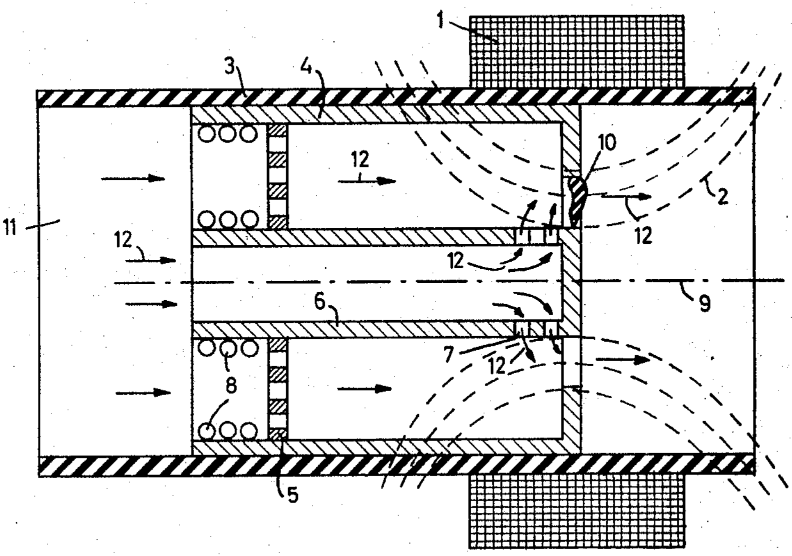


FIG. 1

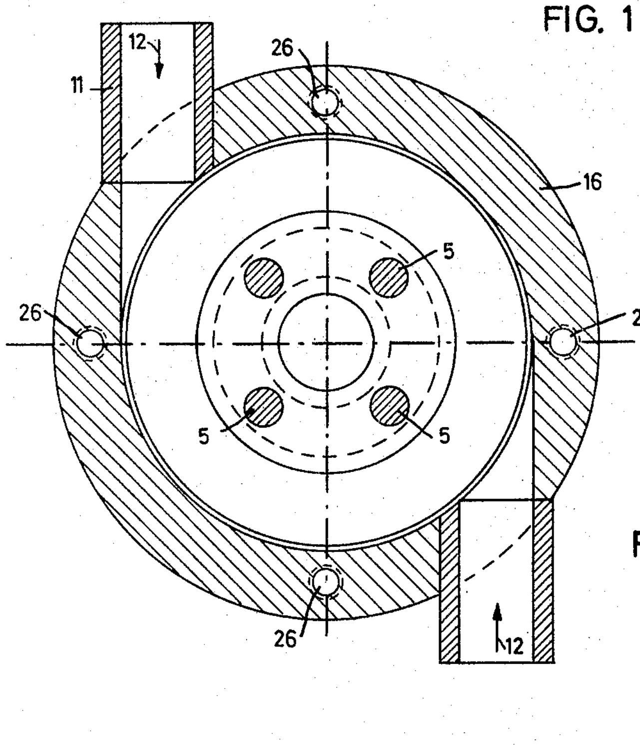
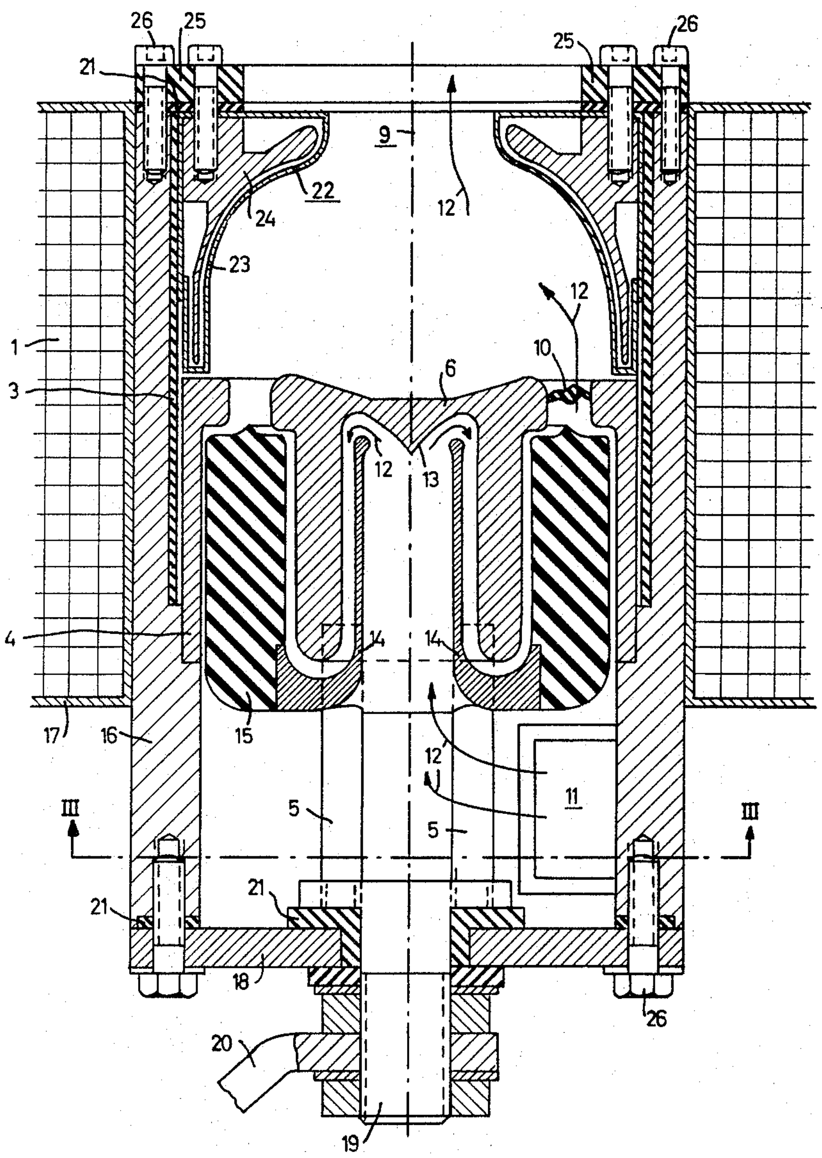


