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

(57) The present invention relates to a plasma discharge apparatus comprising a first electrode structure comprising a plurality of trigger points; a second electrode structure; and a voltage source connected to the first and/or second electrode structures, the voltage source being configured to create a potential difference between the first and second electrode structures such that at least one electrical discharge occurs in a discharge region, wherein each electrical discharge has a discharge path with a first end contacting the first electrode structure and a second end contacting the second electrode structure. The apparatus further comprises a means for exerting force on the at least one electrical discharge, the means being configured to compel the first end of the discharge path to move along the first electrode structure. Each trigger point is a portion of the first electrode structure which has a smaller gap distance to the second electrode structure than adjacent portions of the first electrode structure, such that the at least one electrical discharge is initiated at one of the plurality of trigger points.

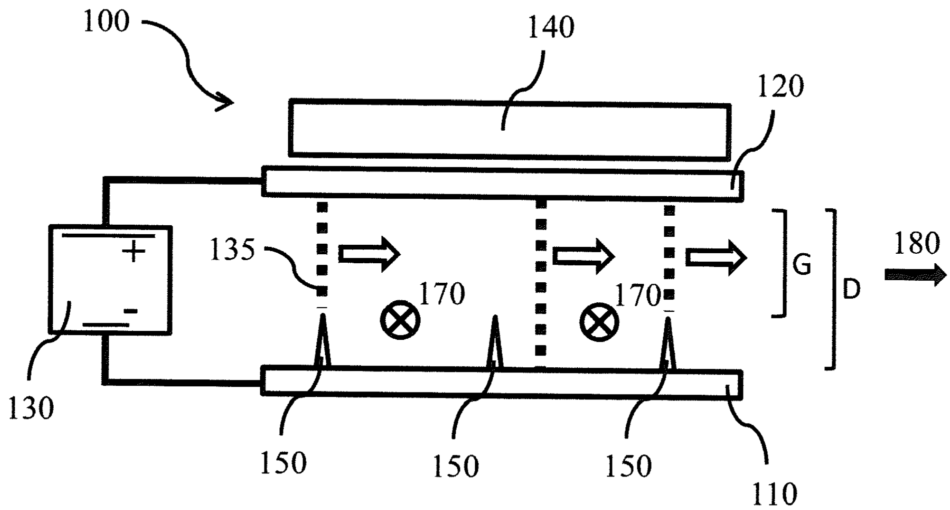

Fig. 1

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Description

Background

[0001] The invention relates to a plasma discharge apparatus, a system or vehicle comprising such apparatus and method for using the apparatus. Specifically, the invention relates to a plasma discharge apparatus comprising an electrode with a trigger.

[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. If said electrical discharge is set into motion with enough speed a "plasma layer" may be created, being an area through which the electrical discharge repeatedly passes.

[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] In such plasma discharge operations the shape and the structure of the plasma layer and the discharge area may be of heightened importance.

[0005] It is an object of the present invention to provide a plasma discharge apparatus which is particularly suited for creating a plasma layer.

Summary

[0006] This object is achieved with the features of the independent claims. Dependent claims refer to preferred aspects of the invention.

[0007] As discussed herein, the term "plasma" refers to an ionized gas consisting of positive ions and free electrons. A plasma apparatus is understood to be an apparatus capable of producing plasma. The terms "plasma discharge", "glow discharge" and "electrical discharge" may be used interchangeably.

[0008] As presented herein the terms "trigger", "trigger point" and "trigger portion" are used interchangeably. A trigger is a portion of an electrode which exhibits the greatest probability of initiating an electrical discharge.

[0009] According to a first aspect, the invention relates to a plasma discharge apparatus comprising a first electrode structure comprising a plurality of trigger points; a second electrode structure; a voltage source connected to the first and/or second electrode structures, the voltage source being configured to create a potential difference between the first and second electrode structures such that at least one electrical discharge occurs in a discharge region between the first and second electrode structures, wherein each electrical discharge has a discharge path with a first end contacting the first electrode structure and a second end contacting the second electrode structure; a means for exerting force on the at least one electrical discharge, the means for exerting force being configured to compel at least the first end of the discharge path to move along the first electrode structure; preferably wherein each trigger point is a portion of the first electrode structure which has a smaller gap distance to the second electrode structure than adjacent portions of the first electrode structure, such that the at least one electrical discharge is initiated between the first and second electrode structures at one of the multiple trigger points. The means for exerting force may be configured to compel the second end of the discharge path to move along the second electrode structure. The electrical discharge path preferably is compelled to rotate through at least a portion of the discharge region.

[0010] Preferably each trigger point is a portion of the first electrode structure which has a smallest gap distance to the second electrode structure. The breakdown potential in a non-ionized (neutral) gas increases with distance between the electrodes, i.e. gap distance. To initiate a discharge at a given voltage difference across the gap, the gap distance must be sufficiently small. Once discharge has been achieved and the gas has become partially ionized, the operating voltage for maintaining a glow discharge is significantly lower. The gap distance is configured such that the applied voltage difference is sufficient to effect breakdown across the small gap distance, the same voltage is also sufficient to maintain the electrical discharge across the larger gap between the two electrodes once ionization has been initiated with the initial breakdown. As the resistance of an arc discharge increases with greater gap distance, the electrical discharge is then most likely to form at the trigger point. Depending on the dimensions and design of the plasma discharge apparatus, the first electrode structure may comprise 2, 3, 4, 5, 6 or more trigger points. Preferably, not more than 20 or not more than 10 trigger points are used.

[0011] Preferably the first and/or second electrode structures are rotationally symmetric about a longitudinal axis. Such a configuration may be beneficial for providing the plasma discharge apparatus within a tube or other cylindrical holder. The plasma discharge apparatus preferably forms a duct configured for flowing a gas therethrough, more preferably a cylindrical duct.

[0012] Preferably the discharge region is located radially between the first and second electrode structures. More preferably, the second electrode structure extends around the first electrode structure. As such, the first electrode structure may form an inner electrode while the second electrode structure forms an outer electrode. The second electrode structure may be formed as a unitary or segmented ring electrode.

[0013] Preferably the first electrode structure comprises a plurality of arms, wherein the arms may comprise a first end connected to a base and a second end providing a respective trigger point. Providing a plurality of arms and a plurality of trigger points may allow for simultaneous initiation of plural electrical discharges. The base can provide an electrical connection between each of the triggers such that the potential difference between each trigger and the second electrode structure is the same. The arms may also be referred to as protrusions in the context of the present disclosure.

[0014] Preferably a distance between each arm and the second electrode structure increases along the arm, in particular when following the arm from the trigger point towards the base. Preferably the distance increases gradually along the arm. This configuration may provide a smoother transition of the electrical discharge away from the trigger point and ensure that the electrical discharge is less likely to terminate immediately upon leaving the trigger point.

[0015] More preferably, the distance between each arm of the first electrode and the second electrode increases in the direction in which the first end of the discharge path is compelled to move along the first electrode structure. For this purpose, each arm may extend in the direction of movement and towards the base when following the arm in said direction of movement.

