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(54) **PLASMA-GENERATING DEVICE HAVING A THROTTLING PORTION**

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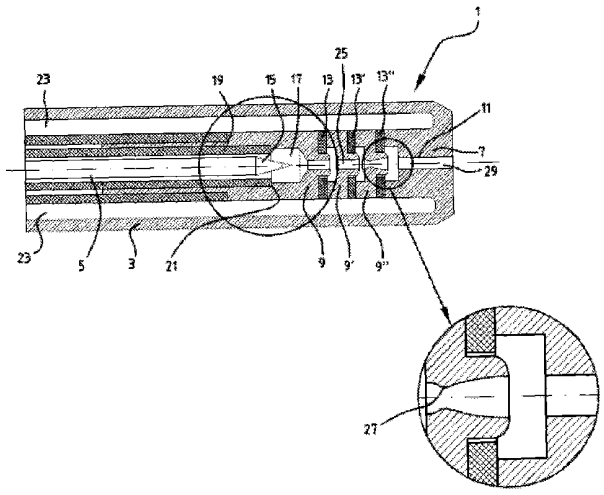
(57) **ABSTRACT**

The present invention relates to a plasma-generating device comprising an anode, a cathode, and intermediate electrodes. The intermediate electrodes and the anode form an elongate plasma channel that extends from a point between the cathode and the anode and through the anode. The plasma channel has a throttling portion with a throat having the smallest cross-sectional area of the entire plasma channel. As a plasma flow passes through the throttling portion, the plasma flow's speed is increased while its pressure is decreased. By varying the position of the throttling portion in the plasma channel properties of the discharged plasma can be changed. Plasma flows with different properties can be used for various applications, especially, medical procedures.

22 Claims, 4 Drawing Sheets



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current supplied to the device is preferably between 4 and 8 Amperes. With these operating currents, a supplied voltage is preferably between 50 and 150 volts.

Low operating currents are desirable in, for example, a surgical environment, where it can be difficult and not safe to provide the necessary supply of higher current levels. As a rule, high operating current levels require difficult to handle, extensive, unwieldy wiring, which is problematic for application requiring great accuracy, such as surgery, and in particular laparoscopic surgery. High operating currents can also be a safety risk for an operator and/or patient in certain environments and applications.

It is known that plasma suitable for biological tissue cutting can be obtained by designing the plasma channel in a suitable manner. The use of a throttling portion and a high pressure chamber, which allow heating of the plasma to desirable temperatures at preferred operating currents, provides the means for generating such plasma. Pressurizing the plasma in the high pressure chamber, upstream of the throttling portion, increases the energy density of the plasma. "Energy density" refers to the energy stored in a unit of plasma volume. Increased energy density is the result of the plasma, in the high pressure chamber, being heated by an electric arc established between the cathode and the anode in the plasma channel. The increased pressure in the high pressure chamber has also been found to enable operation of the plasma-generating device at lower operating currents. Furthermore, the increased pressure of the plasma in the high pressure chamber has also been found to enable operation of the device at lower plasma-generating gas flow rates. For example, experiments have shown that pressurization of the plasma in the high pressure chamber to about 6 bar can improve efficiency of the device by 30% compared to prior art devices, in which the plasma channel is arranged without a throttling portion and a high pressure chamber.

It has also been found that power loss in the anode can be reduced, compared with prior art plasma-generating devices, by pressurizing the plasma in a high pressure chamber.

It is also desirable to discharge plasma at a lower pressure than the pressure built up in the high pressure chamber. For example, the pressure built up in the high pressure chamber can be harmful to a patient. However, it has been found that the divergent portion of the throttling portion reduces the increased pressure of the plasma in the high pressure chamber as the plasma passes through it. (In this disclosure the term "pressure" refers to the static plasma flow pressure.) When passing the divergent portion, some of the excess pressure occurring in the high pressure chamber is converted into kinetic energy and the plasma flow is accelerated from the flow rate in the high pressure chamber.

A further advantage of the plasma-generating device according to the invention is that the plasma discharged through the plasma channel outlet has a higher kinetic energy than the kinetic energy of plasma flowing through the high pressure chamber. A plasma flow discharged with such an increased kinetic energy has been found suitable for cutting living biological tissue. Such a kinetic energy is sufficient for a plasma flow to penetrate an object and thus produce a cut.

It has also been found preferable, for surgical applications, to supply to the device a plasma-generating gas at a relatively low flow rate because a relatively high flow rate can be harmful to the treated patient. With low flow rates of the plasma-generating gas supplied to the device, it has been found that there exists the risk of one or more electric arcs forming between the cathode and walls of the high pressure chamber. This phenomenon is known as cascade electric arcs.

It has also been found that the possibility of such cascade electric arcs occurrence increases with a reduced cross-section of the plasma channel. Such cascade electric arcs can have a detrimental effect on the function of the plasma device, and the elements forming the high pressure chamber can be damaged and/or degraded as a result of the cascade electric arcs. There is also the risk that substances released from elements forming the high pressure chamber, as a result of the cascade electric arcs, would contaminate plasma, which can be harmful to a patient. Experiments have shown that the above-noted problems can arise with a gas flow rate of less than 1.5 l/min and a cross-section of the plasma channel of less than 1 mm^2.

In one aspect of the invention, it is preferable to arrange at least one intermediate electrode in the high pressure chamber to reduce the risk of the cascade electric arcs occurrence. Preferably, the cross-section of the high pressure chamber, formed by at least one intermediate electrode, is selected so that the desired temperature of the electric arc, and thus the desired temperature of plasma, can are achieved at the above operating current levels. The arrangement of at least one intermediate electrode forming the high pressure chamber reduces the risk of the plasma contamination. In the high pressure chamber formed by the intermediate electrode(s), the electric arc heats the generated plasma. Intermediate electrodes refer to one or more electrodes arranged upstream of the anode. It should also be appreciated that electric voltage is applied across each intermediate electrode during operation of the plasma-generating device.

In the preferred embodiment, the plasma-generating device comprises at least one intermediate electrode arranged upstream of the throttling portion and forming the high pressure chamber with a relatively small cross-section. Such a device is capable of generating plasma with unexpectedly low contamination levels and other desirable properties, which are particularly useful for cutting biological tissue. However, it is noted that the plasma-generating device can also be used for other surgical applications. It is possible to generate plasma suitable for vaporization or coagulation of biological tissue by changing current and/or gas flow rates.

It has also been found that the plasma-generating device allows controlled variations of the relationship between thermal energy and kinetic energy of the generated plasma. It has been found convenient to be able to use plasma with different relationships between thermal energy and kinetic energy when treating different objects, such as soft and hard biological tissue. It has also been found convenient to vary the relationship between thermal energy and kinetic energy depending on the blood flow rate in the biological tissue that is to be treated. In some cases it is convenient to use a plasma with a greater amount of thermal energy in connection with higher blood flow rate in the tissue and a plasma with lower thermal energy in connection with lower blood flow rate in the tissue. The relationship between thermal energy and kinetic energy of the generated plasma can be controlled, for example, by the pressure level established in the high pressure chamber. Higher pressure in the high pressure chamber results in the increased kinetic energy of the plasma flow when it is being discharged. Consequently, the ability to vary the relationship between thermal energy and kinetic energy of the generated plasma permits the combination of the cutting action and the coagulating action to be adjusted for treatment of different types of biological tissue, in surgical applications.

Preferably, the high pressure chamber is formed mainly of the one or more intermediate electrodes. In the high pressure chamber formed by the intermediate electrode(s), the electric arc effectively heats the passing plasma. Having the interme-

diate electrode(s) form a part of the high pressure chamber provides an advantage of the high pressure chamber being of a suitable length without the cascade electric arcs forming between the cathode and the inside surface of these electrode (s). As mentioned above, an electric arc formed between the cathode and the inner surface of an intermediate electrode can damage and/or degrade the high pressure chamber.

In one embodiment of the plasma-generating device, the high pressure chamber is formed by two or more intermediate electrodes. In that embodiment, the plasma channel is formed by multielectrodes. By forming the high pressure chamber by multielectrodes, the high pressure chamber can be given an increased length to allow the plasma to be heated to about the temperature of the electric arc. The smaller cross-section and the larger length of the high pressure chamber have been found necessary for heating the plasma to about the temperature of the electric arc. Experiments focusing on the length of the intermediate electrodes forming the plasma channel have been performed. The experiments have shown that a higher number of intermediate electrodes can be used to decrease the length of each electrode forming the plasma channel. Increasing the number of the intermediate electrodes results in reduction of the applied electric voltage across each intermediate electrode.