FIG. 3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III
III
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18
26
20
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FIG. 2

Sept. 19, 1967 H. FRÖHLICH **3,343,027**
ARC PLASMA DEVICE HAVING GAS COOLED ELECTRODES
CONTAINING LOW WORK FUNCTION MATERIAL
Filed Aug. 5, 1964 4 Sheets-Sheet 3

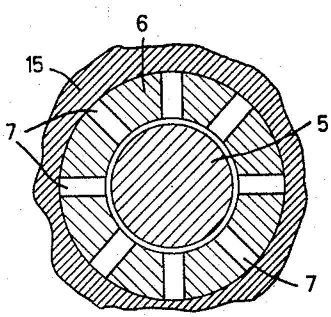

FIG. 5

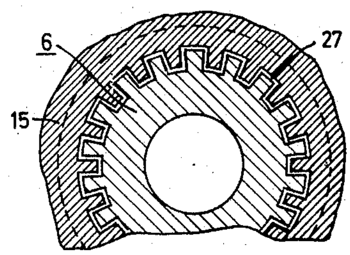

FIG. 7

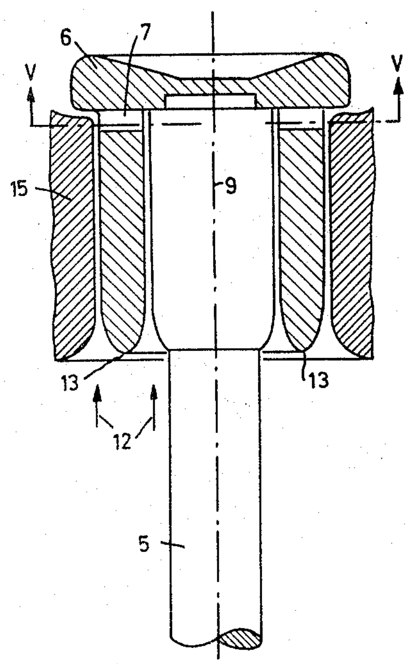

FIG. 4