[0016] Preferably the first electrode structure has a pinwheel configuration. Alternatively or additionally, the arms of the first electrode structure may curve away from the base, preferably wherein the arms have a spiral configuration. Spiral and pinwheel configurations allow for smooth migration of the electrical discharge.

[0017] At least a first side of each arm facing in the direction in which the discharge moves may be curved, e.g., convex or concave.

[0018] Preferably the arms of the first electrode structure curve away from the base in a direction opposite to the direction in which the first end of the discharge path is compelled to move along the first electrode structure.

[0019] Preferably the arms extend around the base over an angle, preferably as measured from a center of the base (in particular from the longitudinal axis) of at least 5°, at least 10°, at least 20°, or at least 30°. The more gradual the increase in distance away from the trigger point, the lesser the probability that the electrical discharge will spontaneously terminate.

[0020] Preferably the arms extend around the base over an angle, preferably as measured from a center of the base (in particular from the longitudinal axis) of 50° or less, 40° or less, 30° or less, or 20° or less. Electrode arms which extend over too much of the discharge region can impede one another and develop a less even distribution of electrical discharges.

[0021] Preferably the potential difference provided by the voltage source is within the range of 1 kV to 10 kV, more preferably from 2 kV to 8 kV, even more preferably from 3 kV to 7 kV.

[0022] Preferably the potential difference and/or current provided by the voltage source is configured to be constant during operation.

[0023] Preferably the gap distance between each of the trigger points and the second electrode structure is a predetermined constant distance. Providing each trigger point with the same gap distance promotes that electrical discharges form at each of the trigger points with the same frequency.

[0024] Preferably the gap distance at each of the trigger points satisfies the following: $G < U$, wherein G is the gap distance measured in millimeter and U is the potential difference between the first and second electrode structures measured in kilovolt. This relationship between the gap distance and the potential difference aids in creating a configuration wherein the dielectric resistance of the medium between electrodes is reliably overcome during operation.

[0025] Preferably the means for exerting force is a magnetic field generator, wherein the magnetic field generator creates a magnetic field having a magnetic field vector within the discharge region, the magnetic field vector having a component perpendicular to the electrical discharge path, preferably wherein the main component of the magnetic field vector is perpendicular to the electrical discharge path. A magnetic field can exert forces on electrical currents through the Lorentz force.

[0026] Preferably the plasma discharge apparatus is configured to accommodate a flow of gaseous particles through the discharge region, such that at least a portion of the gaseous particles are excited, dissociated and/or ionized. For this purpose, the plasma apparatus may form a duct, preferably of cylindrical or toroidal shape. The duct may provide a lumen through which the gaseous particles flow, wherein the lumen may have an outer diameter of at least 2 cm, preferably at least 3 cm and/or less than 5 cm, preferably less than 4 cm.

[0027] According to a second aspect the invention relates to a plasma discharge apparatus comprising a first electrode structure; a second electrode structure; a voltage source connected to the first and/or second electrode structures, the voltage source being configured to create a potential difference between the first and second electrode structures such that at least one electrical discharge occurs in a discharge region between the first and second electrode structures, wherein each electrical discharge has a discharge path with a first end contacting the first electrode structure and a second end contacting the second electrode structure; a means for exerting force on the at least one electrical discharge, the means for exerting force being configured to compel the discharge path to rotate within the discharge region; wherein at least one trigger portion of the first electrode structure has a smaller gap distance to the second electrode structure than adjacent portions of the first electrode structure such that the electrical discharge is initiated between the first and second electrode structures at the trigger portion, and wherein a gap distance between the first electrode structure and the second electrode structure gradually increases in the direction of rotation. The first electrode structure may comprise a plurality of such trigger portions. As such, the preferred configurations described for the first aspect above are equally applicable to this second aspect of the invention.

[0028] Preferably the first and second electrode structures are centered about a longitudinal axis. More specifically, the first and/or second electrode structures may be rotationally symmetric about the longitudinal axis.

[0029] Preferably the discharge region is located radially between the first and second electrode structures. More preferably, the second electrode structure extends around the first electrode structure. As such, the first electrode structure may form an inner electrode while the second electrode structure forms an outer electrode. The second electrode structure may be formed as a unitary or segmented ring electrode.

[0030] Preferably the first electrode structure comprises a base and one or more arms, wherein the at least one arm comprises a first end connected to the base and a second end providing the trigger portion, preferably wherein the gap distance between the first electrode structure and the second electrode structure is smallest at the trigger portion. The one or more arm(s) may also be referred to as one or more protrusion(s).

[0031] Preferably a minimum distance between the at least one arm and the second electrode structure increases along the arm. Alternatively or additionally, the at least one arm may curve away from the base, preferably wherein the arm has a spiral configuration, more preferably wherein the arm extends from the base following a spiral.

[0032] Preferably the at least one arm curves away from the base in a direction opposite to the direction of rotation of the discharge path.

[0033] Preferably the at least one arm extends around the base over an angle of at least 5°, at least 10°, at least 20°, or at least 30°, preferably as measured from a center of the base (in particular from the longitudinal axis).

[0034] Preferably the at least one arm extends around the base over an angle of 50° or less, 40° or less, 30° or less, or 20° or less °, preferably as measured from a center of the base (in particular from the longitudinal axis).

[0035] The first electrode structure may comprise a plurality of such arms. As such, the first electrode structure may have a pinwheel configuration, as described above.

[0036] Preferably the potential difference provided by the voltage source is within the range of 1 kV to 10 kV, preferably from 2 kV to 8 kV, more preferably from 3 kV to 7 kV. Preferably the potential difference provided by the voltage source is configured to be constant during operation.

[0037] Preferably the smallest gap distance between the first electrode structure and the second electrode structure is a predetermined distance. When the first electrode structure comprises a plurality of the above-mentioned arms, the smallest gap distance preferably is the same for each of these arms.

[0038] Preferably the smallest gap distance satisfies the following: $G < U$, wherein G is the gap distance measured in millimeter and U is the potential difference between the first and second electrode structures measured in kilovolt.

[0039] Preferably the means for exerting force is a magnetic field generator, wherein the magnetic field generator creates a magnetic field having a magnetic field vector within the discharge region, the magnetic field vector having a component perpendicular to the electrical discharge path. Preferably the main component of the magnetic field vector is perpendicular to the electrical discharge path.

[0040] Preferably the plasma discharge apparatus is configured to accommodate a flow of gaseous particles through the discharge region, such that at least a portion of the gaseous particles are excited, dissociated and/or ionized. For this purpose, the plasma apparatus may form a duct, preferably of cylindrical or tensional shape. The duct may provide a lumen through which the gaseous particles flow, wherein the lumen 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.

[0041] Preferably the first electrode structure has a plurality of distinct trigger portions.

