



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
30.01.2002 Bulletin 2002/05

(51) Int Cl.7: **H05H 1/24**

(21) Application number: **00115997.9**

(22) Date of filing: **26.07.2000**

(84) Designated Contracting States:
**AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU
MC NL PT SE**
Designated Extension States:
AL LT LV MK RO SI

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(54) **DC plasma generator for generation of a non-local, non-equilibrium plasma at high pressure**

(57) DC plasma generator for generation of a non-local, non-equilibrium plasma at high pressure (atmospheric pressure) is described. The device comprises two electrodes, a DC voltage generator for generating

a DC voltage between the two electrodes, thus creating an electric field between the electrodes, and a magnetic field generator for generating a magnetic field perpendicular to the electric field. The crossed electric and magnetic fields distribute the plasma.

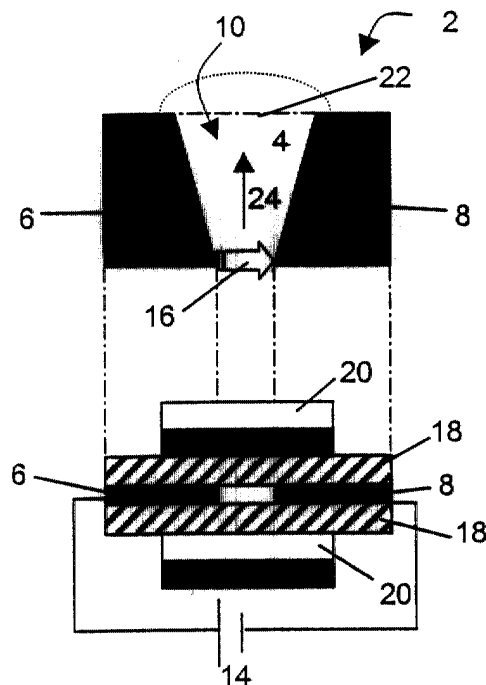


Fig. 1

Description

Technical field of the invention

[0001] The present invention relates to the generation of a non-local, non-equilibrium plasma generated at a pressure greater than about 0.5 atmospheres, preferably at atmospheric pressure.

Background of the invention

[0002] The term "plasma" is used to identify gaseous complexes which may comprise electrons, positive or negative ions, gaseous atoms and molecules in the ground state or any higher state of excitation including light quanta. The most common method for achieving a plasma state is through an electrical discharge. Electrical discharge plasmas are either "hot", i.e. thermal, or "cold", i.e. non-thermal.

[0003] Hot or thermal plasmas comprise gas atoms and electrons which are essentially in thermal equilibrium with each other. Therefore, hot plasmas are also called "thermal equilibrium plasmas" or "equilibrium plasmas". They are produced from electrical arcs, plasma jets, and magnetic fields. Hot plasmas produced from electrical arcs and plasma jets require equilibrium conditions in which the gas and electron temperatures are very high (5×10^3 K) and nearly identical. As a result, most organic molecules and polymers cannot be treated under these conditions because they would be rapidly degraded.

[0004] Cold or non-thermal plasmas, which are not at thermal equilibrium and are therefore also called "non-equilibrium plasmas", comprise gas atoms at a relatively low temperature, room temperature, and electrons at much higher temperatures (several 1000 K). In a cold plasma, the electron mean energy is much higher than the ion and gas mean energies. This plasma state provides an ambient gas temperature along with electrons which have sufficient kinetic energy to cause the cleavage of chemical bonds. As a result, cold plasmas are highly suitable for chemical reactions, such as organic synthesis, polymerizations and surface treatments. Cold plasmas are characterised, typically, by average electron energies of 1-20 electron Volts and electron densities of 10^9 to 10^{12} cm⁻³. Other synonymous terms for cold plasma are "glow discharge" or "low temperature plasma".

