliseconds, at least 50 milliseconds, or at least 100 milliseconds.

16. The plasma discharge system of any of the previous aspects, wherein the voltage source is configured to provide a pulsed electrical current having a duty cycle of:

between 0.7 and 0.05, preferably between 0.5 and 0.1; or

at most 0.7 or at most 0.5.

17. The plasma discharge system of any one of the previous aspects, wherein the plasma discharge system is suitable for operations at a temperature of 350° C or higher, preferably at a temperature of 900° C or higher, and more preferably at a temperature of 1500° C or higher.

18. The plasma discharge system of any one of the previous aspects, wherein the plasma discharge system is configured to receive a flow of exhaust particles between the first and second electrode structures such that a portion of the exhaust particles is excited, disassociated, and/or ionized through contact with the electrical discharge.

19. Method for operating a plasma discharge system, wherein the method comprising at least the following steps:

providing a voltage source, a conductive coil, a first electrode structure, and a second electrode structure;

electrically connecting the voltage source to the conductive coil, the first electrode structure, and the second electrode structure, wherein the conductive coil is connected in series with the first and/or the second electrode structure;

operating the voltage source to generate an electrical discharge between the first and second electrode structures and to induce a magnetic field around the conductive coil, wherein the magnetic field is oriented so as to exert a force on the electrical discharge.

20. Method for operating a plasma discharge system according to aspect 19, the method further comprising the step of positioning the first and/or second electrode structure radially inside the conductive coil.

21. Method for operating a plasma discharge system according to aspect 19 or aspect 20, the method further comprising the step of flowing exhaust particles between the first and second electrode structures such that a portion of the exhaust particles is excited, disassociated, and/or ionized through contact with the electrical discharge.

Claims

1. A plasma discharge system, the system comprising:

a voltage source;
a conductive coil electrically connected to the voltage source, the conductive coil being configured to generate a magnetic field when an electric current is flowed therethrough;
a first electrode structure electrically connected to the voltage source;
a second electrode structure positioned apart from the first electrode structure, the second electrode structure being electrically connected

to the voltage source so as to create a potential difference between the first and second electrode structures such that at least one electrical discharge occurs in between the first and the second electrode structures;

wherein the conductive coil, the first electrode structure and the second electrode structure are positioned such that the magnetic field exerts a force on the electrical discharge, and wherein the conductive coil is electrically connected in series with the first and/or the second electrode structures.

2. The plasma discharge system of claim 1, wherein the conductive coil has a coil resistance, the coil resistance limiting a maximum current of the plasma discharge system.

3. The plasma discharge system of claim 1 or claim 2, wherein the first electrode structure and/or the second electrode structure are positioned radially inside the conductive coil.

4. The plasma discharge system of any one of the previous claims, wherein the first electrode structure comprises a cylinder electrode centered about a longitudinal axis and the second electrode structure comprises a wire or pin electrode aligned along the longitudinal axis, preferably wherein the second electrode structure further comprises a cylinder electrode centered about the longitudinal axis and spaced apart from the first electrode structure.

5. The plasma discharge system of any one of the previous claims, wherein the voltage source, the conductive coil, the first electrode structure, the electrical discharge, and the second electrode structure form a circuit.

6. The plasma discharge system of any one of the previous claims, wherein the conductive coil is comprised of flat wire, wherein the flat wire has a width to height ratio greater than 1, preferably with a width to height ratio greater than 5, and more preferably with a width to height ratio greater than 9.

7. The plasma discharge system of any one of the previous claims, wherein the plasma discharge system comprises low resistance conductive wires, preferably wherein the low resistance conductive wires comprise copper and/or silver.

8. The plasma discharge system of any one of the previous claims, wherein the magnetic field has a magnetic field strength of between 0.1 Tesla and 10 Tesla, preferably between 0.2 Tesla and 2 Tesla, more preferably between 0.3 Tesla and 1.0 Tesla.