[0042] According to a third aspect, the invention relates to a system comprising the plasma discharge apparatus according to any of the preceding aspects. Such system may be a system used for neutralizing and/or processing particles contained in various types of gaseous flows. For example, such system may be an exhaust treatment system for treating exhausts from kitchens, factories, hospitals, laboratories and other facilities. According to preferred embodiments, the apparatus of the present invention can be used for treating exhaust from a combustion process, e.g., a heating installation or a combustion engine. For example, the exhaust of a vehicle's combustion engine may be treated. According to a further aspect, the invention relates to a vehicle comprising a combustion engine and such treatment system.

[0043] According to a fourth aspect, the invention relates to a method for using a plasma discharge apparatus comprising the steps of providing a plasma discharge apparatus as described herein; operating the voltage source to establish a potential difference between the first and second electrode structures; initiating at least one electrical discharge having a discharge path between the first and second electrode structures; operating the means for exerting force such that the discharge path moves within the discharge region and increases in length until the electrical discharge terminates; and repeating the third and fourth steps.

[0044] Preferably the potential difference provided by the voltage source is maintained constant during use of the plasma discharge apparatus. Maintaining a constant voltage and/or current from the voltage source may help to compensate the intrinsic variability of the plasma discharge apparatus. As such, the potential difference provided should not increase or decrease depending on the number of electrical discharges present.

[0045] Preferably multiple electrical discharges exist simultaneously during operation of the plasma discharge apparatus. Multiple simultaneous electrical discharges may lead to a more uniform occupation of the discharge area.

[0046] As optionally applicable to all aspects described herein, the voltage source may provide a pulsed electrical current. The pulsed electrical current may have a period between 10 and 1000 milliseconds, preferably between 100 and 500 milliseconds, 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

[0047] 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 configuration of a plasma discharge apparatus;

Fig. 2 schematically shows a configuration of a plasma discharge apparatus with multiple segments;

Fig. 3 schematically shows a configuration of a plasma discharge apparatus with longitudinally aligned electrode structures;

Fig. 4a schematically shows a configuration of a plasma discharge apparatus with arms in a pinwheel arrangement;

Fig. 4b schematically shows a perspective view of a plasma discharge apparatus with a flow of medium therethrough.

Detailed Description

[0048] Fig. 1 depicts a plasma discharge apparatus 100 including a first electrode structure 110 with multiple trigger points 150. The first electrode structure 110 in the present example is elongated along one direction and may be formed as a wire electrode or a strip electrode. A second electrode structure 120 may also be elongated along the same direction. The second electrode structure 120 may be a wire electrode or a strip electrode. In the illustrative example according to Fig. 1 three triggers 150 are used, but those skilled in the art will appreciate that 1, 2, 4, 5, or more triggers 150 may be employed depending on the dimensions of the apparatus 100 and the length of the electrode structures 110, 120.

[0049] In connection with at least one of the electrode structures 110, 120 is a voltage source 130. The voltage source must be capable of supplying a potential difference between the first and second electrode structures 110, 120 such that the resistance of the air or other material in between the two electrode structures can be overcome. When the resistance of the material between the first electrode structure 110 and the second electrode structure 120 is overcome, an electrical discharge 135 initiates between the first and second electrode structures 110, 120. The electrical discharge 135 comprises a discharge path, which at one end contacts the first electrode structure 110 and at the other end contacts the second electrode structure 120. The electrical discharge path will generally assume the path of least resistance from the first to the second electrode structure 110, 120. Thus, the discharge path may be straight, angled, curved, or some other geometry based on the properties of the intervening material and the form of the first and second electrode structures 110, 120. The area of the plasma discharge apparatus 100 in which an electrical discharge may arise is referred to as the discharge area. In some cases the discharge area may be the space directly between the first electrode structure 110 and the second electrode structure 120. The discharge area may include areas adjacent to the first and second electrode structures 110, 120 or take on a number of different configurations.

[0050] The voltage source is configured to provide a potential difference to overcome the resistance of the medium between the first and second electrode structures. The resistance between the first and second electrode structures 110, 120 is dependent on the distance between the two, and the properties of the intervening medium. Preferably, the voltage source is configured to provide a potential difference within the range of 1 kV to 10 kV, more preferably from 2 kV to 8 kV, even more preferably from 3 kV to 7 kV.

[0051] A means for exerting force 140 exerts a force that acts on the electrical discharge 135. The force is configured to cause at least the first end of the discharge path to move along the length of the first electrode structure 110 but may alternatively cause both the first end and the second end of the discharge path to move along the first and second electrode structures 110, 120, respectively. The means for exerting force 140 may be a permanent magnet or an electromagnet configured to produce a magnetic field within the discharge area. A magnetic field whose magnetic field lines 170 are not parallel with the discharge path will exert a Lorentz force on the electrical discharge 135, thereby causing the electrical discharge 135 to travel along the first electrode structure 110. An alternative means for exerting force 140 is a wind or flow generating system. If wind or flow of medium 180 is generated in the discharge area and the direction of flow is not parallel to the discharge path

135, it will likewise cause the electrical discharge 135 to migrate along at least the first electrode structure 110 and/or along the first and second electrode structures 110, 120. Preferably, magnetic field lines, wind and/or flow through the discharge region are essentially perpendicular to the discharge path. For example, the magnetic field lines, wind and/or flow may be oriented at an angle of at least 60°, at least 70° or at least 80° to the discharge path.

[0052] As shown in Fig. 1, each trigger 150 is a portion of the first electrode structure 110 which is closer to the second electrode structure 120 than the surrounding portions of the first electrode structure 110. Each trigger 150 may be an extension protruding out from the first electrode structure 110. A distance measured between the first electrode structure 110 and the second electrode structure 120 is the gap distance G. The gap distance G is smaller than a distance D between the first and second electrode structures along the other portions of the discharge region. It some configurations the gap distance G at each of the trigger points is chosen such that the same potential difference U, which is sufficient to trigger the discharge across the trigger gap G, is also sufficient to maintain the potential different across the electrode separation at points D other than trigger 150. According to preferred embodiments of the illustrative example, the distance D is less than 5 cm, less than 4 cm, less than 3 cm or less than 2 cm. A trigger 150 can also take the form of a tapered protrusion wherein the narrowest point is also the point closest the second electrode structure 120, i.e. the point with the smallest gap distance G. As a rule of thumb and without wanting to be bound by theory, the value of the gap distance measured in millimeters between the trigger point and the second electrode structure 110, 120 preferably is smaller than the value of the potential difference between the first and second electrode structures 110, 120 measured in kilovolts. Such an arrangement may help to promote the reliable initiation of electrical discharge between the first and second electrode structures 110, 120. Preferably, the potential difference between the first electrode structure 110 and the second electrode structure 120 is held constant during operation of the plasma discharge apparatus to prevent spontaneous termination and/or initiation of electrical discharges in undesired locations or with an undesired frequency. Alternatively the current provided by the voltage source is held constant during operation of the plasma discharge apparatus.