[0005] Generally, in order to generate a non-equilibrium plasma, the pressure must be low, of the order of less than 100 torr. When the pressure is increased, the glow discharge becomes an arc discharge and thus the cold plasma becomes a hot plasma. The two types of discharge are distinguished by their electrical characteristics and their mode of operation. A glow discharge operates at high voltage and low currents, while an arc discharge operates at low voltage and high currents. As the current is increased for a glow discharge, the dis-

charge tends to cover more and more of the available cathode area until at some point the current density exceeds a critical value and the discharge suddenly becomes an arc. When this occurs, there is an abrupt drop in voltage and an increase in current. In the glow discharge, electrons are produced in the gas phase by ionization of neutral species by electrons accelerated by the electric field; in the arc discharge, the electrons are produced by copious emission of electrons from a hot cathode. Generally, the electrodes are not consumed in a glow discharge; while in an arc discharge, the cathode is consumed and must be replaced frequently.

[0006] The use of a low-pressure plasma has the disadvantage that high priced vacuum chambers and pumping systems are needed. This may still be attractive for certain applications, e.g. in gas lasers. Use of a plasma at approximately ambient atmospheric pressure would not require that any article to be treated is held under vacuum, thereby significantly reducing processing costs. It furthermore removes the requirement that the article to be treated must be capable of surviving under reduced pressure. For many industrial processes, e.g. flue gas cleaning with the aid of plasma, it is necessary to use a plasma at atmospheric pressure.

[0007] It is generally so that, because of atmospheric pressure operation, ions do not survive for a sufficiently long distance beyond the active plasma discharge to bombard a workpiece, unlike low-pressure plasma sources and conventional plasma processing methods. Therefore, stabilisation of the plasma beam is necessary in order for it to be useful.

[0008] It is known from US-5,405,514 to stabilise a glow discharge DC plasma beam at atmospheric pressure by means of a swirling gas stream. Therefore, a first and a second opposing electrode are provided within a glow discharge chamber, and a DC power is applied between the two electrodes. Gas or vapour is passed in a swirling pathway to form a vortex between the electrodes and around the generated plasma beam.

[0009] It is also known from S. Pellerin et al., "Determination of the electrical parameters of a bi-dimensional d.c. Glidearc", Appl. Phys. 32 (1999) 891-897, to use a gas flow and horn-shaped electrodes to generate a gliding arc. Here, a high-pressure, non-equilibrium cold plasma is generated by applying a high DC voltage between two electrodes. An electric arc discharge is created at the narrowest electrode gap, and then the arc string is pushed towards the top of the electrodes by a transverse gas flow.

[0010] Stabilisation of high-pressure glow discharges by a fast gas flow is an established technique. However, for some applications, e.g. surface treatment, the needed flow rates are impracticably high.

[0011] US-5,369,336 discloses a plasma generating device in which glow discharges are generated in a gas containing helium as the main ingredient under atmospheric pressure by means of an AC voltage applied between two concentric electrodes disposed as concentric

cylinders. A magnetic field, generated by a permanent magnet provided on a straight extension line from the axis of the concentric electrodes, acts on the plasma and draws it out of the discharging space between the concentric electrodes, for using it for substrate treatment. The use of an AC voltage for generating the plasma is a disadvantage, as this requires a large and expensive power supply. If a plasma is generated using radio frequencies, impedance matching between the plasma and the radio frequency generator is needed, which is not easy to obtain.

[0012] It is known from US-4,755,999 to generate a cold plasma by DC at the very low pressures generally used in a laser apparatus, thus at pressures in the range of 1 to 10 kPa. The generated plasma is moved by a magnetic field, which exerts a force on the discharge. It is furthermore known from C.E. Capjack et al., "Magnetic laser discharge stabilization scaling to high-pressure systems", Journal of Applied Physics 70(11), 1 December 1991, that the required magnetic field strength for stabilisation of laser discharges scales as the square of the pressure. From application of this square law, it would be impractical to try and stabilise a cold DC plasma at atmospheric pressure (100 kPa) by means of a magnetic field, because of the large magnetic field strengths that would be required.