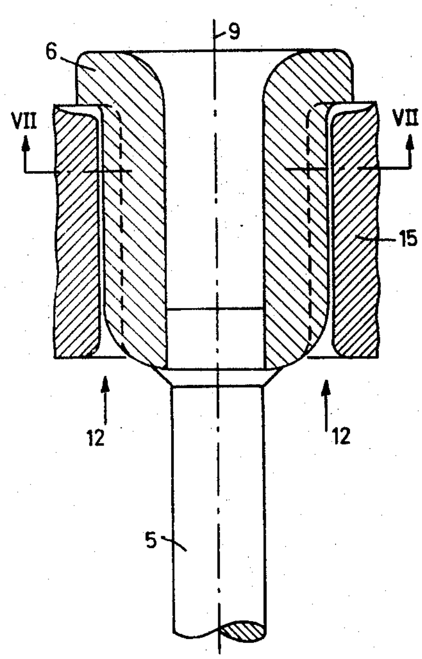

FIG. 6

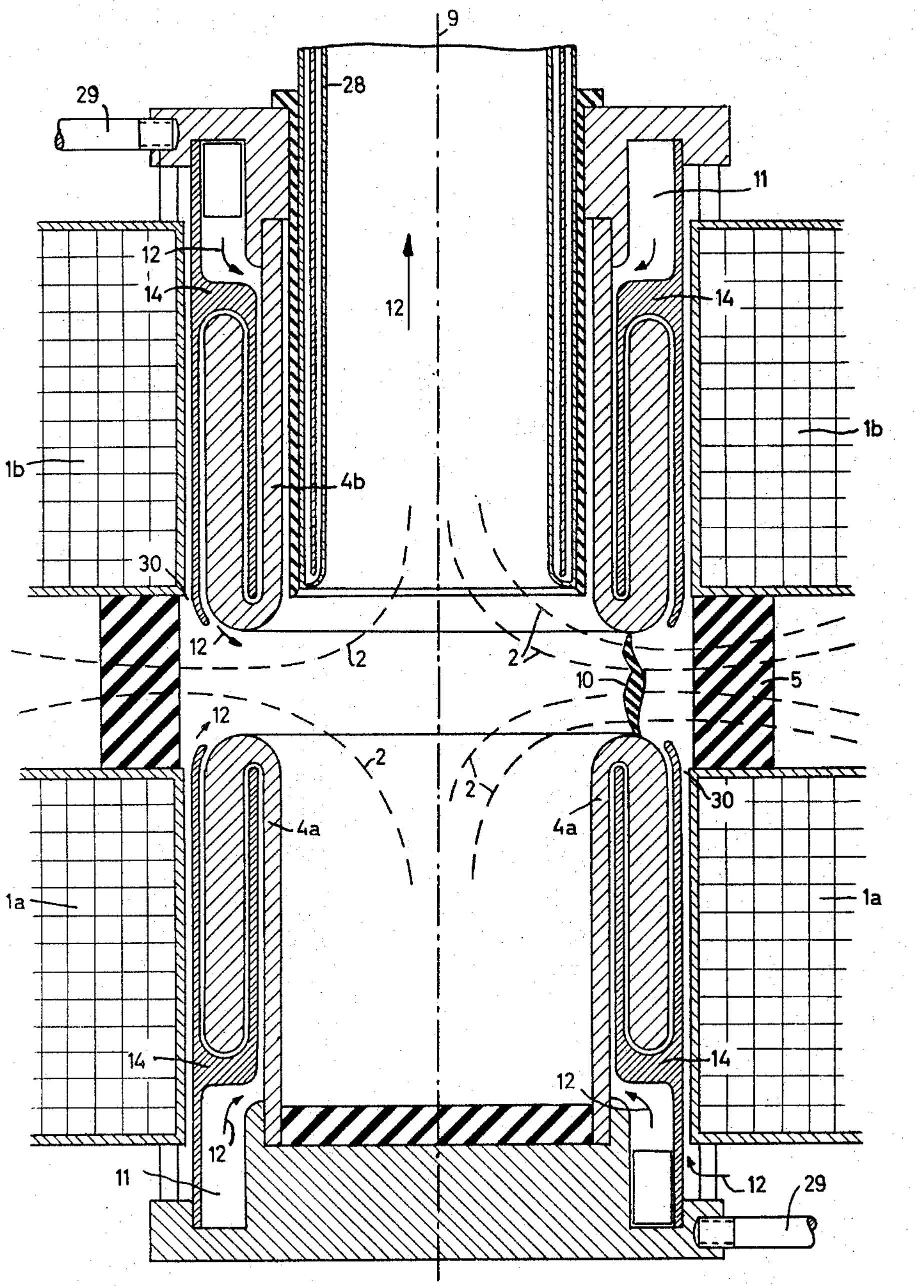

FIG. 8

United States Patent Office

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Patented Sept. 19, 1967

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ARC PLASMA DEVICE HAVING GAS COOLED ELECTRODES CONTAINING LOW WORK FUNCTION MATERIAL

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14 Claims. (Cl. 313—231)

My invention relates to a method and device for heating gases in a plasma gun.