[0053] In some, optional, configurations the voltage source may be configured to provide a pulsed or intermittent potential difference between the first and second electrode structures 110, 120. 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.

[0054] The number of trigger points 150 of the first electrode structure 110 depends on the requirements of the plasma discharge apparatus 100 and may depend on the desired size of the discharge area. A plasma discharge system 100 with multiple trigger points 150 may promote the creation of a plasma layer with greater uniformity. Preferably, the gap distance between each of the trigger points 150 and the second electrode structure 120 is a constant distance such that each trigger has substantially equal probabilities for initiating an electrical discharge 135. In the illustrative example according to Fig. 1 three triggers 150 are used, but those skilled in the art will appreciate that 1, 2, 4, 5, or more triggers 150 may be employed depending on the dimensions of the apparatus 100 and the length of the electrode structures 110, 120.

[0055] Because the electrical resistance of a discharge path increases with increasing distance, the electrical discharge 135 is more likely to initiate between the trigger 150 and the second electrode structure 120 than at any random location along the first electrode structure 110, as the smaller gap distance poses the path of least resistance. With multiple triggers 150, multiple simultaneous electrical discharges 135 may initiate or exist simultaneously. Each electrical discharge 135 experiences forces from the means for exerting force 140, which will cause at least the first end of each discharge path to move along the first electrode structure 110. Thus, while the first end of the electrical discharge 135 initiates with the highest probability at any one of the triggers 150, after initiating the electrical discharge 135 experience forces, illustrated as arrows 160 in Fig. 1, that cause it to move away from the initiation point. However, as the electrical discharge 135 moves along the first electrode structure 110 away from the trigger 150, the gap distance G between the first and second electrode structures 110, 120 of the discharge path increases. An increasing gap distance G increases the resistance of the electrical discharge path 135. This causes the electrical discharge 135 to be more likely to terminate at any time after leaving the trigger 150 than before leaving the trigger 150.

[0056] Taken together, the plasma discharge apparatus 100 operates by first initiating an appropriate voltage between the first electrode structure 110 and the second electrode structure 120. When the potential difference between the electrode structures is large enough, the medium between the first and second electrodes experiences dielectric breakdown and an electrical discharge 135 is formed between at least one of the trigger points 150 and the second electrode structure 120. Each electrical discharge 135 experiences forces due to the means for exerting force 140 which compels the discharge path to wander away from the trigger point 150. Once the discharge path has moved away from the trigger 150 it will eventually terminate. However, once the electrical discharge 135 leaves the trigger and/or terminates a new electrical discharge 135 can again be initiated at the trigger 150. This process will repeat indefinitely as long as the voltage between the first and second electrode structures 110, 120 is maintained and forces continue to act on the electrical discharge 135.

[0057] Placing multiple triggers 150 along the first electrode structure can help to shape the plasma layer in the discharge area between the first and second electrodes 110, 120. Thus, the plasma layer may be more uniform when multiple triggers 150 are employed.

[0058] Fig. 2 illustrates another possible configuration of a plasma discharge apparatus 200 which includes a first electrode structure 210, a second electrode structure 220, a voltage source (not shown) in connection with both the first and second electrode structures 210, 220 and a means for exerting force (not shown). The means for exerting force preferably provides a magnetic field that compels the electrical discharge(s) to move in the direction of arrows 260. The means for exerting force may be a magnet (e.g., a cylindrical magnet or a coil) extending around the outer electrode structure (in Fig. 2 the second electrode structure 220).

[0059] In this configuration both the first and second electrode structures 210, 220 assume an arc-shaped or annular form. As depicted the first electrode structure 210 has a smaller radius of curvature than the second electrode structure 220, however this arrangement may also be inverted. In other words, one of the first and second electrode structures 210, 220 forms a radially inner electrode structure, while the other one forms a radially outer electrode structure.

[0060] The first electrode structure 210 preferably comprises multiple triggers 250 for initiating electrical discharges. The discharge area between the first and second electrode structures 210, 220 is optionally divided in this example into multiple different segments, wherein each segment comprises at least one trigger 250. The segments may, as in this example, assume a truncated wedge-shaped form, but may also assume other shapes (e.g., they may be rectangular). The segments may assume any number of shapes. The apparatus 200 may be rotationally symmetric over a longitudinal axis 290 thereof.

[0061] Notably, the first electrode structure is divided into multiple segments 211, 212, 213. The segments may either be connected in parallel with the voltage source 230 or may each be connected to an independent voltage source. Similarly, the second electrode structure 220 is divided into multiple segments 221, 222, 223 which may be each connected to an independent voltage source or may be connected in parallel to a single voltage source 230. Dividing the electrodes into segments helps to ensure that the each trigger 250 develops its own electrical discharge 235 which is then confined within the limits of the respective electrode segment. Such a configuration may result in more uniform occupation of the discharge area with plasma discharge and in producing a more homogenous plasma layer. Such a segmented configuration may be used in a number of different geometries and may be employed in combination with any of the other configurations described herein.

[0062] Fig. 3 depicts another example of a plasma discharge apparatus 300. In this plasma discharge apparatus both the first and second electrode structures 310, 320 are circular, the first electrode structure 310 having a larger radius than the second electrode structure 320. Multiple triggers 350 form a part of the first electrode structure 310 and extend radially inward from the first electrode structure 310 toward the second electrode structure 320. The triggers 350 may be simple conducting pins. The plasma discharge apparatus 300 of this example is radially symmetric.

[0063] The same functioning principles as explained in previous configurations also apply to the plasma apparatus 300 of Fig. 3. The one or more electrical discharge(s) 235, 335 according to the embodiments of Figs. 2 and 3 travel in either a clockwise direction or a counterclockwise direction around the longitudinal axis, i.e. the axis about which the first electrode structure 210, 310 and the second electrode structure 220, 320 are centered. The electrical discharge(s) 235, 335 repeatedly terminate and are repeatedly formed between the triggers 250, 350 and the second electrode structure 220, 320. In such a configuration it may be advantageous to provide a first electrode structure 210, 310 and a second electrode structure 220, 320, which are rotationally symmetric about the longitudinal axis 290, 390. The discharge region may be located between the first and second electrode structures. Alternatively, based on the properties of the intervening material and the presence of any material flow, the discharge region may be out of plane with respect to the first electrode structure 210, 310 and the second electrode structure 220, 320.

[0064] In any of the examples described above, first electrode structure 110, 210, 310 may have a base which is shown as the ring-shaped portion of the first electrode structure 110, 210, 310, and one or more arms ending in the trigger points 150, 250, 350. A first end of each arm is connected to the base of the first electrode structure 110, 210, 310. The second end of each arm forms the trigger point 150, 250, 350 and extends toward the second electrode structure 120, 220, 320. In the example of Fig. 2, the base may be formed as a ring segment. Also the first electrode 410 described with reference to Figs. 4a and 4b below may include such base.

[0065] It should also be noted that the example plasma discharge apparatus 100, 300 of Figs. 1 and 3 could be divided into individual segments, with each segment including at least one trigger portion, as explained with respect to Fig. 2 above. The same holds true for the example described with reference to Fig. 4a below.