It has also been found beneficial to arrange a larger number of intermediate electrodes downstream of the throttling portion when increasing the pressure of the plasma in the high pressure chamber. In addition, it has been observed that by using a larger number of intermediate electrodes when increasing the pressure of the plasma in the high pressure chamber, it is possible to maintain substantially the same voltage differential per intermediate electrode, which reduces the risk of the cascade electric arcs occurrence.

The use of a relatively long high pressure chamber demonstrates the risk that the electric arc does not get established between the cathode and the anode if each individual electrode is too long. Instead, shorter electric arcs are established between the cathode and the intermediate electrodes and/or between adjacent intermediate electrodes. Preferably, a relatively high number of intermediate electrodes form the high pressure chamber and, thus, reducing the voltage applied to each intermediate electrode. Consequently, a relatively high number of intermediate electrodes should be used when forming a long high pressure chamber, especially when the high pressure chamber has a small cross-sectional area. Experiments have shown that the voltage of less than 22 volt can be safely applied to each of the intermediate electrodes. With preferred operating current levels as stated above, it has been found that the voltage level across the electrodes is preferably between 15 and 22 volt/mm.

In one embodiment, the high pressure chamber is formed by three or more intermediate electrodes as a part of a multi-electrode plasma channel.

In one embodiment of the plasma-generating device, the second maximum cross-sectional area is equal to or is smaller than 0.65 mm^2. In one embodiment, the second maximum cross-sectional area is between 0.05 and 0.44 mm^2. In an alternative embodiment, the second maximum cross-sectional area is between 0.13 and 0.28 mm^2. By arranging the low pressure chamber with such cross-sectional areas, it has been found possible to discharge, through the plasma channel outlet, a plasma flow with high energy concentration. A plasma flow with high energy concentration is particularly useful for cutting biological tissue. A small cross-sectional area of the generated plasma flow is also advantageous for procedures requiring a great accuracy. Moreover, a low pressure chamber with such cross-sections facilitates plasma acceleration, increase in kinetic energy, and reduction in pressure, making the plasma suitable for use in surgical applications.

The third cross-sectional area is preferably in the range between 0.008 and 0.12 mm^2. In an alternative embodiment, the third cross sectional area is between 0.030 and 0.070 mm^2. The throttling portion with the throat having such a cross-sectional area has been found to produce an optimal pressure increase of plasma in the high pressure chamber. Furthermore pressurization of the plasma in the high pressure chamber affects plasma's energy density as described above. The pressure increase of plasma in the high pressure chamber by the throttling portion is thus advantageous to obtain desirable heating of the plasma at preferred plasma-generating gas flow rates and operating current levels.

The selected cross-sectional area of the throttling portion throat results in the pressure, in the high pressure chamber, that is capable of accelerating the plasma flow to a supersonic speed with a value equal to or greater than Mach 1, when the plasma passes through the throttling portion. The critical pressure level required in the high pressure chamber for the plasma flow to achieve supersonic speeds in the low pressure chamber has been found to depend on, among others, the cross-sectional area of the throat and the geometric shape of the throttling portion. It has also been found that the critical pressure for achieving supersonic speeds is also dependent on the kind of plasma-generating gas used and the plasma temperature. It should be noted that the third cross sectional area (of the throttling portion throat) is always smaller than the first maximum (of the high pressure chamber) and the second (of the low pressure chamber) maximum cross-sectional areas.

Preferably, the first maximum cross-sectional area of the high pressure chamber is in the range between 0.03 and 0.65 mm^2. Such a maximum cross-sectional area has been found suitable for heating the plasma to the desired temperature at the preferred levels of gas flow rates and operating currents.

The temperature of an electric arc established between the cathode and the anode depends on, among others, the first maximum cross-sectional area of the high pressure chamber. A smaller cross-sectional area of the high pressure chamber results in the increased energy density of the electric arc. The temperature of the electric arc along the center axis of the plasma channel is proportional to the quotient of the discharge current (passing between the cathode and the anode) and the cross-sectional area of the plasma channel.

In an alternative embodiment, the high pressure chamber has the first cross-sectional area of between 0.05 and 0.33 mm^2. In another alternative embodiment, the high pressure chamber has the first cross-sectional area between 0.07 and 0.20 mm^2.

Preferably, the throttling portion is formed by an intermediate electrode. This arrangement reduces the risk of the cascade electric arcs occurring between the cathode and the throttling portion. Similarly, this arrangement decreases the risk of the cascade electric arcs occurring between the throttling portion and other intermediate electrodes, such as electrodes adjacent to the throttling portion.

Preferably, the low pressure chamber is formed by at least one intermediate electrode. Forming the low pressure chamber with one or more intermediate electrodes reduces the risk of the cascade electric arcs occurring between the cathode and the surface of the low pressure chamber. This also reduces the risk of the cascade electric arc occurring between neighboring intermediate electrodes.

Preferably, the intermediate electrodes forming the throttling portion and the low pressure chamber contribute to the

properly established electric arc between the cathode and the anode. For some applications it may be desirable to arrange the throttling portion between two intermediate electrodes, one forming the high pressure chamber and another forming the low pressure chamber. In one embodiment, the throttling portion can be arranged between (1) at least two intermediate electrodes that form a part of the high pressure chamber and (2) at least two intermediate electrodes that form a part of the low pressure chamber.

It has been found suitable to design the plasma-generating device in such a manner that a substantial part of the plasma channel that extends from a point between the cathode and the anode to the anode is formed by intermediate electrodes. Such a channel also makes possible heating of plasma along substantially the entire length of the plasma channel.

In one embodiment, the plasma-generating device comprises at least two intermediate electrodes, preferably at least three intermediate electrodes. In an alternative embodiment, the plasma-generating device comprises between 2 and 10 intermediate electrodes, and according to another alternative embodiment between 3 and 10 intermediate electrodes. Varying the number of intermediate electrodes allows forming the plasma channel of an optimal length for heating plasma at desirable levels of the plasma-generating gas flow rate and operating current. Moreover, the intermediate electrodes are preferably spaced from each other with insulator washers. The intermediate electrodes are preferably made of copper or alloys containing copper.

In one embodiment, the first maximum cross-sectional area, the second maximum cross-sectional area, and the third cross-sectional area are circles. Circular cross-sections of the plasma channel simplify and make less expensive the manufacture of the device.

In one embodiment, the distal portion of the cathode has a tip tapering toward the anode. Further in one embodiment, an intermediate electrode forms a plasma chamber connected to the inlet of the plasma channel. A part of the cathode tip extends over a partial length of the plasma chamber. The plasma chamber has a fourth cross-sectional area that is larger than the first maximum cross-sectional area. Such a plasma chamber makes it possible to reduce the plasma-generating device's outer dimensions. The plasma chamber provides space around the distal end of the cathode, especially the tip. This space reduces the risk that, in operation, the heat emanating from the cathode would damage and/or degrade elements in the proximity of the cathode. The plasma chamber is particularly important for long continuous periods of the device operation.

Another advantage is achieved by the plasma chamber in the proper generation of the electric arc. Specifically, for proper operation, the electric arc must be established between the cathode and the anode. For that to happen, the initial spark must enter into the plasma channel. The plasma chamber allows the tip of the cathode to be positioned in the vicinity of the plasma channel inlet without the surrounding elements being damaged and/or degraded due to the high temperature of the cathode. If the tip of the cathode is positioned at too great a distance from the plasma channel inlet, an electric arc is often established between the cathode and another structure, which may result in incorrect operation of the device and in some cases even in the device being damaged.

According to a second aspect of the invention, a plasma surgical device, comprising a plasma-generating device as described above, is provided. Such a plasma surgical device can be used for destruction or coagulation of biological tissue, and especially for cutting. Moreover, such a plasma surgical device can be used in heart or brain surgery. Alternatively, such a plasma surgical device can be used in liver, spleen, or kidney surgery.

According to a third aspect of the invention, a method of generating plasma is provided. This method comprises, at an operating current of 4 to 10 Amperes, supplying to the plasma-generating device a plasma-generating gas at the flow rate of 0.05 to 1.00 l/min. The plasma-generating gas preferably comprises an inert gas, such as argon, neon, xenon, helium etc. This method produces a plasma flow suitable for cutting biological tissue.

In an alternative embodiment, the flow rate of the supplied plasma-generating gas can be between 0.10 and 0.80 l/min. In another alternative embodiment, the flow rate can be between 0.15 and 0.50 l/min.