In a plasma gun a direct-current or alternating-current arc serves to heat and ionize a flow of gases passing through the gun channel, thus producing a plasma. Such plasma guns are applicable for a great variety of purposes. For example, they are used in plasma chemistry for releasing chemical energy, they can be used for deposition welding and also for cutting. If the plasma is passed through a nozzle, high flow velocities are attained which can be used for supplying wind channels or reaction thrust for space-vehicle propulsion.

A known design of plasma burners is provided with rod- or pin-shaped cathodes at which electrons issue from emissive materials, such as thoriated tungsten, by thermal field emission. During operation of these burners, the tip of the cathode is heated to such a high temperature that a portion of the electrons is emitted thermally and the other portion is emitted by field emission and hence by the high field strength in the cathode drop of the arc. The heat dissipation from such a cathode enforces temperature limitations because of the limited geometrical dimensions. These cathodes, therefore, can be subjected only up to a relatively low current load. If this limit is exceeded, the cathode will fuse off, which results in a short useful life of the equipment.

Plasma guns have therefore been developed in which an arc burns between annular electrodes and, while being energized by direct current or alternating current, rotates in a transvese magnetic field. In these plasma guns, the annular electrodes are intensively cooled, for example by designing them as water-cooled copper cathodes. This expedient reduces the efficiency of the plasma gun. It has also been found that, at high current intensities, the material will commence to melt in the burning spot of the cathode, so that material vaporizes and leads to a reduction in lifetime of the electrodes.

It is an object of my invention to minimize or overcome the difficulties encountered with plasma guns in which an arc between annular electrodes rotates in a transverse magnetic field.

More particularly, it is an object of the invention to enlarge the burning spot of the arc in such a plasma gun so as to reduce the energy density and thereby promote the thermal emission while reducing the danger of melting and vaporization at the spot.

According to the invention, I employ annular electrodes formed of a main material whose melting point is above 1200° C. and with an addition of substances whose electron work function is in the range of 0.15 to 0.7 of the electron work function of the main material, and I further adjust the working temperature of the electrodes by maintaining them at a value below the melting point of the electrodes but above 1000° C.

The invention is based upon the recognition that due to the intensive cooling of the electrode acting as the cathode, the arc must contract strongly in the region of the cathode drop in order to attain a small burning spot such a high temperature, within very short intervals of time, that thermal emission also can take place. In the known

2

electron guns, this phenomenon causes the electrode material, when operating with high current intensities and consequently with a high energy density in the small burning spot, to become heated to the temperatures at which the electrode material melts and vaporizes. In contrast thereto, the present invention, by virtue of the above-mentioned features, provides for a large burning spot on the cathode which distributes the energy furnished through the electrode material and promotes thermal emission.

When performing the method according to the invention and employing the permissible proper cooling commensurate with the large burning spot, a high average electrode temperature is maintained. This results in good efficiency. Preferably the gas to be heated is employed as the cooling medium. By the rotation of the arc and the geometry of the electrode, the median energy density can be so limited that even with maximum current intensities the electrodes remain largely unaffected which is tantamount to a long useful life.

The above-mentioned main material of the electrodes may consist of high-temperature steel or other refractory metal such as tungsten, molybdenum, tantalum or an alloy, or it may consist of a sintered body of refractory metals or alloys. Also suitable are the electro-conducting compounds of these metals such as the carbides, borides and silicides. The added substances of low work function may consist, for example, of ThO_2, K_2O, BaO, SrO, UO_2, UC, LaB_6. The maximum amount of the added substances should be 20% of the mass of the main material.

The addition substance of low work function may be added to the main material of the electrode by dissolving and/or alloying therein, by admixture in powdered form to the powdered main material prior to pressing and sintering according to the techniques of powder metallurgy, by surface deposition using common metallurgical techniques, by diffusion, by ceramic surface coating and/or surface inserts at the work face. These expedients for the application of such low work function additions to the main material are not critical as long as the choice of specific material used as the main material and the additive substance is made and the combination is operated at the temperatures and in the manner set forth.