[0066] Fig. 4a depicts another example of a plasma discharge apparatus 400. Again, the first and second electrode structures 410, 420 are formed as rings (full or segmented) centered about a longitudinal axis. In this illustrated configuration the first electrode structure 410 has a smaller radius than the second electrode structure 420. One or more arms 440, each having a trigger point 450, form a part of the first electrode structure 410 and extend radially outward toward the second electrode structure 420. The space between the end of each of the trigger points 450 and the second electrode structure 420 presents the smallest gap distance.

[0067] The triggers 450 in this configuration of the plasma discharge apparatus 400 are configured such that the gap distance between the first electrode structure 410 and the second electrode structure 420 gradually increases from the end of arm 440 in the direction of rotation one or more discharges 435. This configuration may include a singular trigger 450 or multiple triggers 450 as shown in Figs. 4a and 4b.

[0068] The one or more arms 440 preferably extend radially outward in a slanted and/or non-linear manner. For example, each arm 440 may take on a linear or nonlinear geometry, in which the trigger 450 does not extend directly radially outward from the first electrode structure 410, but instead forms an angle relative to the radial direction such that the gap distance between the first electrode structure 410 and the second electrode structure 420 gradually increases in the direction of rotation, of the discharge(s) 435.

[0069] Arms 440 which gradually increase the gap distance G along the direction of rotation provide the benefit of a smoother transition of the electrical discharge 435 away from the tip of the arm 440. Leading the first end of the discharge 435 away from the trigger point 450 increases the size of the discharge area. Moreover, the electrical discharge 435 becomes increasingly likely to terminate the farther away the first end of the electrical discharge path is from the tip of the trigger 450. Consequently, this may aid in regulating the termination of electrical discharges 435 and to produce a more uniform plasma layer.

[0070] When an arm 440 is oriented at an angle to the radial direction in a circular plasma apparatus, the arm 440 will extend over a certain arc angle θ of the plasma apparatus 400. This arc angle θ may be chosen to meet the needs of the plasma discharge apparatus 400. The arc angle θ may be in the range of 1° to 90°, preferably in the range of 3° to 45°, or more preferably in the range of 5° to 30°. The arc angle θ may be related to the number of arms 440 included in the plasma apparatus 400, whereby the number of arms 440 multiplied by the arc angle θ may in some cases exceed 360° or alternatively be 360° or less. In other words, the arms 440 may partially overlap or have space separating them. Each arm 440 may also extend around an angle θ of at least 5°, at least 10°, at least 20°, or at least 30°. Alternatively, each arm 440 may extend around the base over an angle θ of 50° or less, 40° or less, 30° or less, or 20° or less.

[0071] As shown in Fig. 4a and 4b, a side of the one or more arms facing in the direction in which the one or more discharges 435 rotate is preferably convex, in particular when the first electrode structure 410 is the radially inner electrode. However, the side of the one or more arms facing in the direction of rotation may also be concave, in particular when the first electrode structure 410 forms the radially outer electrode.

[0072] An advantageous configuration, as depicted in Fig. 4a is wherein the first electrode structure 410 comprises a base and multiple arms terminating in trigger points 450. The arms, in particular the frontside thereof facing in the direction of rotation are curved such that the first electrode structure 410 assumes the form of a spiral or pinwheel. The backside of the one or more arms facing opposite the direction of rotation may be curved (for example, as shown in Fig. 4a, concavely), but could also be straight and/or extend in a radial manner. A straight configuration may help avoiding dead zones in which into plasma discharge cannot reach.

[0073] Fig. 4b shows a perspective view of the apparatus 400 of Fig. 4a, in which a means for exerting force 440 is also illustrated. The means for exerting force 440 may be a cylindrical magnet extending around the periphery of the outer electrode structure (in Figs. 4a and 4b the second electrode structure 420), such that a magnetic field is produced within the discharge region as indicated by the dashed lines in Fig. 4b. The magnetic field lines within the discharge region are at an angle relative to the orientation of the discharge path 435 and may be substantially perpendicular to the direction of the discharge path 435, as also indicated for Fig. 1 above. The magnitude of the Lorentz force exerted on the electrical discharge is dependent on the mutual angle between the discharge path and the magnetic field lines and the strength of the magnetic field. Thus, a perpendicular orientation between the magnetic field lines and the electrical discharge 435 provides the greatest force acting on the one or more electrical discharges 435.

[0074] Fig. 4b also illustrates a direction of a particle flow through the plasma discharge apparatus 400 as indicated by the parallel arrows 470. Particles that pass through the plasma layer within the discharge region preferably encounter the one or more migrating electrical discharges 435. By coming into contact with the electrical discharge 435, the particles may be excited, disassociated and/or ionized. Such a configuration may be useful for providing a plasma discharge apparatus as a part of a system or vehicle in combination with a combustion engine.

[0075] From a three-dimensional consideration it is also envisioned that the one or more arms 440 may either extend along a two-dimensional plane perpendicular to a longitudinal axis of the first and/or second electrode structures 410, 420 or the one or more arms 440 may extend in the longitudinal direction as well as in the radial direction. The first electrode structure 410 may also be longitudinally offset from the second electrode structure 420.

[0076] As shown, the first and/or second electrode structures 410, 420 of the example illustrated in Figs. 4a and 4b may be rotationally symmetric.

[0077] 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".

[0078] The following are preferred aspects of the invention:

1. A plasma discharge apparatus comprising
a first electrode structure comprising a plurality of trigger points;
a second electrode structure;
a voltage source connected to the first and/or second electrode structures, the voltage source being configured to create a potential difference between the first and second electrode structures such that at least one electrical discharge occurs in a discharge region between the first and second electrode structures, wherein each electrical discharge has a discharge path with a first end contacting the first electrode structure and a second end contacting the second electrode structure;
a means for exerting force on the at least one electrical discharge, the means for exerting force being configured to compel the first end of the discharge path to move along the first electrode structure;
wherein each trigger point is a portion of the first electrode structure which has a smaller gap distance to the second electrode structure than adjacent portions of the first electrode structure, such that the at least one electrical discharge is initiated between the first and second electrode structures at one of the plurality of trigger points.

2. The plasma discharge apparatus of aspect 1, wherein each trigger point is a portion of the first electrode structure which has a smallest gap distance to the second electrode structure.

3. The plasma discharge apparatus of aspect 1 or 2, wherein the first and second electrode structures are rotationally symmetric about a longitudinal axis.

4. The plasma discharge apparatus of aspect 3, wherein the discharge region is located radially between the first and second electrode structures.

5. The plasma discharge apparatus of any of the preceding aspects, wherein the first electrode structure comprises a base and a plurality of arms, wherein the arms comprise a first end connected to the base and a second end providing a respective trigger point.

6. The plasma discharge apparatus of aspect 5, wherein a distance between each arm and the second electrode structure increases along the arm, preferably wherein the distance increases gradually along the length of the arm.