[0013] It is nevertheless an object of the present invention to provide a method and a device for generating and stabilising a non-local, non-equilibrium plasma at high pressure, the plasma being generated by a DC field. By a non-local plasma is meant a spatially distributed plasma, i.e. a plasma which is extended over a space.

Summary of the invention

[0014] The above objective is accomplished by a DC plasma generator for generating a non-local, non-equilibrium plasma at a pressure greater than about 0.5 atmospheres, comprising two electrodes, a DC voltage generator for generating a DC voltage between the two electrodes, thus creating a DC electric field between the electrodes, and a magnetic field generator for generating a magnetic field perpendicular to the electric field, the crossed electric and magnetic fields distributing the plasma. Preferably the plasma is created at a pressure between 0.5 and 2 atmospheres, and more preferred under atmospheric pressure. The use of a DC voltage enables use of a simpler power supply with less interference compared to an AC voltage generator, thus decreasing the cost of the power supply. Furthermore, using a DC voltage makes the DC plasma generator much more scalable and reduces electromagnetic radiation emission problems. Preferably, the magnetic field is not an oscillating field, i.e. a unidirectional field.

[0015] The electrodes may be made of copper or of any conductive material. Magnets used may comprise ferrite, with a surface magnetic field of 0.15 T, or ceramic

magnets or where appropriate, electromagnets.

[0016] According to a preferred embodiment, the electrodes of the DC plasma generator are disposed such that there is an expanding gap between them. This gap has a centre line lying in the direction of expansion of the gap, which is perpendicular to both the direction of the electric field and the direction of the magnetic field. The expanding gap allows the plasma to be distributed by the magnetic field in a stable manner.

[0017] According to another preferred embodiment, the DC plasma generator furthermore comprises at least one gas inlet tube for creating a gas flow between the two electrodes in order to assist the magnetic field in distributing the plasma. The gas flow may be a straight flow in the direction of the centre line of the gap, or a vortex flow surrounding the generated non-equilibrium plasma.

[0018] A method for generating and stabilising a non-local, non-equilibrium plasma at a pressure greater than about 0.5 atmosphere is also provided. It comprises the steps of generating a non-equilibrium plasma between two electrodes between which an electric DC field is applied, generating a magnetic field in a direction perpendicular to the electric field, and distributing the plasma by the use of the crossed electric and magnetic fields.

[0019] Other features and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, which illustrate, by way of example, the principles of the invention.

Brief description of the drawings

[0020] Fig. 1 is a schematic representation of a top view and a front view of a DC plasma generator according to a first preferred embodiment of the present invention.

[0021] Fig. 2 is a schematic representation of a top view and of a front view of the same DC plasma generator.

[0022] Fig. 3 illustrates a surface treatment reactor using the DC plasma generator of the first preferred embodiment.

[0023] Fig. 4 is a schematic representation of a perspective view of a DC plasma generator according to a second preferred embodiment of the present invention.

[0024] Fig. 5 is a vertical cross-section of the DC plasma generator of Fig. 4, according to line V-V' in Fig. 4.

[0025] Fig. 6 is a schematic representation of a top view and a front view of a DC plasma generator according to a further embodiment of the present invention.

[0026] Same objects bear the same reference numbers throughout the different drawings.

Description of the illustrative embodiments

[0027] The present invention will be described with reference to certain drawings and embodiments but the

present invention is not limited thereto but only by the claims.

[0028] Turning now to the drawings Fig. 1, illustrates in diagrammatic form a top view and a front view, respectively, of a first embodiment of a DC plasma generator 2 for generating a non-local, non-equilibrium plasma 4 according to an embodiment of the present invention.