The rotating speed of the arc can be adjusted in known manner by correspondingly selecting the strength of the magnetic field, the current intensity of the arc, the type of gas or the gas pressure. The magnetic field can be produced by electromagnets or permanents magnets. For operation with an alternating-current arc, it is preferred that the material of both electrodes contain the same constituents. When operating with a direct-current arc, the anode may consist only of refractory metals or alloys without the above-mentioned additives of low work function. The cooling of the electrodes can be augmented, if necessary, by radiation cooling with the aid of vanes on the electrodes. Any other suitable cooling means may also be employed or added.

The above-mentioned and further objects, advantages and features of the invention, said features being set forth with particularity in the claims annexed hereto, will be apparent from, and will be mentioned in, the following with reference to embodiments of plasma guns according to the invention illustrated by way of example on the accompanying drawings in which:

FIG. 1 shows schematically in axial section the fundamental design of a plasma gun with annular electrodes and the rotating direct-current arc.

FIG. 2 is an axial section of another plasma gun embodying the principles of the gun shown in FIG. 1.

FIG. 3 is a cross section along the line III—III in FIG. 2.

FIG. 4 shows in axial section, a modified electrode applicable in a plasma gun otherwise corresponding to FIG. 2.

FIG. 5 is a cross section through the electrode of FIG. 4 along the line V—V in FIG. 4.

FIG. 6 is an axial section through another electrode applicable in a plasma gun otherwise similar to FIG. 2.

FIG. 7 is a cross section along the line VIII—VIII in FIG. 6.

FIG. 8 shows in axial section another embodiment of the plasma gun according to the invention in which the arc burns parallel to the rotational axis, in contrast to the preceding embodiments where it burns perpendicularly to the axis of rotation.

Corresponding components are denoted by the same respective reference characters in all illustrations.

According to the schematical illustration in FIG. 1, a coil **1** produces a magnetic field whose field lines, indicated by broken lines **2**, extend transversely of the arc **10**. The magnetic field causes the arc to rotate in an annular gap formed between two cylindrical electrodes **4** and **6** which are coaxially mounted in cylindrical sleeve **3** insulated for the purpose of electrical and thermal insulation. The inner electrode **6** has a closed end at the location of the arc gap and is coaxially centered and held in the outer electrode **4** by means of one or more insulating spaces **5** which are perforated by large openings for the passage of gas. It serves as cathode for the direct-current arc.

The outer cylindrical electrode **4** serves as the anode for the direct-current arc. It consists of high-temperature steel or of any of the other refractory metals, alloys, sintered materials mentioned above, or of the likewise mentioned carbides, borides and silicides of refractory metals. Preferably employed is high-temperature, corrosion-resistant steel having a melting point above 1200° C., which also constitutes the base material for the cathode **6**. The cathode material, however, contains an addition of substances whose work function is 0.15 to 0.7 of that of the base material. As mentioned, the addition amounts to no more than 20% of the mass of the base material and consists for example of ThO_2 or the other substances mentioned in the foregoing. Suitable as base material for the cathode are also any of the other materials applicable for the anode.

At any moment, the burning arc **10** extends substantially in a radial direction within the annular gap between the cathodes **6** and the anode **4**. At the closed end near the arc gap, the cylindrical cathode **6** is perforated by circular rows of holes **7** for the passage of gas. The cylindrical hollow space within the cathode **6** and the cylindrically annular space between the cathode **6** and the anode **4** constitute cooling channels. These are traversed by the gas which is to be heated by the arc **10** and which is supplied through the inlet opening at **11**. The gas flow is schematically indicated by arrows **12**. As the gas passes along the electrode walls, each electrode is individually cooled. By adjusting the gas volume throughput, the working temperature of each electrode can be adjusted to a value independent of that of the other electrode. For additional cooling, helical coils or cooling tubes **8** may be provided for coolants such as water.

Due to the heat exchange, the gas is heated as it passes through the annulus of the electrodes until it reaches the annular gap and the rotating arc. By properly adjusting the cooling expedients, the median temperature of the electrodes in the region of the arc can be readily adjusted to a value below the melting point of the electrodes and above 1000° C., thus securing a high efficiency of the plasma gun. The arc **10** rotating in the electrode gap about the axis **9** converts the preheated gas to the ionized condition, so that a flow of plasma issues from the gun. For this purpose, the arc is energized by connecting the anode **4** to the positive pole of a direct-current supply, and the cathode **6** to the negative pole by any suitable electrical means, such as the terminal and cable connection shown in FIG. 2.