According to a fourth aspect of the invention, a method of generating plasma by a plasma-generating device is provided. The device comprises an anode, a cathode, and a plasma channel extending from a point between the cathode and the anode and through the anode, the plasma channel having a throttling portion. The method comprises providing plasma flowing from the cathode to the anode (this direction of the plasma flow gives meaning to the terms "upstream" and "downstream" as used herein); increasing energy density of the plasma flow by pressurizing plasma in a high pressure chamber positioned upstream of the throttling portion; heating the plasma by using at least one intermediate electrode which is arranged upstream of the throttling portion; and depressurizing and accelerating the plasma flow by passing it through the throttling portion and discharging the plasma flow through the plasma channel outlet.

With such a method, it is possible to generate a substantially contaminant free plasma flow that can be heated to the desired temperature and be given the desired kinetic energy at the operating currents and gas flow levels as described above.

The pressure of plasma in the high pressure chamber is between 3 and 8 bar, preferably 5-6 bar. Such pressure levels are preferred for providing the plasma flow with energy density that facilitates heating to desirable temperatures at desirable operating current levels. Such pressure levels have also been found to result in acceleration of the plasma flow to a supersonic speed when the flow passes through the throttling portion.

In the low pressure portion, the plasma flow is preferably pressurized to a level that exceeds the prevailing atmospheric pressure outside the plasma channel outlet by less than 2 bar, alternatively 0.25-1 bar, and according to another alternative 0.5-1 bar. Reducing the pressure of the plasma flow discharged from the plasma channel outlet to the above levels reduces the risk of the plasma flow injuring the treated patient.

As mentioned above, the increased pressure of the plasma flow in the high pressure chamber enables the plasma flow to accelerate to supersonic speed of Mach 1 or higher, when the plasma flow passes through the throttling portion. The pressure required to achieve a speed higher than Mach 1 depends on the pressure of the plasma flow and the nature of the supplied plasma-generating gas. The pressure in the high pressure chamber depends, in turn, on the shape of the throttling portion and the cross-sectional area of the throat. Preferably, the plasma flow is accelerated to 1-3 times the supersonic speed, that is the flow speed between Mach 1 and Mach 3.

Inside the plasma channel, in some embodiments the plasma is preferably heated to a temperature between 11,000 and 20,000° C., in other embodiments 13,000 to 18,000° C.,

and 14,000 to 16,000° C. Such temperature levels are sufficient to make the discharged plasma flow suitable for cutting biological tissue.

To generate and discharge the plasma flow, as described above, a plasma-generating gas is supplied to the plasma-generating device. It has been found preferable to provide the plasma-generating gas at the rate between 0.05 and 1.00 l/min, in other embodiments 0.10-0.80 l/min, and in the preferred embodiments, 0.15-0.50 l/min. With such flow rates of the plasma-generating gas, it is possible for plasma to be heated to the desired temperatures at desired operating current levels. The above-mentioned flow rates are also suitable in surgical applications because they do not create significant risk of injuries to a patient.

The plasma flow should be discharged through an outlet with a certain cross-sectional area. In some embodiments a cross-sectional area is below 0.65 mm^2, in some embodiments between 0.05 and 0.44 mm^2, and in the preferred embodiments 0.13-0.28 mm^2. In some embodiments the operating current is between 4 and 10 Amperes, preferably 4-8 Amperes is supplied to the device.

According to another aspect of the invention, the above-mentioned method of generating a plasma flow can be used as a part of a method for cutting biological tissue.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described in more detail with reference to the accompanying schematic drawings, which by way of example illustrate currently preferred embodiments of the invention.

FIG. **1***a* is a longitudinal cross-sectional view of an embodiment of a plasma-generating device according to the invention;

FIG. **1***b* is partial enlargement of the embodiment in FIG. **1***a;*

FIG. **1***c* is a partial enlargement of a throttling portion arranged in a plasma channel of the plasma-generating device in FIG. **1***a;*

FIG. **2** illustrates an alternative embodiment of a plasma-generating device;

FIG. **3** illustrates another alternative embodiment of a plasma-generating device;

FIG. **4** shows exemplary power levels to affect biological tissue in different ways; and

FIG. **5** shows the relationship between the temperature of a plasma flow and the plasma-generating gas flow rate at different operating power levels.

DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. **1***a* is a longitudinal cross-sectional view of one embodiment of a plasma-generating device **1** according to the invention. The cross-section in FIG. **1***a* is taken through the center of the plasma-generating device **1** in its longitudinal direction. The device comprises an elongated end sleeve **3** that encloses other elements of the device. In operation, plasma flows from the proximal end of the device (left side of FIG. **1***a*) and is discharged at the end of sleeve **3** (right side of FIG. **1***a*). The flow of plasma gives meaning to the terms "upstream" and "downstream." The discharge end of sleeve **3** is also referred to as the distal end of device **1**. In general, the term "distal" refers to facing the discharge end of the device; the term "proximal" refers to facing the opposite direction. The terms "distal" and "proximal" can be used to describe the ends of device **1**, as well as its elements. The generated plasma can be used, for example, to stop bleeding in tissues, vaporize tissues, cut tissues, etc.

The plasma-generating device **1** according to FIG. **1***a* comprises cathode **5**, anode **7** and a number of electrodes **9**, **9'**, **9"**, referred to as intermediate electrodes in this disclosure, arranged upstream of anode **7**. In the preferred embodiment, the intermediate electrodes **9**, **9'**, **9"** are annular and form a part of a plasma channel **11**, which extends from a position downstream of the cathode **5** and further toward and through anode **7**. Plasma channel **11** extends through anode **7**, where its outlet is arranged. In plasma channel **11**, plasma is heated and discharged through the outlet. Intermediate electrodes **9**, **9'**, **9"** are insulated and separated from each other by an annular insulator washers **13**, **13'**, **13"**. The shape of intermediate electrodes **9**, **9'**,**9"** and the dimensions of the plasma channel **11** can be adjusted for any desired purpose. The number of intermediate electrodes **9**, **9'**, **9"** can also be varied. The exemplary embodiment shown in FIG. **1***a* is configured with three intermediate electrodes **9**, **9'**, **9"**.

In the embodiment shown in FIG. **1***a*, cathode **5** is formed as an elongated cylindrical element. Preferably, cathode **5** is made of tungsten, optionally with additives, such as lanthanum. Such additives can be used, for example, to lower the temperature that the distal end of cathode **5** reaches.

In the preferred embodiment, the distal portion of cathode **5** has a tapering portion **15**. Tapering portion **15** forms a tip as shown in FIG. **1***a*. Preferably, cathode tip **15** is a cone. In some embodiments, cathode tip **15** is a truncated cone. In other embodiments, cathode tip **15** may have other shapes, tapering toward anode **7**.

The proximal end of cathode **5** is connected to an electrical conductor that is connected to an electric energy source. The conductor, which is not shown in FIG. **1***a*, is preferably surrounded by an insulator.

Plasma chamber **17** is connected to the inlet of plasma channel **11**. Plasma chamber **17** has a cross-sectional area that is greater than the maximum cross-sectional area of plasma channel **11** at its inlet. Plasma chamber **17**, as shown in FIG. **1***a*, has a circular cross-section and has length L_{ch}, which approximately equals diameter D_{ch} of plasma chamber **17**. Plasma chamber **17** and plasma channel **11** are substantially concentrically arranged relative to each other. In the preferred embodiment, cathode **5** is arranged substantially concentrically with plasma chamber **17**. Cathode **5** extends into the plasma chamber **17** over approximately half of the plasma chamber **17**'s length. Plasma chamber **17** is formed by a recess in the proximal-most intermediate electrode **9**.

FIG. **1***a* also shows insulator sleeve **19** extending along and around a portion of cathode **5**. Cathode **5** is arranged substantially in the center of the through hole of insulator sleeve **19**. The inner diameter of insulator sleeve **19** is slightly greater than the outer diameter of cathode **5**. The difference in these diameters results in a gap formed by the outer surface of cathode **5** and the inner surface of insulator sleeve **19**.

Preferably insulator sleeve **19** is made of a temperature-resistant material, such as ceramic, temperature-resistant plastic, or the like. Insulator sleeve **19** protects constituent elements of plasma-generating device **1** from heat generated by cathode **5**, and in particular by cathode tip **15**, during operation.

Insulator sleeve **19** and cathode **5** are arranged relative to each other so that the distal end of cathode **5** projects beyond the distal end of insulator sleeve **19**. In the embodiment shown in FIG. **1***a*, approximately half of the length of cathode tip **15** extends beyond distal end **21** of insulator sleeve **19**, which, in that embodiment, is a surface.