7. The plasma discharge apparatus of aspect 6, wherein the distance increases in the direction in which the first end of the discharge path is compelled to move along the first electrode structure.

8. The plasma discharge apparatus of aspect 5, 6 or 7, wherein the first electrode structure has a pinwheel configuration.

9. The plasma discharge apparatus of any of aspects 5 to 8, wherein the arms curve away from the base, preferably wherein the arms have a spiral configuration.

10. The plasma discharge apparatus of aspect 9, wherein the arms curve away from the base in a direction opposite to the direction in which the first end of the discharge path is compelled to move along the first electrode structure.

11. The plasma discharge apparatus of any of aspects 5 to 10, wherein the arms extend around the base over an angle of at least 5°, at least 10°, at least 20°, or at least 30°, preferably as measured from a longitudinal axis of the apparatus.

12. The plasma discharge apparatus of any of aspects 5 to 11, wherein the arms extend around the base over an angle of 50° or less, 40° or less, 30° or less, or 20° or less, preferably as measured from a longitudinal axis of the apparatus.

13. The plasma discharge apparatus of one of the previous aspects, wherein the first electrode structure and/or the second electrode structure is segmented such that each segment comprises a trigger point, and wherein each segment is electrically isolated from the other segments.

14. The plasma discharge apparatus of any of the preceding aspects, wherein the potential difference provided by the voltage source is within the range of 1 kV to 10 kV, preferably from 2 kV to 8 kV, more preferably from 3 kV to 7 kV.

15. The plasma discharge apparatus of any of the preceding aspects, wherein the potential difference and/or current provided by the voltage source is configured to be constant during operation.

16. The plasma discharge apparatus of any of the previous aspects, 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.

17. The plasma discharge apparatus of any of the previous aspects, wherein the voltage source is configured to provide a pulsed electrical current having a duty cycle between 0.7 and 0.05, preferably between 0.5 and 0.1.

18. The plasma discharge apparatus of any of the preceding aspects, wherein the gap distance between each of the trigger points and the second electrode structure is a fixed distance.

19. The plasma discharge apparatus of any of the preceding aspects, wherein the gap distance at each of the trigger points satisfies the following:
$G < U$
wherein G is the gap distance measured in millimeter and U is the potential difference between the first and second electrode structures measured in kilovolt.

20. The plasma discharge apparatus of any of the preceding aspects,
wherein the means for exerting force is a magnetic field generator,
wherein the magnetic field generator creates a magnetic field having a magnetic field vector within the discharge region, the magnetic field vector having a component perpendicular to the electrical discharge path, preferably wherein the main component of the magnetic field vector is perpendicular to the electrical discharge path.

21. The plasma discharge apparatus of any of the preceding aspects, wherein the plasma discharge apparatus is configured to accommodate a flow of gaseous particles through the discharge region, such that at least a portion of the gaseous particles are excited, dissociated and/or ionized.

22. A plasma discharge apparatus comprising
a first electrode structure;
a second electrode structure;
a voltage source connected to the first and/or second electrode structures, the voltage source being configured to create a potential difference between the first and second electrode structures such that at least one electrical discharge occurs in a discharge region between the first and second electrode structures, wherein each electrical discharge has a discharge path with a first end contacting the first electrode structure and a second end contacting the second electrode structure;
a means for exerting force on the at least one electrical discharge, the means for exerting force being configured to compel the discharge path to rotate within the discharge region;
wherein at least one trigger portion of the first electrode structure has a smaller gap distance to the second electrode structure than adjacent portions of the first electrode structure such that the electrical discharge is initiated between the first and second electrode structures at the trigger portion, and wherein a gap distance between the first electrode structure and the second electrode structure gradually increases in the direction of rotation.

23. The plasma discharge apparatus of aspect 22, wherein the first and second electrode structures are centered about a longitudinal axis.

24. The plasma discharge apparatus of aspect 23, wherein the discharge region is located radially between the first and second electrode structures.

25. The plasma discharge apparatus of any of aspects 22 to 24, wherein the first electrode structure comprises a base and at least one arm, wherein the at least one arm comprises a first end connected to the base and a second end providing the trigger portion, preferably wherein the gap distance between the first electrode structure and the second electrode structure is smallest at the trigger portion.

26. The plasma discharge apparatus of aspect 25, wherein a minimum distance between the at least one arm and the second electrode structure increases along the arm.

27. The plasma discharge apparatus of aspect 25 or 26, wherein the at least one arm curves away from the base, preferably wherein the arm has a spiral configuration, more preferably wherein the arm extends from the base following a spiral.

28. The plasma discharge apparatus of aspect 27, wherein the at least one arm curves away from the base in a direction opposite to the direction of rotation.

29. The plasma discharge apparatus of any of aspects 25 to 28, wherein the at least one arm extends around the base over an angle of at least 5°, at least 10°, at least 20°, or at least 30°.

30. The plasma discharge apparatus of any of as-

pects 25 to 28, wherein the at least one arm extends around the base over an angle of 50° or less, 40° or less, 30° or less, or 20° or less.

31. The plasma discharge apparatus of any of aspects 25 to 30, wherein the first electrode structure comprises a plurality of such arms.

32. The plasma discharge apparatus of any of aspects 22 to 31, wherein the first electrode structure has a pinwheel configuration.

33. The plasma discharge apparatus of any of aspects 22 to 32, wherein the potential difference provided by the voltage source is within the range of 1 kV to 10 kV, preferably from 2 kV to 8 kV, more preferably from 3 kV to 7 kV.

34. The plasma discharge apparatus of any of aspects 22 to 33, wherein the potential difference and/or current provided by the voltage source is configured to be constant during operation.

35. The plasma discharge apparatus of any of aspects 22 to 34, 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.

36. The plasma discharge apparatus of any of aspects 22 to 35, 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 0.3 and 0.1; or

at most 0.7 or at most 0.5.

37. The plasma discharge apparatus of any of aspects 22 to 36, wherein the smallest gap distance between the first electrode structure and the second electrode structure is a fixed distance.

38. The plasma discharge apparatus of any of aspects 33 to 37, wherein the smallest gap distance satisfies the following:
$G < U$
wherein G is the gap distance measured in millimeter and U is the potential difference between the first and second electrode structures measured in kilovolt.

39. The plasma discharge apparatus of any of aspects 22 to 38,
wherein the means for exerting force is a magnetic field generator,
wherein the magnetic field generator creates a magnetic field having a magnetic field vector within the discharge region, the magnetic field vector having a component perpendicular to the electrical discharge path,
preferably wherein the main component of the magnetic field vector is perpendicular to the electrical discharge path.

40. The plasma discharge apparatus of any of aspects 22 to 39, wherein the plasma discharge apparatus is configured to accommodate a flow of gaseous particles through the discharge region, such that at least a portion of the gaseous particles are excited, dissociated and/or ionized.

41. The plasma discharge apparatus of any of aspects 22 to 40, wherein the first electrode structure has a plurality of distinct trigger portions.