For operating a plasma gun with a direct-current arc it suffices to add the above-mentioned additives of low work function only to the base material of the cathode. However, such substances are added to the base material of both electrodes if the gun is to operate with alternating current.

The plasma gun according to FIGS. 2 and 3 comprises a cylindrical and cup-shaped inner electrode **6** in coaxial relation to a cylindrical outer electrode **4**. The electrodes consist of nonmagnetic materials in accordance with the foregoing explanations. The electrode **6** has a flow-dividing internal profile at **13**. The electrode **6** is held together with a cylindrical gas-guiding structure **14** by means of copper centering rods **5**. The cylindrical guide structure **14** has an outwardly protruding flange portion by means of which it is inserted into a recess of a ring-shaped intermediate body **15**. The body **15** consists of electrically insulating, heat-resistant material such as a putty-like mass of zirconium oxide or boron nitride press-molded to the proper shape, or the body may also be pressed and molded from Blakite putty. The annular interspaces between the intermediate body **15** and the outer electrode **4** on the one hand, and between the electrode **6** and the body **15** as well as the guide structure **14**, on the other hand, provide for hollow cylindrical cooling channels. The flow cross-sectional area of these cooling channels may have the same dimension. For this purpose, the width of the cooling channels having a larger diameter is smaller than the width of the cooling channels having a smaller diameter.

The outer electrode **4** is mounted by a tight fit or force fit in a tubular housing **16** of brass or nonmagnetic steel (such as available in the trade under the name V2A-steel). The two electrodes **4** and **6** form between each other an annular gap in which, during operation of the gun, the arc **10** is maintained while rotating about the axis **9**. A heat shield consisting of a cylindrical body **3** of thermally and electrically insulating material such as boron nitride is mounted on the inner wall of the tubular housing **16** at a location where this heat shield protects the housing **16** from being impaired by the arc. As shown, an air gap may remain between the cylindrical heat shield **3** and the electrode **4**.

The magnet coil **1** for rotating the arc is wound upon a carrier **17** of brass which is coaxially mounted upon the cylindrical housing **16**.

The housing **16** is closed by a circular plate **18** of structural steel or brass. The plate **18** carries a terminal **19** for attachment of a copper tape or cable **20** by means of which the inner electrode is connected to one pole of current source for the arc. The outer electrode **4** is connected to the other pole of the same source through the cylindrical housing **16**.

The inner electrode **6** is held in concentric relation to the rotational axis **9** of the plasma gun by the centering action of the rods **5** which abut against the terminal **19** and thus are held in proper position by the closure plate **18**. Interposed between the terminal **19** and the closure plate **18** is an electrically insulating seal **21** consisting for example of polytetrafluoroethylene. Further sealing members or gaskets, which may consist of the same material, are denoted by **21**.

A gas collector nozzle **22** which simultaneously mixes the heated and ionized working gas, is fitted into the thermally and electrically insulating heat shield **3**. The nozzle **22** comprises a jacket **23** and a flow-guiding core **24** and may be cooled in its interior by circulating water. Due to the provision of an adjacent insulating gasket **21** and the insulating heat shield **3**, the collector nozzle **22** is isolated from the electrical potentials of the electrodes **4** and **6**. This prevents the arc from finding a foot point on the nozzle jacket **23**.

A mounting ring **25** is gas-tightly fastened to the housing **16** and is joined with the collecting nozzle **22** by means of screw bolts **26**. The closure plate **18** on the opposite end of the housing **16** is likewise fastened to the housing by bolts **26**.

The working gas which simultaneously serves as a coolant for the electrodes **4** and **6**, is supplied through inlet ducts **11** which are distributed about the periphery of the housing **16** and extend tangentially thereto (FIGS. 2, 3), the flow direction of the gas being indicated by arrows **12**. The working gas contacts during its flow the inner and outer cylinder wall of the electrode **6** as well as the inner wall of the electrode **4**. Thus the electrodes **4** and **6** are cooled by separate gas flows.

Relative to the dimensions of the wall cross section and axial length of the cylindrical electrodes **4** and **6**, as well as the cross sections of the cylindrical cooling channels adjacent to the electrodes, the following considerations may serve as a guide. In the first place, the wall cross section is essential to heat dissipation with respect to cylinders supplied with heat at an axial end thereof. Also essential in this respect is the area of the cooled wall surface.