A gas supply part (not shown in FIG. **1***a*) is connected to the plasma-generating device. The gas supplied, under pressure, to plasma-generating device **1** consists of the same type of gases that are used in prior art instruments, for example, inert gases, such as argon, neon, xenon, or helium. The plasma-generating gas flows through the gas supply part and into the gap formed by the outside surface of cathode **5** and the inside surface of insulator sleeve **19**. The plasma-generating gas flows along cathode **5** inside insulator sleeve **19** toward anode **7**. (As mentioned above, this direction of the plasma flow gives meaning to the terms "upstream" and "downstream" as used herein.) As the plasma-generating gas passes distal end **21** of the insulator sleeve **19**, the gas enters into plasma chamber **17**.

The plasma-generating device **1** further comprises one or more auxiliary channels **23**. Auxiliary channels **23** traverse a substantial length of device **1**. In some embodiments, a proximal portion of each channel **23** is formed, in part, by a housing (not shown) which is connected to end sleeve **3**, while a distal portion of each channel **23** is formed, in part, by end sleeve **3**. End sleeve **3** and the housing can be interconnected by a threaded joint or by other coupling means, such as welding, soldering, etc. Preferably end sleeve **3** has a relatively small outer diameter, such as less than 10 mm, or, preferably, even less than 5 mm. The housing portion positioned at the proximal end of sleeve **3** has an outer shape and dimension that substantially correspond to the outer shape and dimension of sleeve **3**. In the embodiment of the plasma-generating device shown in FIG. **1***a*, end sleeve **3** is circular in cross-section.

In one embodiment, plasma-generating device **1** has two channels **23** connecting inside end sleeve **3** in the vicinity of anode **7**. In this configuration, channels **23** collectively form a cooling system with one channel **23** having an inlet and the other channel **23** having an outlet. The two channels are connected with each other to allow the coolant to pass between them inside end sleeve **3**. It is also possible to arrange more than two channels **23** in the plasma-generating device **1**. Preferably, water is used as coolant, although other fluids are contemplated. The cooling channels are arranged so that the coolant is supplied to end sleeve **3** and flows between intermediate electrodes **9**, **9'**, **9"** and the inner wall of end sleeve **3**.

Intermediate electrodes **9**, **9'**, **9"** and insulator washers **13**, **13'**, and **13"** are arranged inside end sleeve **3** of the plasma-generating device **1** and are positioned substantially concentrically with end sleeve **3**. The intermediate electrodes **9**, **9'**, **9"** and insulator washers **13**, **13'**, and **13"** have outer surfaces, which together with the inner surface of sleeve **3** form auxiliary channels **23**.

The number and cross-section of auxiliary channels **23** can vary. It is also possible to use all, or some, of auxiliary channels **23** for other purposes. For example, three auxiliary channels **23** can be arranged, with two of them being used for cooling, as described above, and the third one being used for removing undesired liquids or debris from the surgical site.

In the embodiment shown in FIG. **1***a*, three intermediate electrodes **9**, **9'**, **9"** are spaced apart by insulator washers **13**, **13'**, **13"** arranged between each pair of the intermediate electrodes, and between the distal-most intermediate electrode and anode **7**. The first intermediate electrode **9**, the first insulator **13'** and the second intermediate electrode **9'** are press-fitted to each other.

The proximal-most electrode **9"** is in contact with annular insulator washer **13"**, which, in turn, is in contact with anode **7**. While in the preferred embodiment insulators **13**, **13'**, and **13"** are washers, in other embodiments they can have any annular shape.

Anode **7** is connected to elongated end sleeve **3**. In the embodiment shown in FIG. **1***a*, anode **7** and end sleeve **3** are formed integrally with each other. Note that in this configuration, "anode" refers to the portion of the joint structure that forms a part of the plasma channel. In alternative embodiments, anode **7** can be formed as a separate element coupled to end sleeve **3** by any known means, such as a threaded joint, welding, or soldering. The connection between anode **7** and end sleeve **3** provides electrical contact between them.

Plasma-generating device **1** shown in FIG. **1***a* has plasma channel **11** which comprises high pressure chamber **25**, throttling portion **27**, and low pressure chamber **29**. Throttling portion **27**, which generally has an hourglass shape, is positioned between high pressure chamber **25** and low pressure chamber **29**. In this disclosure, high pressure chamber **25** refers to the part of the plasma chamber **11** positioned upstream of throttling portion **27**. Low pressure chamber **29** refers to the part of plasma channel **11** positioned downstream of the throttling portion **27**.

Throttling portion **27** shown in FIG. **1***a* has a throat, which constitutes the smallest cross-section of the plasma channel **11**. Consequently, the cross-section of the throttling portion throat is smaller than the maximum cross-section of high pressure chamber **25** and the maximum cross-section of low pressure chamber **29**. As shown in FIGS. **1***a* and **1***c*, the throttling portion is preferably a supersonic nozzle or a de Laval nozzle.

In operation, throttling portion **27** results in the pressure of plasma in high pressure chamber **25** being greater than in low pressure chamber **29**. When plasma flows through throttling portion **27**, the plasma flow speed is increased and the pressure of the plasma flow drops. Consequently, the plasma flow discharged through the plasma channel outlet has a higher kinetic energy and a lower pressure than plasma in high pressure chamber **25**. In the plasma-generating device shown in FIG. **1***a*, the outlet of the plasma channel **11** in anode **7** has the same cross-sectional area as the maximum cross-sectional area of low pressure chamber **29**.

In the embodiment shown in FIG. **1***a*, as viewed in the direction of the plasma flow, the throttling portion **27** gradually converges toward the throat and gradually diverges from the throat. This shape of throttling portion **27**, among others, reduces turbulence in the plasma flow. This is desirable because turbulence may reduce the plasma flow speed.

In the partial enlargement shown in FIG. **1***c*, throttling portion **27** converges upstream of the throat and diverges downstream of the throat. In the embodiment shown in FIG. **1***c*, the diverging portion is shorter than the converging portion.

With the design of the throttling portion **27**, shown in FIG. **1***c*, it has been found possible to accelerate the plasma flow to a supersonic speed of Mach 1 or above.

Plasma channel **11** shown in FIG. **1***a* is circular in cross-section. High pressure chamber **25** has a maximum cross-sectional diameter between 0.20 and 0.90 mm; in some embodiments it is between 0.25 and 0.65 mm; and in the preferred embodiment it is between 0.30-0.50 mm. Moreover, low pressure chamber **29** has a maximum cross-sectional diameter between 0.20 and 0.90 mm; in some embodiments it is between 0.25 and 0.75 mm; and in the preferred embodiment it is between 0.40 and 0.60 mm. The throat of throttling portion **27** has a cross-sectional diameter between 0.10 and 0.40 mm, preferably between 0.20-0.30 mm.

FIG. **1***a* shows an exemplary embodiment of plasma-generating device **1** with high pressure chamber **25** having a cross-sectional diameter of 0.4 mm, low pressure chamber **29**

having a cross-sectional diameter of 0.50 mm, and the throat of throttling portion **27** having a cross-sectional diameter of 0.27 mm.

In the embodiment shown in FIG. **1***a*, throttling portion **27** is positioned approximately in the middle of plasma channel **11**. By changing the location of throttling portion **27** in plasma channel **11**, it is possible, however, to vary the relationship between kinetic energy and thermal energy of the generated plasma flow.

FIG. **2** is a cross-sectional view of an alternative embodiment of plasma-generating device **101**. In the embodiment shown in FIG. **2**, throttling portion **127** is formed by anode **107** in the vicinity of the plasma channel **111** outlet. By arranging throttling portion **127** in the distal portion of plasma channel **111**, for example, in or near anode **107**, it is possible to generate and discharge a plasma flow with a higher kinetic energy compared with the embodiment of device **1** shown in FIG. **1***a*. It has been found that certain types of tissue, for example, soft tissues such as liver, can be cut easier with a plasma flow having a higher kinetic energy. Specifically, it has been found preferable for the plasma flow used for cutting such tissues to have approximately 50% of its energy be thermal and approximately 50% be kinetic.

The embodiment of plasma-generating device **101** in FIG. **2** comprises seven intermediate electrodes **109**. It will be appreciated, however, that the embodiment of the plasma-generating device **101** in FIG. **2** can have more or fewer than seven intermediate electrodes **109**.

FIG. **3** shows another alternative embodiment of plasma-generating device **201**. In the embodiment shown in FIG. **3**, throttling portion **227** is formed by the proximal-most intermediate electrode **209**. By arranging throttling portion **227** in the proximal portion of plasma channel **211**, it is possible to generate and discharge a plasma flow with lower kinetic energy compared with embodiments of devices **1** and **101** shown in FIGS. **1***a*. and **2**, respectively. It has been found that certain hard tissues, such as bone, can be cut easier with a plasma flow having higher thermal energy and lower kinetic energy. For example, it has been found preferable for bone cutting to generate a plasma flow with 80-90% of the total energy being thermal and 10-20% of the total energy being kinetic.