[0029] Fig. 1 principally depicts two electrodes, an anode 6 and a cathode 8, with a wedge-shaped gap 10 between them. The centre line 12 of the gap 10 extends along the gap in a direction perpendicular to electric and magnetic fields acting on the gap. When the cathode 8 is connected to a negative pole of a DC power supply 14, the anode 6 is connected to a positive pole and electric field E created therebetween. When a suitable DC voltage is applied between the cathode 8 and the anode 6, a non-equilibrium plasma 4 is generated between the electrodes 6, 8 which is stabilised by the action of a magnetic field applied perpendicular to the electric field. The plasma which is generated is distributed in the expanding gap 10. It is therefore described as non-local, or non-localised or distributed. With a "suitable voltage" is meant a potential difference (which is typically between 100 and 5000 Volts), as necessary to create a plasma 4. A typical range of suitable electric fields is 1-40 kV/cm, more preferably 2-20 kV/cm. The voltage to be applied to create the plasma 4 depends on the gas which is present between the electrodes 6, 8, which is to be ionised. Normally air at atmospheric pressure is used, but for surface treatment it may be useful to use other gases, or even gas mixtures. The DC plasma generator 2 of the present invention is not limited to a particular kind of gas.

[0030] Once a plasma beam is generated, a current of about 10 mA, typically between 5 and 30 mA, flows through the electrodes 6, 8. This means that an energetic power of some Watts is generated, which creates some heating. Therefore, the electrodes 6, 8 are preferably made of a material with good electrical and thermal conductivity. The electrodes 6, 8 may be cooled although for smaller devices with electrodes of good electrical and thermal conductivity such as copper electrodes 6, 8 cooling may not be necessary. Still further improvements in plasma stability may be achieved by making the electrodes 6, 8 from resistive material, i.e. material having a resistivity exceeding 1×10^{-6} ohm.meter.

[0031] The glow discharge generally starts at that point where the two electrodes 6, 8 are closest to each other, as indicated by the block arrow 16.

[0032] As represented in the front view, above and under the electrodes 6, 8 a dielectric layer 18 is provided. The wedge-shaped gap 10, limited at the upper and under side by the dielectric layers 18 forms a plasma chamber, in which the plasma 4 is generated, and through which the plasma 4 is distributed. The dielectric layer 18 may be Pyrex glass or ceramic, or any heat-resilient dielectric material, preferably an inert insulator

and may also comprise a laminate, e.g. of a metal layer covered with dielectric material. Optionally, the dielectric layer 18 may be cooled, for instance, the dielectric layer may be provided by a metal layer covered in a dielectric layer, cooling fluid passing through the metal layer.

[0033] A magnetic field is applied to the plasma 4 e.g. by applying permanent magnets or an electromagnet 20 at the upper and under sides of the electrode/dielectric arrangement. In the embodiment represented in Fig. 1, the south poles of the permanent magnets or electromagnets 20 are black, and the north poles are white. The magnetic field is perpendicular to the electric field, and thus creates a Lorentz action on the moving charged particles in plasma 4, which distributes the plasma along the gap 10, and moves it towards an output opening 22, as represented by the black arrow 24, where it can be used. The continuously widening gap will reduce the energy of the plasma until it finally extinguishes. Once the plasma comes beyond the electrodes 6, 8, it will usually extinguish. The generation of new plasma channels is continuous and at such a density that one discharge merges into the next thus resulting in a stable plasma of relatively constant properties. The plasma is a non-equilibrium plasma, that is a "cold" plasma. Generally, individual conductive glow discharge channels can no longer be distinguished. A typical magnetic field strength range is 0.01 T to 1 T. It is a surprising aspect of the present invention that useful, stable, distributed, non-equilibrium plasmas can be generated at such low electric and magnetic fields at atmospheric pressure.

[0034] The use of permanent magnets 20 is convenient as no additional power supply is required. For applying higher field strengths electromagnets may be used for applying the magnetic field.