It is to be noted that a prolongation of the cylinder is not as effective as an increase in cylinder diameter because the relatively poor heat conductance through the electrode walls, since they consist of the base material such as tungsten, causes the occurrence of a temperature gradient whose magnitude cannot be neglected. Accordingly, approximately two thirds of the heat quantity generated by the arc must be dissipated on the last third of the electrode cylinder length adjacent to the arc. A suitable dimensioning will be further elucidated with reference to an example. Assume that a plasma gun serves to heat a working gas to a temperature of 3000° K. (about 2700° C.) at an efficiency of 80%, operating with an arc having an output power of 1 megawatt and a voltage of 500 volts at 2000 amps, the voltage drop per electrode being 10 volts. Under these conditions, 800 kilowatts will heat the working gas to the desired temperature. Accordingly, an quantitative gas flow of 225 g. gas per second should be provided, corresponding to approximately 112 g. per second per electrode.

The proper dimensioning of the electrodes can be arrived at by considering a simplified model. Used is a cylinder of tungsten having an inner diameter of 80 mm. a wall thickness of 3.6 mm. and a length of 80 mm. The cylinder is heated along a generatrix. If one assumes that the source of heat is an electric arc corresponding to the above-mentioned data, then for an electrode drop of 10 volt per electrode, it is necessary to dissipate 20 kilowatt by cooling. The heat conductance of the tungsten cylinder may be set approximately to be 90 kcal./m h. ° C., wherein kcal.=kilocalories, m=length of the cylinder in meters, h.=hours. The heat transfer between electrode cylinder and cooling gas may be set as 1000 kcal./m^2 h. ° C., wherein m^2=area of the electrode cylinder. This corresponds to a mathematical product of flow speed and specific gravity of the coolant gas of approximately 300 kg./sec./cm.^{2}. It follows that when the gas is supplied under a superatmospheric pressure of 1, 10 or 100 atmospheres, it must flow at respective speeds of 158, 32 and 4.3 m./sec. The median cooling-gas temperature at a mass flow of 112 g./sec. then amounts to 100° C. With a temperature gradient along the cylinder of 3400 to 3000° C., 16,300 kcal./h.=19 kw. are then dissipated to the coolant gas. The cylinder area under these conditions and for the above-assumed cylinder dimensions amounts to 15 cm.^{2}.

On the basis of these reference data for the electrodes, the dimensions required for the cooling channels of the plasma gun can be determined. For the required gas flow of 112 g./sec. for each electrode, and with the above-mentioned values for the heat transfer and for the product of flow speeds and specific gravity of the coolant gas, there results an area of 3.7 cm.^{2} as required for the flow cross section of the annular gaps that constitute the respective cooling channels.

In the embodiment according to FIG. 2, the inner electrode **6** is contacted on both sides by the gas flow, whereas the outer electrode **4** is contacted only on one side because the inner wall surface of the inner electrode **6** is smaller than that of the electrode **4**. Consequently, by cooling both sides of the inner electrode **6** an equalization of the cooling effect at both electrodes is obtained.

FIGS. 4 and 5 show a different embodiment of an inner electrode **6'** applicable for the inner electrode of a plasma gun as shown in FIG. 2. The electrode **6'** according to FIG. 4 has a cylindrical cup shape. The open end of the electrode cylinder has a flow-dividing contour **13'** of tapering cross section. This causes two separate gas flows to cool the electrode walls on both sides. The inner gas flow passes through a row of holes **7'** to merge with the outer gas flow. The annular cooling channels are formed between a single centering body **5'**, the cylindrical portion of the electrode **6'** and an intermediate body **15'** of which only a portion is illustrated in FIGS. 4 and 5.

FIGS. 6 and 7 show another embodiment of the inner electrode **6''** with a single centering body **5''** and a partially illustrated cylindrical intermediate body **15''**. The electrode **6''** has a cylindrical body which at the upstream side of the gas flow, indicated by arrows **12**, is rounded from the outer periphery to the inner periphery, and whose other end forms a bulge protruding radially and peripherally beyond the cylindrical main portion. In this embodiment only the outer surface of the electrode **6''** is cooled by the gas flow. For that reason, this surface is enlarged by blunt cooling ribs **27** which extend in the longitudinal direction and are uniformly distributed over the periphery.