The embodiment of the plasma-generating device **201** in FIG. **3** comprises five intermediate electrodes **209**. It will be appreciated, however, that the embodiment of the plasma-generating device **201** in FIG. **3** can have more or fewer than five intermediate electrodes **209**.

It will be appreciated that depending on the desired properties of the discharged plasma flow, the throttling portion can be arranged in practically any position in the plasma channel. Moreover, it will be appreciated that alternative arrangements of elements described with reference to the embodiment shown in FIGS. **1***a*-**1***c*, similarly apply to the embodiments shown in FIGS. **2**-**3**, as well as other embodiments.

FIG. **4** shows power levels of a plasma flow for achieving different effects (i.e., coagulation, vaporization, or cutting) on an exemplary living biological tissue. It is apparent that the same effect can be achieved at different power levels depending on the diameter of the discharged plasma flow. FIG. **4** shows the relationships between these power levels and the diameter of plasma flows discharged from plasma channel **1**; **111**; or **211** of respective devices **1**; **101**; **201**, as described above. To reduce the operating current, it has been found preferable to reduce the diameter of plasma channel **11**; **111**; **211**, and consequently reduce the diameter of the discharged plasma flow, as shown in FIG. **4**.

FIG. **5** shows the relationship between the temperature of the discharged plasma flow and the plasma-generating gas flow rate. To achieve the desirable effect, such as coagulation, vaporization, or cutting at different power levels, a certain plasma-generating gas flow rate is required, as shown in FIG. **5**. As described above, even with relatively low plasma-generating gas flow rates, it is possible to generate a plasma flow with a certain temperature, at a certain power level. At the same time, with relatively low plasma-generating gas flow rates, it is possible to keep the operating current below a predetermined threshold that is known not to be harmful to the treated patient.

It has been found that embodiments 1; 101; 201 of the plasma-generating devices shown in FIGS. **1***a*-**3** enable the generation of a plasma flow with the desired properties. Thus, embodiments 1, 101, and 201 can be used to generate plasma flows suitable for cutting living biological tissue at safe operating currents and plasma-generating gas flow rates.

Preferred geometric relationships between parts of the plasma-generating device **1**; **101**; **201** are described below with reference to FIGS. **1***a*-**1***b*. It is noted that the dimensions described below are only exemplary and can be varied depending on the application and the desired plasma properties. It is also noted that the examples given in connection with FIGS. **1***a*-*b* are applicable to embodiments shown in FIGS. **2**-**3**.

The inner diameter d_i of insulator sleeve **19** is only slightly greater than the outer diameter d_c of cathode **5**. In one embodiment, the area of the gap between insulator sleeve **19** and cathode **5** is equal to or greater than a cross-sectional area of the inlet of plasma channel **11** in a common cross-section.

In the embodiment shown in FIG. **1***b*, the outer diameter d_c of the cylindrical portion of cathode **5** is about 0.50 mm and the inner diameter d_i of insulator sleeve **19** is about 0.80 mm.

In one embodiment, cathode **5** is arranged so that a partial length of cathode tip **15** projects beyond distal boundary surface **21** of insulator sleeve **19**. In FIG. **1***b*, cathode tip **15** is positioned so that approximately half of cathode tip **15** length, L_c, projects beyond boundary surface **21**. In the embodiment shown in FIG. **1***b*, the length by which cathode tip **15** projects beyond boundary surface **21**, l_c, approximately equals to the diameter d_c of cathode **5** at the base of tip **15**.

The total length L_c of cathode tip **15** is greater than 1.5 times the diameter d_c of cathode **5** at the base of cathode tip **15**. Preferably, the total length L_c of the cathode tip **15** is about 1.5-3 times the diameter d_c of cathode **5** at the base of cathode tip **15**. In the embodiment shown in FIG. **1***b*, the length L_c of cathode tip **15** is approximately 2 times the diameter d_c of cathode **5** at the base of cathode tip **15**.

In one embodiment, the diameter d_c of cathode **5** at the base of cathode tip **15** is about 0.3-0.6 mm. In the embodiment shown in FIG. **1***b*, this diameter is about 0.50 mm. Preferably, cathode **5** has a uniform diameter d_c between the base of cathode tip **15** and its proximal end. However, it should be appreciated that it is possible for cathode **5** to have a non-uniform diameter between the base of cathode tip **15** and the proximal end.

In one embodiment, plasma chamber **17** has a diameter D_{ch} that is approximately 2-2.5 times the diameter d_c of cathode **5** at the base of cathode tip **15**. In the embodiment shown in FIG. **1***b*, plasma chamber **17** has the diameter D_{ch} that is 2 times the diameter d_c of the cathode **5** at the base of cathode tip **15**.

The length L_{ch} of plasma chamber **17** is approximately 2-2.5 times the diameter d_c of cathode **5** at the base of cathode

tip **15**. In the embodiment shown in FIG. **1***b*, the length L_{ch} of plasma chamber **17** is approximately equal to the diameter of the plasma chamber **17**, D_{ch}.

In one embodiment, cathode tip **15** extends over at least a half of plasma chamber **17** length, L_{ch}. In an alternative embodiment, cathode tip **15** extends over ½ to ⅔ plasma chamber **17** length, L_{ch}. In the embodiment shown in FIG. **1***b*, cathode tip **15** extends at least half plasma chamber **17** length, L_{ch}.

In the embodiment shown in FIG. **1***b*, cathode **5** extends into plasma chamber **17** with its distal end positioned some distance away from plasma channel **11** inlet. This distance approximately equals the diameter d_c of cathode **5** at the base of tip **15**.

In the embodiment shown in FIG. **1***b*, plasma chamber **17** is in fluid communication with high pressure chamber **25** of plasma channel **11**. High pressure chamber **25** has a diameter d_{ch} in the range of 0.2-0.5 mm. In the embodiment shown in FIG. **1***b*, the diameter d_{ch} of high pressure chamber **25** is about 0.40 mm. However, it should be appreciated that high pressure chamber **25** does not have to have a uniform diameter.

In some embodiments, as shown in FIG. **1***b*, plasma chamber **17** comprises a cylindrical portion and tapering transitional portion **31**. In those embodiments, transitional portion **31** essentially bridges the cylindrical portion of plasma chamber **17** and high pressure chamber **25**. Transitional portion **31** of plasma chamber **17** tapers downstream, from the diameter D_{ch} of the cylindrical portion of plasma chamber **17** to the diameter d_{ch} of high pressure portion **25**. Transitional portion **31** can be formed in a number of alternative ways. In the embodiment shown in FIG. **1***b*, transitional portion **31** is formed as a beveled edge. Other transitions, such as concave or convex transitions, are possible. It should be noted, however, that the cylindrical portion of plasma chamber **17** and high pressure chamber **25** can be arranged in direct contact with each other without transitional portion **31**. Transitional portion **31** facilitates favorable heat extraction for cooling of structures adjacent to plasma chamber **17** and plasma channel **11**.

Plasma-generating device **1** can be a part of a disposable instrument. For example, an instrument may comprise plasma-generating device **1**, outer shell, tubes, coupling terminals, etc. and can be sold as a disposable instrument. Alternatively, only plasma-generating device **1** can be disposable and be connected to multiple-use devices.

Other embodiments and variants are also contemplated. For example, the number and shape of the intermediate electrodes **9**, **9'**, **9"** can be varied according to the type of plasma-generating gas used and the desired properties of the generated plasma flow.

In use, the plasma-generating gas, such as argon, is supplied to the gap formed by the outer surface of cathode **5** and the inner surface of insulator sleeve **19**, through the gas supply part, as described above. The supplied plasma-generating gas is passed on through plasma chamber **17** and through plasma channel **11**. The plasma-generating gas is discharged through the outlet of plasma channel **11** in anode **7**. Having established the gas supply, a voltage system is switched on, which initiates an electric arc discharge process in plasma channel **11** and ignites an electric arc between cathode **5** and anode **7**. Before establishing the electric arc, it is preferable to supply coolant to various elements of plasma-generating device **1** through auxiliary channels **23**, as described above. Having established the electric arc, plasma is generated in plasma chamber **17**. The plasma is passed on through plasma channel **11** toward the outlet thereof in anode **7**. The electric arc established in plasma channel **11** heats the plasma.