[0035] According to a preferred embodiment, a gas flow is furthermore introduced into the gap 10 between the electrodes 6, 8, which may be of such a velocity that it exerts a force on the plasma 4, in the same direction as the force exerted by the crossed electric and magnetic fields, which is represented by the black arrow 24. The gas flow helps the magnetic field in stabilising the plasma 4. By stabilising is meant that the glow discharge creating the plasma does not deteriorate into an electric arc.

[0036] Possible dimensions of the parts of the plasma generator 2 of Fig. 1 are represented in Fig. 2. For example, $d_1 = 2$ mm, $d_2 = 10$ mm, $\alpha = 10^\circ$, $d_3 = 25$ mm, $d_4 = 1$ mm or less (e.g. 0.5 mm) and $d_5 = 2$ mm. d_2/d_1 is comprised in the range between 1.5 and 10. The angle α and d_3 are a function of d_2/d_1 . d_4 is smaller than 10 mm.

[0037] The generated non-equilibrium plasma 4 may be used for example for flue gas cleaning in which case an array of plasma generators is preferably used and the flue gas may exit through the gaps 10 of the array. The plasma generator in accordance with the present

invention may also be used for surface treatment of paper, plastics such as polymers or for textile treatment. For surface treatment of paper, polymers or for textile treatment, it is important to have a plasma 4 which extends beyond the electrodes 6, 8, because introducing a fibre or another non-conducting material between the electrodes 6, 8 may cause disturbance of the DC current between the electrodes 6, 8, and might cause the plasma generation to be discontinued. It is the part of the plasma 4 pushed by the magnetic field into the region beyond the electrode gap 10 which is used for the surface treatment.

[0038] An example of an application of the DC plasma generator 2 of Fig. 1 is schematically represented in Fig. 3. An array of electrodes 6, 8 is provided. Between each pair of neighbouring electrodes 6, 8, an expanding gap 28, 30, 32 is provided. A material 26 to be treated, for example a textile material, passes next to the electrodes 6, 8, at the widest side of the gap 28, 30, 32. Plasma 4 is generated between each pair of neighbouring electrodes 6, 8, as indicated by the block arrow 16. The electric field lines in neighbouring gaps 28, 30; 30, 32 present the same direction but a different sense, as each electrode is either an anode 6 or a cathode 8 for two neighbouring gaps 28, 30; 30, 32. Permanent magnets 34, 36, 38 are provided at the upper and under sides of the electrode/dielectric arrangements. These are disposed such that the forces on the plasma 4, generated by the crossed electric and magnetic fields, work in the same directions, i.e. towards the wider mouth of the gaps 28-32. Therefore, the north and south poles of the permanent magnets 36 are reversed for each gap 30 as the electric field reverse directions in adjacent gaps 28-32. Plasmas extend beyond the mouths of the gaps 28, 30, 32 and can be used for surface treatment of a material 26 for example. For flue gas cleaning, the flue gas to be cleaned does not need to pass over the plasma 4 extending from the gaps 28, 30, 32, but the pollutants can be introduced into the gaps 28, 30, 32 and transported through the plasma 4 in order to expose pollutants such as hydrocarbons, e.g. toluene, to the free radicals in the plasma 4.

[0039] A second preferred embodiment of the DC plasma generator 2 according to the present invention is shown in Figs. 4 and 5. The anode 6 is formed around a longitudinal axis, and in cross-section, substantially has a helical form. The cathode 8 consists substantially of a curved plate, which is located around the anode 6, such that a spatially and helically extending gap 10 is present between the anode 6 and the cathode 8, with the smallest part of the gap 10 positioned at the smallest part of the helical form of the anode 6. The gap between the anode and the cathode is segregated into a plurality of open channels 43 by insulating plates 45. The anode 6 is connected to a positive pole of a DC power supply (not represented), and the cathode 8 is connected to a negative pole of the power supply. If a suitable voltage is generated between the anode 6 and the cathode 8, a