9. The plasma discharge system of any one of the previous claims, the plasma discharge system further comprising a discharge gap with a gap resistance between the first and second electrode structures, wherein the gap resistance depends at least in part on a width of the discharge gap, wherein the gap width is 10 cm or less, preferably wherein the gap width is 8 cm or less, preferably wherein the gap width is 5 cm or less. 5
10. The plasma discharge system of any one of the previous claims, wherein the electrical discharge comprises a current greater than 20 mA, preferably greater than 50 mA, and more preferably greater than 100 mA. 10 15
11. The plasma discharge system of any one of the previous claims, wherein the conductive coil has a resistance of between 1 kOhm and 100 kOhm, preferably between 10 kOhm and 50 kOhm, more preferably between 15 kOhm and 25 kOhm. 20
12. The plasma discharge system of any one of the previous claims, wherein the voltage source is configured to supply a voltage of at least 1 kV, preferably at least 2 kV, more preferably at least 4 kV; and/or wherein the voltage source is configured to provide a pulsed electrical current having a period between 10 and 1000 milliseconds, preferably between 100 and 500 milliseconds with a duty cycle between 0.7 and 0.05, preferably between 0.5 and 0.1. 25 30
13. The plasma discharge system of any one of the previous claims, wherein the plasma discharge system is suitable for operations at a temperature of 350° C or higher, preferably at a temperature of 900° C or higher, and more preferably at a temperature of 1500° C or higher. 35
14. The plasma discharge system of any one of the previous claims, wherein the plasma discharge system is configured to receive a flow of exhaust particles between the first and second electrode structures such that a portion of the exhaust particles is excited, disassociated, and/or ionized through contact with the electrical discharge. 40 45
15. Method for operating a plasma discharge system, wherein the method comprising at least the following steps: 50
- providing a voltage source, a conductive coil, a first electrode structure, and a second electrode structure;
- electrically connecting the voltage source to the conductive coil, the first electrode structure, and the second electrode structure, wherein the conductive coil is connected in series with the first 55

and/or the second electrode structure; operating the voltage source to generate an electrical discharge between the first and second electrode structures and to induce a magnetic field around the conductive coil, wherein the magnetic field is oriented so as to exert a force on the electrical discharge.

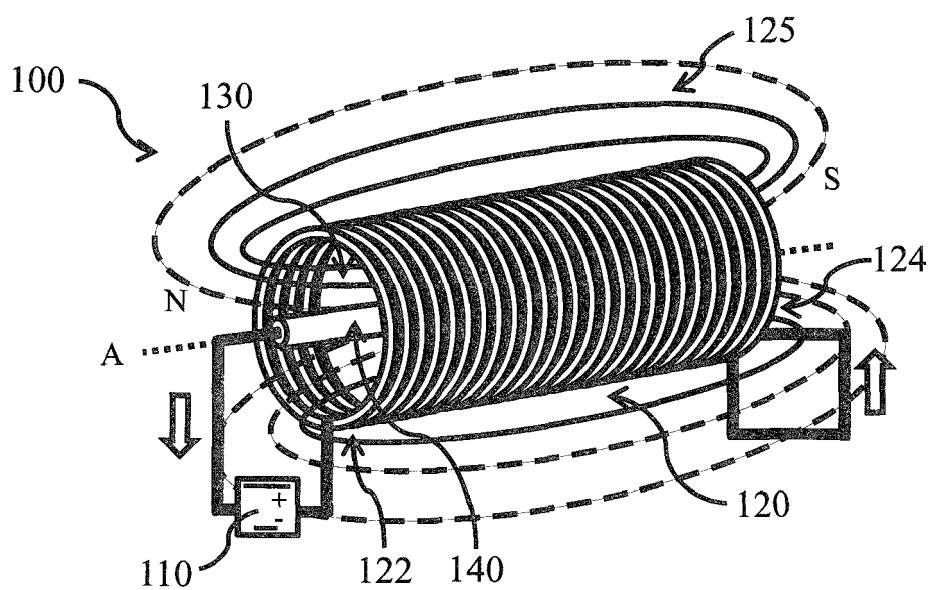


Fig. 1

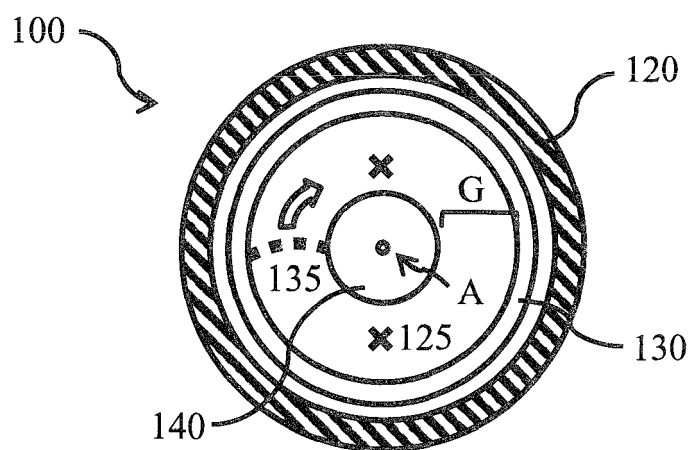


Fig. 2



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