A suitable operating current for the plasma-generating devices **1**, **101**, **201** in FIGS. **1-3** is 4-10 Amperes, preferably 4-8 Amperes. The operating voltage of the plasma-generating device **1**, **101**, **201** depends, among others, on the number of intermediate electrodes and the length of the intermediate electrodes. A relatively small diameter of the plasma channel enables relatively low energy consumption and relatively low operating current when using the plasma-generating device **1**, **101**, **201**.

The center of the electric arc established between cathode **5** and anode **7**, along the axis of plasma channel **11**, has a prevalent temperature T. Temperature T is proportional to the quotient of discharge current I and the diameter d_{ch} of plasma channel **11** according to the following equation: $T=K*I/d_{ch}$. To provide a high temperature of the plasma flow, for example 11,000 to 20,000° C. at the outlet of plasma channel **11** in anode **7**, at a relatively low current level I, the cross-section of plasma channel **11**, and thus the cross-section of the electric arc should be small. With a small cross-section of the electric arc, the electric field strength in plasma channel **11** tends to be high.

The different embodiments of a plasma-generating device according to FIGS. **1***a*-**3** can be used, not only for cutting living biological tissue, but also for coagulation and/or vaporization. An operator, with relatively simple hand motions, can switch the plasma-generating device to a selected mode of coagulation, vaporization, or cutting.

What is claimed:

1. A plasma-generating device comprising:

a. an anode at a distal end of the device, the anode having a hole therethrough;

b. a plurality of intermediate electrodes electrically insulated from each other and from the anode, each of the intermediate electrodes having a hole therethrough, wherein the holes in the intermediate electrodes and the hole in the anode, at least in part, form a hollow space having

i. a first portion having a throat, the throat having a first cross-sectional area,

ii. a second portion, which over a substantial length of this portion has a uniform second cross-sectional area larger than the first cross-sectional area, the second portion being formed by two or more of the intermediate electrodes, the second portion being upstream of the first portion,

iii. a third portion, which over a substantial length of this portion has a uniform third cross-sectional area larger than the first cross-sectional area, the third portion, at least in part, being formed by the anode, the third portion being downstream of the first portion;

c. a cathode having a tapered portion; and

d. an insulator sleeve extending along and surrounding a substantial portion of the cathode,

wherein an inside surface of the insulator sleeve and an outside surface of the cathode form a gap, the gap being in communication with the hollow space.

2. The plasma-generating device of claim **1** further comprising an outer sleeve.

3. The plasma-generating device of claim **2**, wherein the outer sleeve and the anode are parts of an integral structure.

4. The plasma-generating device of claim **1** further comprising an insulator positioned between a pair of adjacent intermediate electrodes of the plurality of intermediate electrodes, and an insulator positioned between a distal-most intermediate electrode and the anode.

5. The plasma-generating device of claim 1, wherein a distal portion of the cathode is tapered, and the tapered portion partially projects beyond a distal end of the insulator sleeve.

6. The plasma-generating device of claim 1, wherein the first portion of the hollow space is formed by one of the intermediate electrodes.

7. The plasma-generating device of claim 1, wherein the first portion of the hollow space is a supersonic nozzle.

8. The plasma-generating device of claim 7, wherein the hollow space has a fourth portion, which over a substantial length of this portion has a uniform fourth cross-sectional area, the fourth cross-sectional area being larger than the second cross-sectional area and the third cross-sectional area, the fourth portion being upstream of the second portion of the hollow space.

9. The plasma-generating device of claim 8, wherein the fourth portion is formed by a proximal-most of the intermediate electrodes.

10. The plasma-generating device of claim 9, wherein a distal end of the cathode is positioned inside the fourth portion of the hollow space.

11. The plasma-generating device of claim 8, wherein the fourth and second portions of the hollow space are connected through a transitional fifth portion of the hollow space tapering toward the anode.

12. The plasma-generating device of claim 8, wherein the fourth portion of the hollow space extends from a distal end of the insulator sleeve to a proximal end of the second portion of the hollow space.

13. A plasma surgical instrument comprising the plasma-generating device of claim 1.

14. The plasma surgical instrument of claim 13 adapted for laparoscopic surgery.

15. The plasma surgical instrument of claim 14 having an outer cross-sectional width of under 10 mm.

16. The plasma surgical instrument of claim 15 having an outer cross-sectional width of under 5 mm.

17. A method of using the plasma surgical instrument of claim 13 comprising a step of discharging plasma from a distal end of the plasma surgical instrument on a biological tissue.

18. The method of claim 17 further comprising one or more steps of: cutting, vaporizing, and coagulating the biological tissue.

19. The method of claim 17, wherein the discharged plasma is substantially free of impurities.

20. The method of claim 17, wherein the biological tissue is one of liver, spleen, heart, brain, kidney, or bone.

21. A method of generating plasma comprising a step of supplying to the plasma-generating device of claim 1 a plasma-generating gas at a rate of 0.05 to 1.00 l/min and establishing an electric arc of 4 to 10 Amperes between the cathode and the anode.

22. The method of claim 21, wherein the plasma-generating gas is an inert gas.

* * * * *

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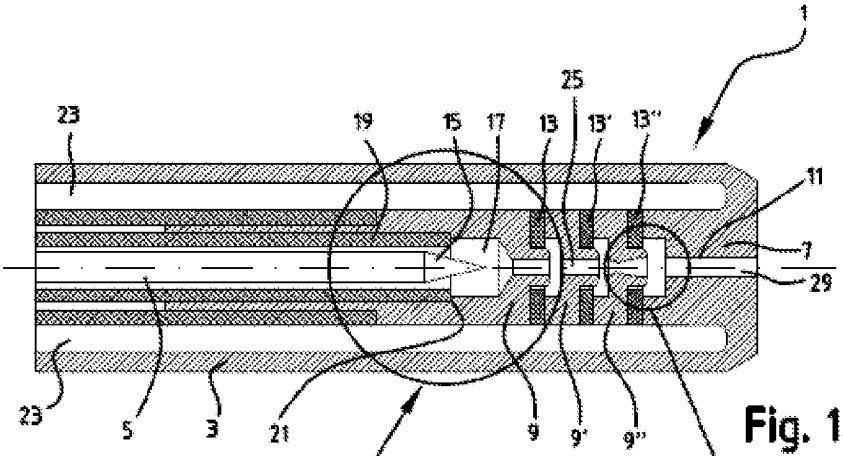