42. System or vehicle comprising a plasma discharge apparatus according to any of the preceding aspects and an exhaust generator, for example a combustion engine.

43. Method for using a plasma discharge apparatus comprising the steps of

(i) providing a plasma discharge apparatus according to any of the preceding aspects;

(ii) operating the voltage source to establish a potential difference between the first and second electrode structures;

(iii) initiating at least one electrical discharge having a discharge path between the first and second electrode structures;

(iv) operating the means for exerting force such that the discharge path moves within the discharge region and increases in length until the electrical discharge terminates;

(v) repeating steps iii and iv.

44. Method for using a plasma discharge apparatus according to aspect 43, wherein the potential difference and/or current provided by the voltage source is maintained constant during use of the plasma discharge apparatus.

45. Method for using a plasma discharge apparatus according to aspect 43 or aspect 44, wherein a plurality of electrical discharges exist simultaneously during operation of the plasma discharge apparatus.

Claims

1. A plasma discharge apparatus comprising
a first electrode structure comprising a plurality of trigger points;
a second electrode structure;
a voltage source connected to the first and/or second electrode structures, the voltage source being configured to create a potential difference between the first and second electrode structures such that at least one electrical discharge occurs in a discharge region between the first and second electrode structures, wherein each electrical discharge has a discharge path with a first end contacting the first electrode structure and a second end contacting the second electrode structure;
a means for exerting force on the at least one electrical discharge, the means for exerting force being configured to compel the first end of the discharge path to move along the first electrode structure;
wherein each trigger point is a portion of the first electrode structure which has a smaller gap distance to the second electrode structure than adjacent portions of the first electrode structure, such that the at least one electrical discharge is initiated between the first and second electrode structures at one of the plurality of trigger points.

2. The plasma discharge apparatus of claim 1, wherein each trigger point is a portion of the first electrode structure which has a smallest gap distance to the second electrode structure.

3. The plasma discharge apparatus of claim 1 or claim 2, wherein the first electrode structure comprises a base and a plurality of arms, wherein the arms comprise a first end connected to the base and a second end providing a respective trigger point.

4. The plasma discharge apparatus of claim 3, wherein a distance between each arm and the second electrode structure increases along the arm, preferably wherein the distance increases gradually along the arm, more preferably wherein the distance increases in the direction in which the first end of the discharge path is compelled to move along the first electrode structure.

5. The plasma discharge apparatus of claim 3 or claim 4 wherein the arms curve away from the base, preferably wherein the arms have a spiral configuration, preferably wherein the arms curve away from the base in a direction opposite to the direction in which the first end of the discharge path is compelled to move along the first electrode structure.

6. The plasma discharge apparatus of any one of the previous claims, wherein the first electrode structure is segmented such that each segment comprises at least one trigger point, and wherein each segment is electrically isolated from the other segments.

7. The plasma discharge apparatus of any one of the preceding claims, wherein the plasma discharge apparatus is configured to accommodate a flow of gaseous particles through the discharge region, such that at least a portion of the gaseous particles are excited, dissociated and/or ionized.

8. The plasma discharge apparatus of any one of the previous claims, wherein the electrical discharge rotates around a longitudinal axis.

9. The plasma discharge apparatus of any one of the previous claims, wherein the plasma discharge apparatus comprises not more than 20 trigger points and/or at least 2 trigger points, preferably at least 3 trigger points, more preferably at least 4 trigger points.

10. The plasma discharge apparatus of any one of the previous claims, wherein the first and second electrode structures are centered about a longitudinal axis, preferably wherein the first and second electrode structures are rotationally symmetric about the longitudinal axis.

11. The plasma discharge apparatus of any one of the previous claims, wherein the at least one arm extends around the base over an angle of at least 5°, at least 10°, at least 20°, or at least 30°.

12. The plasma discharge apparatus of any one of the previous claims,
wherein the means for exerting force is a magnetic field generator,
wherein the magnetic field generator creates a magnetic field having a magnetic field vector within the discharge region, the magnetic field vector having a component perpendicular to the electrical discharge path,
preferably wherein the main component of the magnetic field vector is perpendicular to the electrical discharge path.

13. System or vehicle comprising a plasma discharge apparatus according to any of the preceding claims and a combustion engine.

14. Method for using a plasma discharge apparatus comprising the steps of

   (i) providing a plasma discharge apparatus according to any of the preceding claims;
   (ii) operating the voltage source to establish a potential difference between the first and sec-

ond electrode structures;

(iii) initiating at least one electrical discharge having a discharge path between the first and second electrode structures;

(iv) operating the means for exerting force such that the discharge path moves within the discharge region and increases in length until the electrical discharge terminates;

(v) repeating steps iii and iv.

15. Method for using a plasma discharge apparatus according to claim 14, wherein a plurality of electrical discharges exist simultaneously during operation of the plasma discharge apparatus.