non-equilibrium DC plasma is generated at the level where anode 6 and cathode 8 are closest to each other, as represented by the block arrow 16. A magnetic field is applied along the longitudinal axis of the anode 6, e.g. by means of a coil arrangement whereby two coils 40, 42 of a diameter which is larger than the cross-sectional dimension of the anode 6 are positioned in a long axial alignment with the anode 6, and radially outward of both ends of the electrodes 6, 8. By excitation by a suitable DC current source, a stationary magnetic field is established with a highly uniform field magnetisation and direction, the direction of the magnetic field being represented by arrow 44. The crossed electrical and magnetic fields thus obtained, create a force on the plasma particles generated, which distributes the plasma in the direction of the centre line 12 of the gap 10 as shown in Fig. 5. The plasma is constrained between the plates 45 and is a non-equilibrium, non-local plasma. Due to the force exerted on it, the plasma will move through the gap 10, and finally exit in the space between the two electrodes 6, 8 in the channels 43. The DC plasma generator 2 described in Figs. 4 and 5 could e.g. be used as a brush, to surface treat plastics materials.

[0040] While the invention has been shown and described with reference to preferred embodiments, it will be understood by those skilled in the art that various changes or modifications in form and detail may be made without departing from the scope and spirit of this invention. More particularly it is possible to replace each of the one-piece electrodes 6, 8 by an array of parallel, equally spaced cylindrical electrodes 6A-6H, 8A-8H as represented in Fig. 6, extending through and supported by supporting members 46. Also other electrode arrangements are possible.

Claims

1. Plasma generator (2) for generating a non-local, non-equilibrium plasma (4) at a pressure greater than about 0.5 atmospheres, comprising:

two electrodes (6, 8) with a gap (10) therebetween,
a DC voltage generator (14) for generating a DC voltage between the two electrodes (6, 8), thus creating an electric field in the gap (10) between the electrodes (6, 8), and
a magnetic field generator (20) for generating a magnetic field in the gap perpendicular to the electric field for distributing the plasma (4) between the electrodes (6, 8) along the gap (10), the gap being substantially perpendicular to both the direction of the electric field and the direction of the magnetic field.

2. Plasma generator (2) according to claim 1, wherein the electrodes (6, 8) are disposed such that there

is an expanding gap (10) between them, the direction of expansion of the gap being substantially perpendicular to both the direction of the electric field and the direction of the magnetic field.

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3. Plasma generator (2) according to claims 1 or 2, further comprising at least one gas inlet tube for creating a gas flow between the two electrodes (6, 8) for further distributing the plasma (4).

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4. Plasma generator according to any of the claims, 1 to 3, wherein the electric field between the electrodes is in the range 1-40kV/cm.

5. Plasma generator according to any previous claim, wherein the magnetic field in the gap between the electrodes is in the range 0.01T to 1T.

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6. An array of plasma generators, each plasma generator being in accordance with any one of the claims 1 to 5.

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7. Method for generating and stabilising a non-local, non-equilibrium plasma at a pressure greater than about 0.5 atmospheres, comprising the steps of:

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generating a non-equilibrium plasma in a gap between two electrodes between which a DC electric field is applied,

generating a magnetic field in the gap perpendicularly to the electric field, and

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distributing the plasma by the crossed electric and magnetic fields along the gap, the direction of the gap being substantially perpendicular to both the direction of the electric field and the direction of the magnetic field.

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8. Method according to claim 7, wherein the plasma is furthermore distributed by applying a gas flow to the plasma.

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9. Method according to claim, 7 or 8, wherein the electric field between the electrodes is in the range 1-40kV/cm.

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10. Method according to any of the claims 7 to 9, wherein the magnetic field in the gap between the electrodes is in the range 0.01T to 1T.

11. Use of the plasma generator in accordance with any of the claims 1 to 6 in flue gas cleaning.

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12. Use of the plasma generator in accordance with any of the claims 1 to 6 in surface treatment of plastic, paper or textile materials.