Fig. 1a

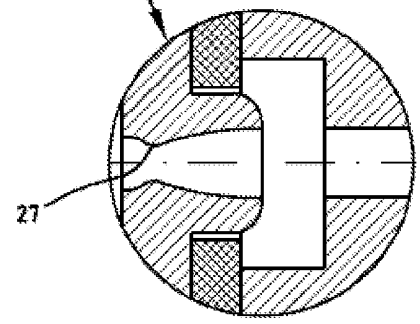

Fig. 1c

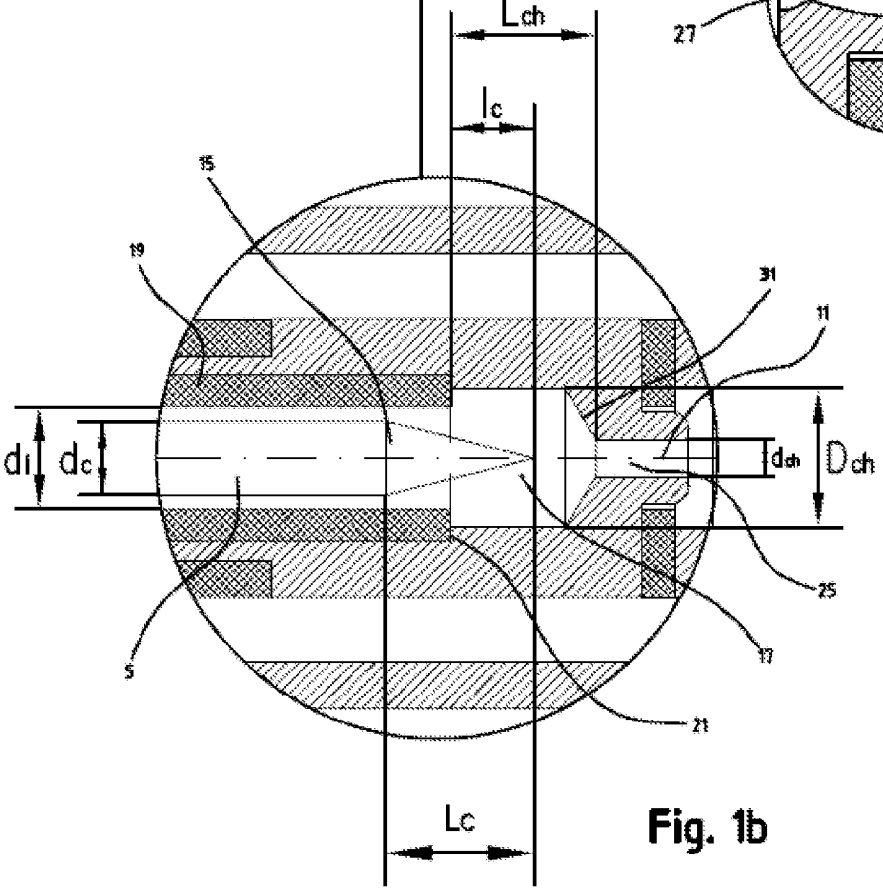

Fig. 1b

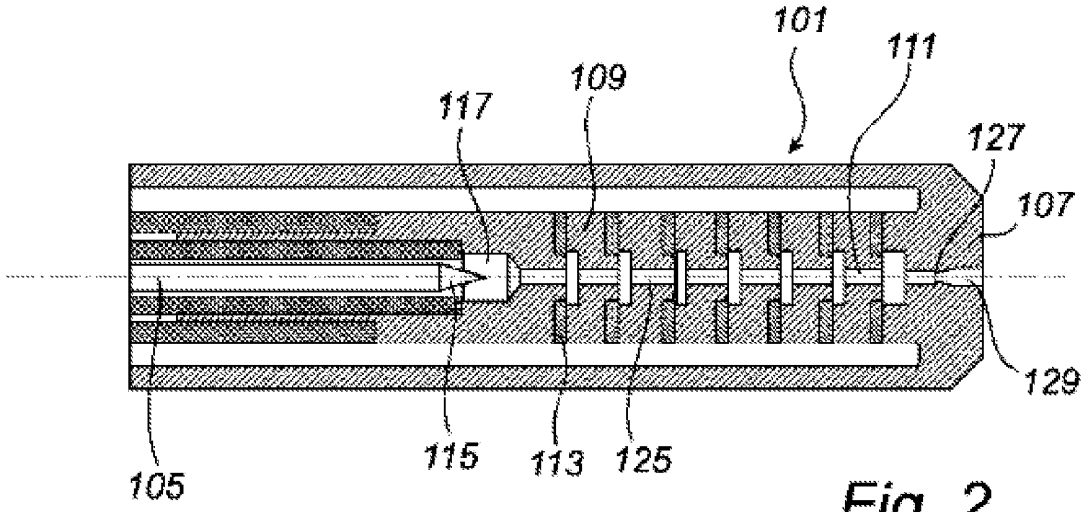
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Fig. 2

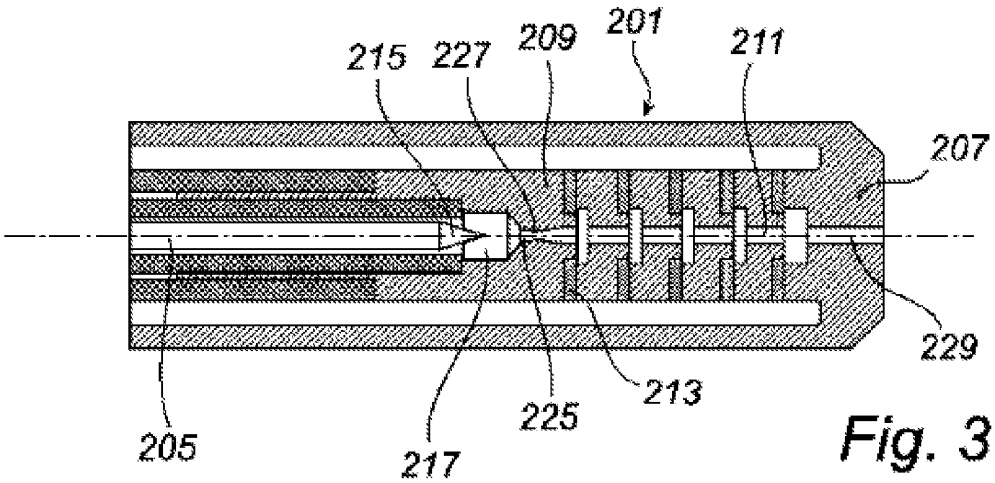
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Fig. 3

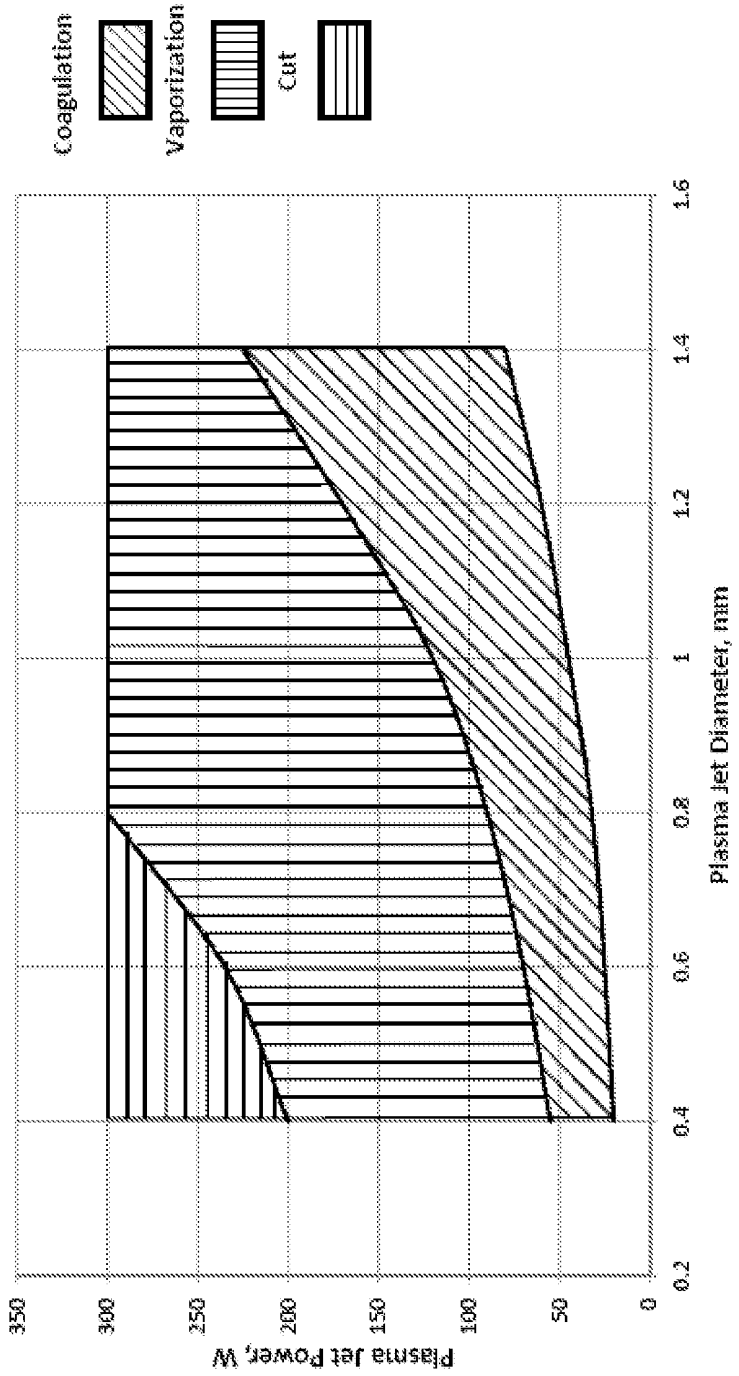
Coagulation
Vaporization
Cut
Plasma Jet Power, W
350
300
250
200
150
100
50
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Plasma Jet Diameter, mm