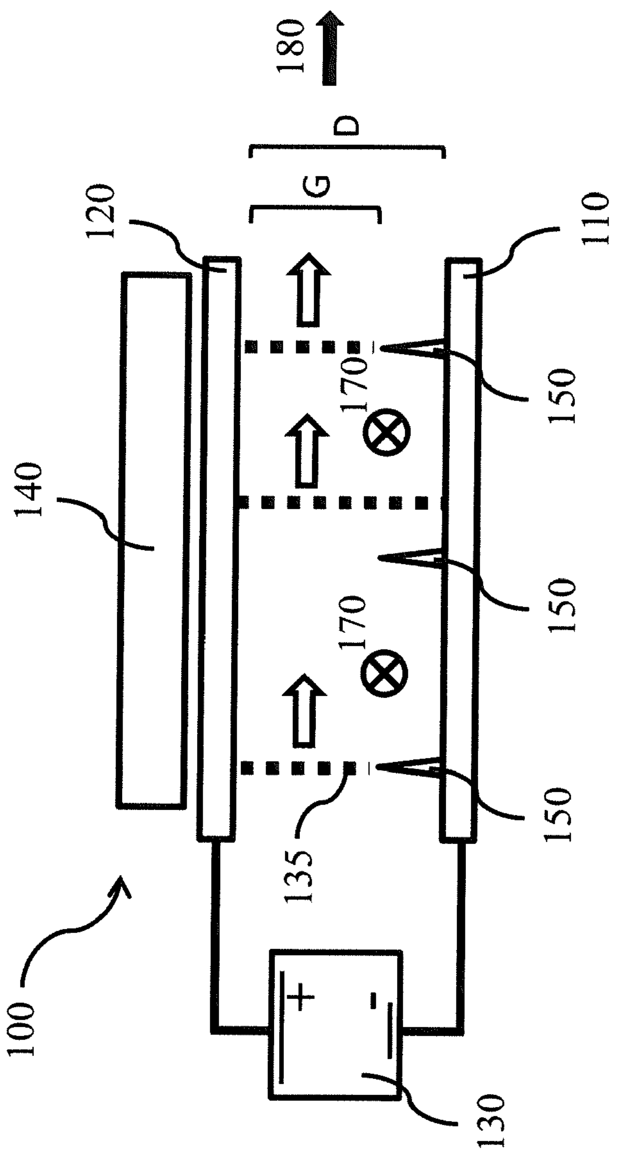

Fig. 1

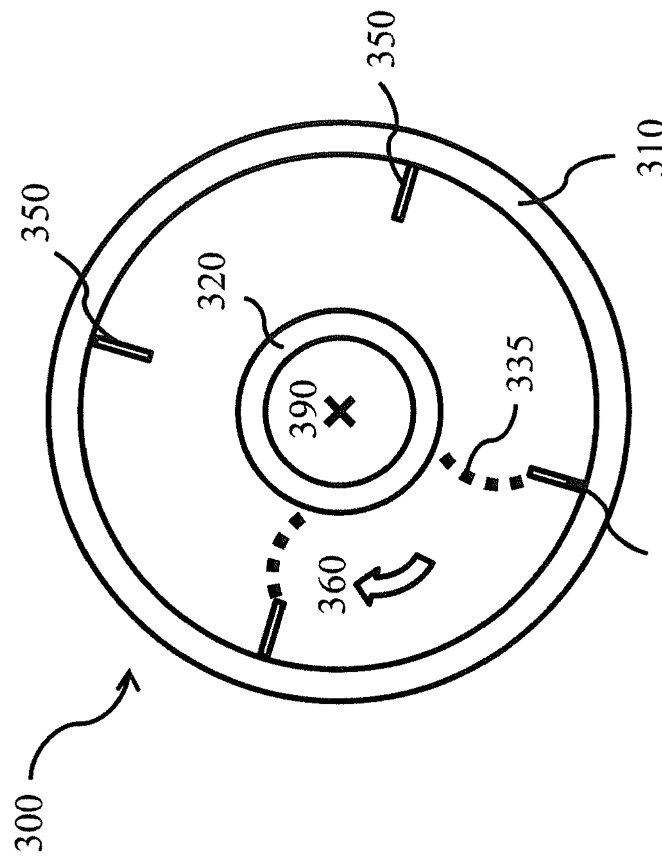
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Fig. 3

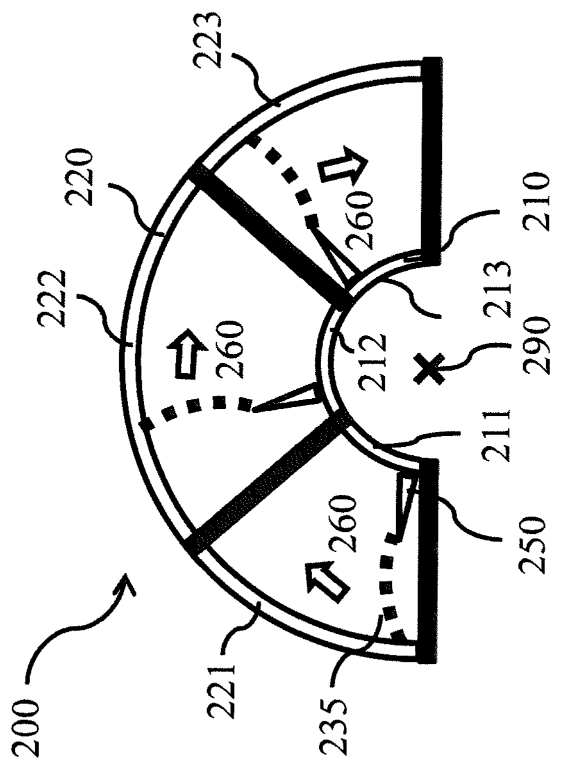
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Fig. 2

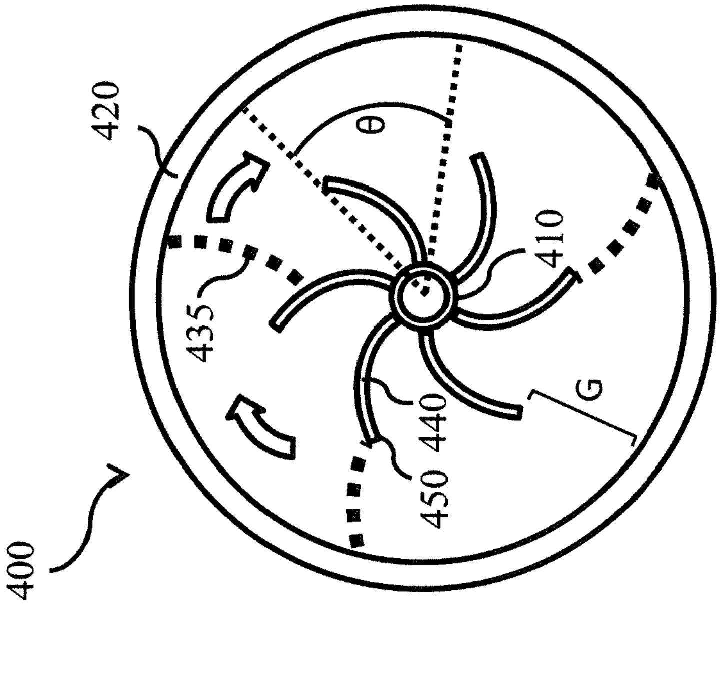

Fig. 4a

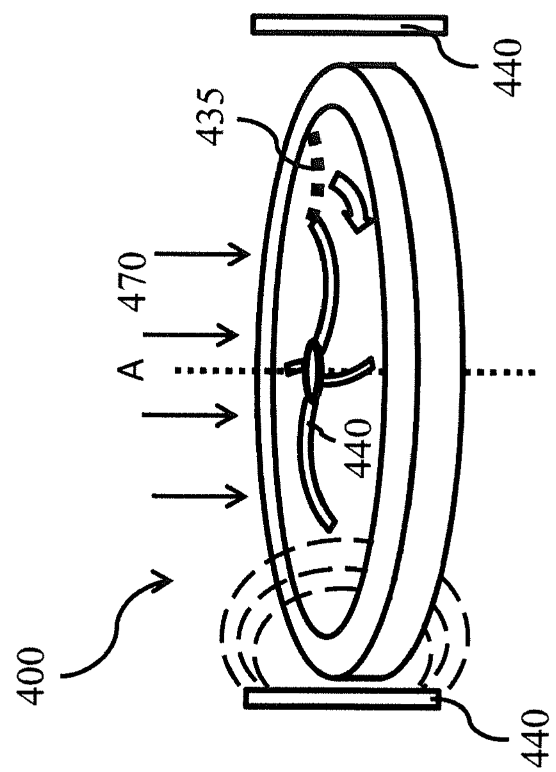

Fig. 4b

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EUROPEAN SEARCH REPORT

Application Number
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2

Place of search	Date of completion of the search	Examiner
The Hague	18 June 2020	Clemente, Gianluigi

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