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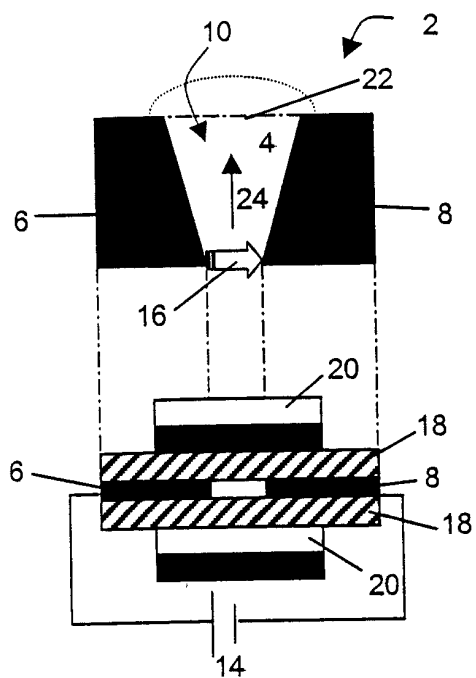


Fig. 1

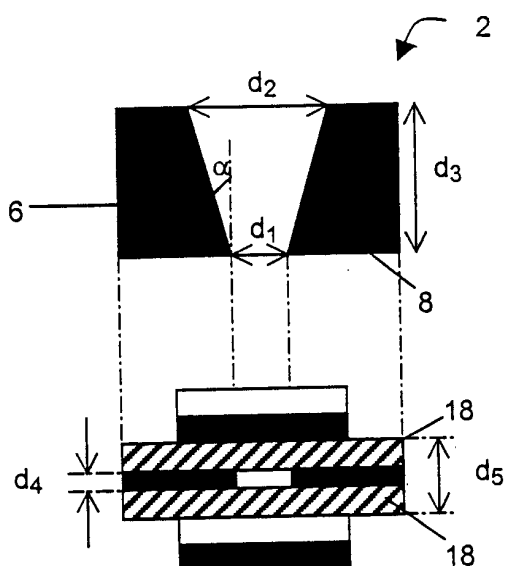


Fig. 2

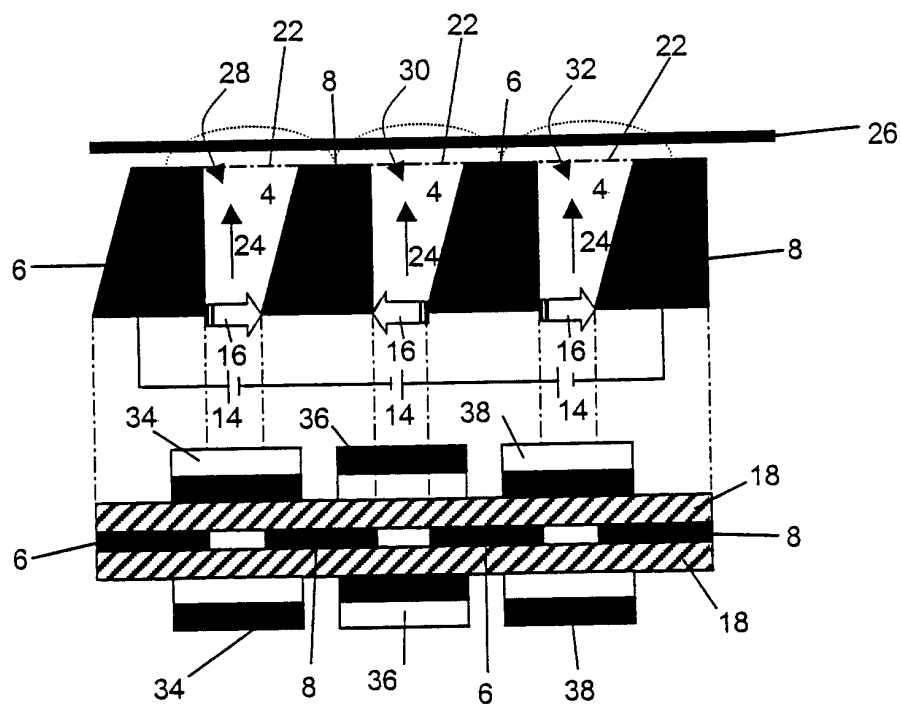


Fig. 3

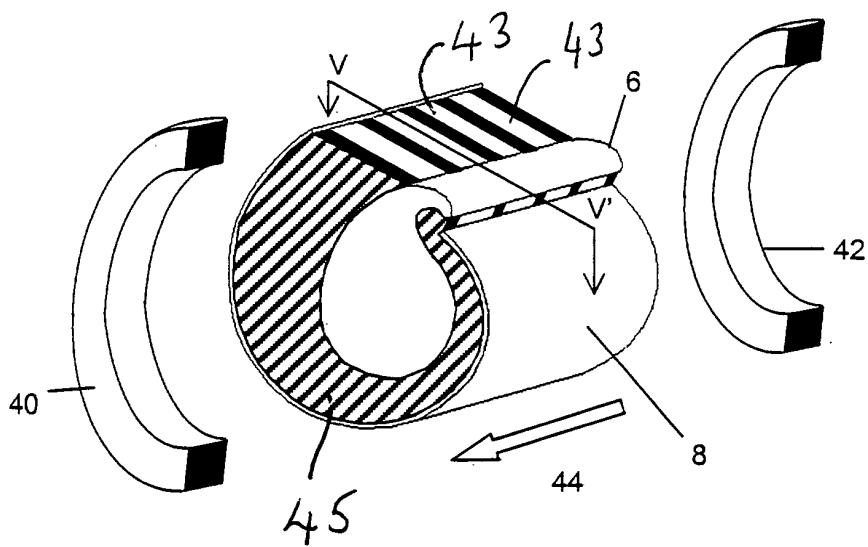


Fig. 4

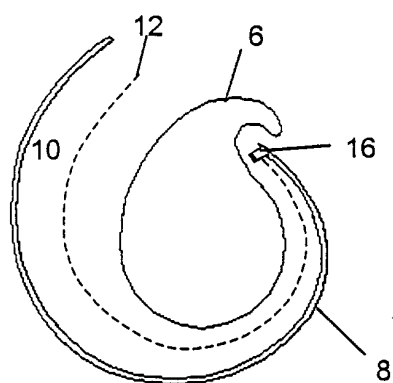


Fig. 5

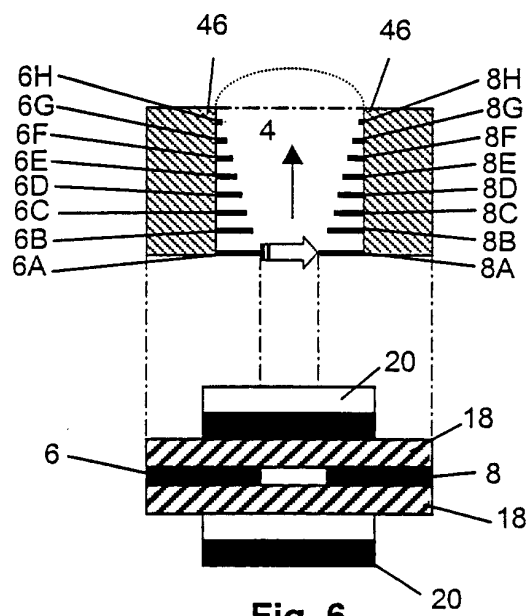


Fig. 6



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EPO FORM 1503 03/82 (P04C01)



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EUROPEAN SEARCH REPORT

Application Number
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