Fig. 4

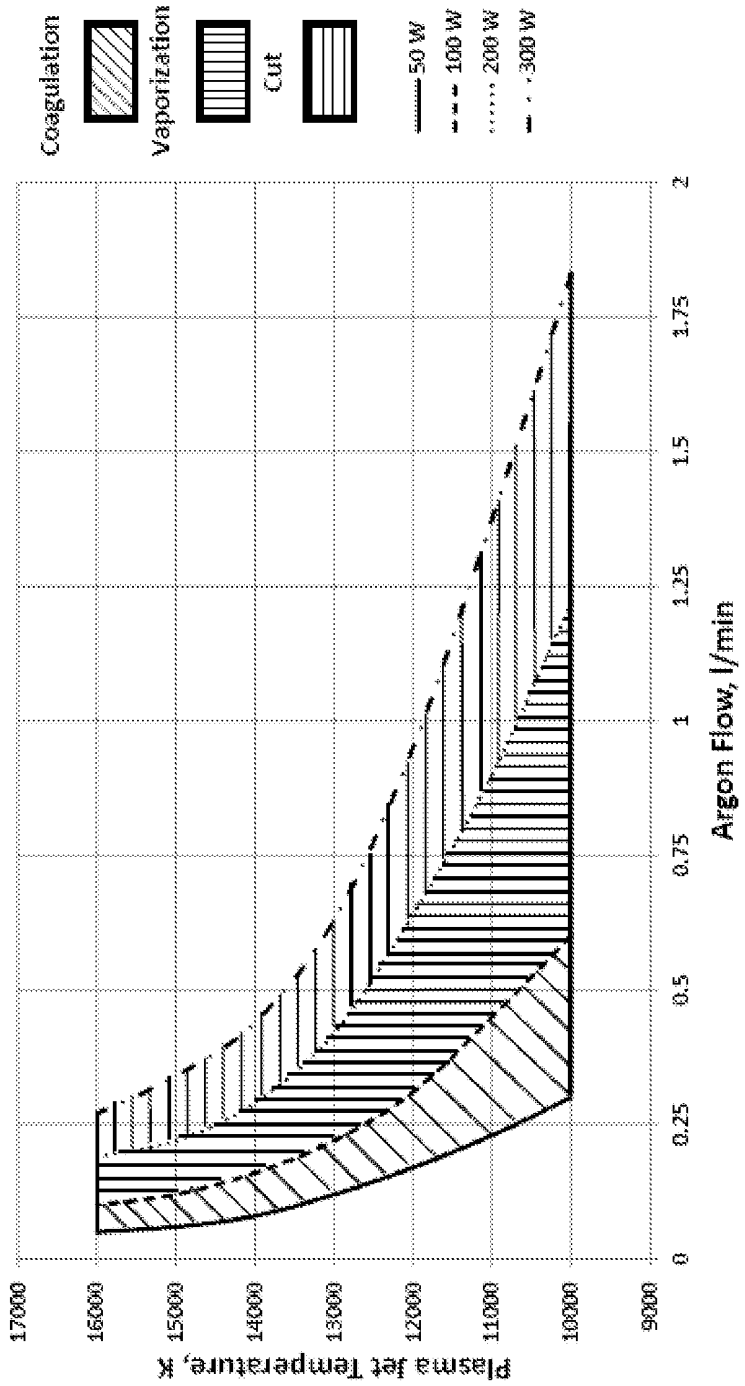
Coagulation
Vaporization
Cut
50 W
100 W
200 W
300 W
Plasma Jet Temperature, K
17000
16000
15000
14000
13000
12000
11000
10000
9000
Argon Flow, l/min
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2

Fig. 5

PLASMA-GENERATING DEVICE HAVING A THROTTLING PORTION

CLAIM OF PRIORITY

This application is a continuation of U.S. application Ser. No. 11/482,582 filed on Jul. 7, 2006, now U.S. Pat. No. 8,105,325 which claims priority of a Swedish Patent Application No. 0501602-7 filed on Jul. 8, 2005.

FIELD OF THE INVENTION

The present invention relates to a plasma-generating device, comprising an anode, a cathode and a plasma channel which in its longitudinal direction extends at least partly from a point located between the cathode and the anode and through the anode. The plasma channel has a throttling portion. The invention also relates to a plasma surgical device, use of such a plasma surgical device in surgery, and a method of generating plasma.

BACKGROUND ART

Plasma devices refer to devices configured for generating plasma. Such plasma can be used, for example, in surgery for destruction (dissection, vaporization) and/or coagulation of biological tissues.

As a general rule, such plasma devices have a long and narrow end that can be easily held and pointed toward a desired area to be treated, such as bleeding tissue. Plasma is discharged from a distal end. The high temperature of the discharged plasma allows for treatment of the affected tissue.

Owing to the recent developments in surgical technology, laparoscopic (keyhole) surgery is being used more often. Performing laparoscopic surgery requires devices with small dimensions to allow access to the surgical site without extensive incisions. Small instruments are also advantageous in any surgical operation for achieving good accuracy.

WO 2004/030551 (Suslov) discloses a prior-art plasma surgical device, which is intended for, among others, reducing bleeding in living tissue with plasma. This device comprises an anode, a cathode, and a gas supply channel for supplying plasma-generating gas to the device. Further, this plasma-generating device comprises at least one electrode arranged upstream of the anode. A housing connected to the anode, made of an electrically conductive material, encloses elements of the plasma-generating system and forms the gas supply channel.

It is desirable to provide a plasma-generating device capable of not only coagulation of bleeding living tissue, but also of cutting it.

With the device according to WO 2004/030551, generally a relatively high plasma-generating gas flow rate is required to generate a plasma flow capable of cutting. To generate a plasma flow with a suitable temperature at such flow rates, it is necessary to apply a relatively high operating electric current to the device.

It is desirable, however, to operate plasma-generating devices at relatively low operating electric currents, since high operating electric currents are often difficult to provide in certain environments, for example, in a medical environment. Also, as a general rule, a high operating electric current also requires extensive wiring, which can get unwieldy to handle during high precision procedures, for example, in laparoscopic surgery.

Alternatively, the device according to WO 2004/030551 could be formed with a relatively long plasma channel to generate a plasma flow with a suitable temperature at the required gas flow speeds. However, a longer plasma channel would make the device long and unwieldy for certain applications, for example, for medical applications, and especially for laparoscopic surgery.

For many applications, the generated plasma should be pure, i.e., have a low amount of impurities. It is also desirable that the discharged plasma flow has a pressure and a flow rate that are not harmful to a patient.

According to the above, there is a need for improved plasma-generating devices capable of effectively cutting biological tissue. The devices should be capable of being easily held and maneuvered. There is also a need for improved plasma-generating devices that can generate a pure plasma at lower operating currents and at lower gas flow rates.

SUMMARY OF THE INVENTION

An object of the present invention is to provide an improved plasma-generating device. Plasma is generated inside the device and is discharged from the distal end, also referred to as the discharge end. In general, the term "distal" refers to facing the discharge end of the device; the term "proximal" refers to facing the opposite direction. The terms "distal" and "proximal" can be used to describe the ends of the device and its elements. The flow of plasma gives meaning to the terms "upstream" and "downstream."

Another object is to ensure that the device is useful in the field of the surgery.

A further object is to provide a method of generating plasma for cutting biological tissue.

According to one aspect of the invention, a plasma-generating device comprises an anode, a cathode, and an elongated plasma channel that has an inlet at a point between the cathode and the anode and an outlet at the distal end of the device. The plasma channel has a throttling portion arranged in it. The throttling portion divides the plasma channel into a high pressure chamber and a low pressure chamber. The high pressure chamber is located upstream of the throttling portion. The high pressure chamber has a first maximum cross-sectional area transverse to the longitudinal direction of the plasma channel opening into the anode. The low pressure chamber, downstream of the throttling portion, has a second maximum cross-sectional area transverse to the longitudinal direction of the plasma channel. (In the remainder of the disclosure, unless expressly stated otherwise, the term "cross-section" and its variations refer to a cross-section transverse to the longitudinal axis of the device.) The throttling portion has an hourglass shape. The throttling portion has a throat having a third cross-sectional area that is smaller than both the first maximum cross-sectional area and the second maximum cross-sectional area. At least one intermediate electrode is arranged between the cathode and the throttling portion. Preferably, the intermediate electrode can be arranged inside the high pressure chamber or form a part thereof.

This construction of the plasma-generating device allows plasma flowing in the plasma channel to be heated to a high temperature at a low operating current supplied to the plasma-generating device. In this disclosure, "high temperature" refers to a temperature above 11,000° C., preferably, above 13,000° C. The plasma flowing through the high pressure chamber is heated to a temperature between 11,000 and 20,000° C. In one embodiment, the plasma is heated to a temperature between 13,000 and 18,000° C. In another embodiment, the plasma is heated to a temperature between 14,000 and 16,000° C. In this disclosure, a "low operating current" means a current of below 10 Amperes. The operating

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摘要(译)

等离子体发生装置本发明涉及一种等离子体发生装置，包括阳极，阴极和中间电极。中间电极和阳极形成细长的等离子体通道，其从阴极和阳极之间的点延伸并穿过阳极。等离子体通道具有节流部分，喉部具有整个等离子体通道的最小横截面积。当等离子体流通过节流部分时，等离子体流的速度增加而其压力降低。通过改变等离子体通道中的节流部分的位置，可以改变放电等离子体的特性。具有不同性质的等离子体流可用于各种应用，尤其是医疗程序。