In the plasma gun according to FIG. 8, the arc **10** extends generally in a direction parallel to the rotational axis **9**. The two annular electrodes **4*a*** and **4*b*** are axially spaced from each other to form the arc gap between each other so that the travel path of the rotating arc extends peripherally along the ends of the respective cylindrical electrodes.

Each electrode has the shape of a cuff whose bight portion is adjacent to the arc gap and whose outer portion is doubled back with respect to an inner cylindrical portion. If desired, the electrodes may each be composed of several parts, particularly in the arc-gap region.

The working gas is supplied through ducts **11** and is guided by cylindrical guide bodies **14** to pass through annular cooling channels along the electrode surfaces.

The magnetic field for rotating the arc, extending in the direction of field lines schematically represented at **2**, is produced by magnet coils **1*a*** and **1*b***. The flow of gas is heated by the rotating arc and leaves the plasma gun through a tube **28** located inside the electrode **4*b***.

The interior of the tube **28** is subdivided by a cylindrical partition to permit being cooled by a circulating coolant such as water. However the electrodes proper are cooled only by the working gas which, for this purpose, can be controlled as to flow quantity as explained heretofore. The two electrodes **4*a*** and **4*b*** are kept in proper positions by means of a spacer body **5** of electrically insulating and heat-resistant material. Copper rods **29** serve as electric current conductors for the electrodes **4*a*** and **4*b*** respectively.

If the plasma gun according to FIG. 8 is mounted in a pressure-resistant container wtih only the tube **28** for issuance of the hot working gas from the container, then the windings **1*a*** and **1*b*** may be cooled by having them exposed to the flow of cooling gas. Applicable as cooling gas for the latter purpose is the working gas, or a different gas with which the working gas is to be mixed and which is supplied to the arc through annular gaps **30**. By means of such mixing, the arc energy can be controlled, and the temperature and properties of the working gas can also be varied. If desired in the control of the plasma generation, the mixing of gases can be altered by closing the annular gaps **30**.

It is essential to the invention that by virtue of the cooling applied in the above-described manner, the electrodes are cooled only moderately so that the burning spot of the arc on the electrodes is enlarged. On the other hand, such enlargement of the burning spot is a prerequisite for permitting such a mild or moderate cooling because the energy density for a given arc energy on an electrode is lower in a large burning spot than in a small burning spot.

To those skilled in the art it will be obvious from a study of this disclosure that my invention permits of various modifications and can be given embodiments other than particularly illustrated and described herein, without departing from the essential features of my invention and within the scope of the claims annexed hereto.

I claim:

1. A plasma gun, comprising two coaxial annular electrodes spaced from each other and forming an annular arc gap between each other, said electrodes consisting of an electroconductive refractory main material having a melting point above 1200° C., and at least one of said electrodes containing an addition of substance having a work function within 0.15 to 0.7 that of said main material, magnet means having transverse field in said annular gap for causing the arc between said electrodes to rotate along said gap, gas duct means for passing the gas to be ionized through said gap, said duct means comprising cooling channels along said electrodes for maintaining their working temperature by heat exchange with substantially all of the gas flow at a value below the melting point of the electrodes and above 1000° C.

2. A plasma gun, comprising two cylindrical electrodes coaxially mounted one within the other in radially spaced relation, the inner one of said electrodes having one axial end closed and forming with the outer electrode at said end an annular arc gap coaxial with said electrodes and smaller in radial width than the radial spacing between said electrodes along the axial length thereof extending from said end, said electrodes consisting of electroconductive refractory material having a melting point above 1200° C. and an addition of substance having a work function within 0.15 to 0.7 of the work function of said refractory material, magnet coil means coaxially surrounding said annular arc gap and having therein a transverse field for causing the arc between said electrodes to rotate along said gap, gas duct means for passing the gas to be ionized through said gap, said duct means comprising cooling channels along said electrodes for maintaining their working temperature by heat exchange with substantially all of the gas flow at a value below the melting point of the electrodes and above 1000° C.

3. In a plasma gun according to claim **1**, said two electrodes having cylindrical shapes of substantially the same diameters and being axially spaced from each other to form said annular arc gap axially between each other.

4. In a plasma gun according to claim **3**, said magnet means comprising two magnet coils coaxially surrounding said respective two electrodes and axially spaced from each other at said annular gap.

5. In a plasma gun according to claim **1**, said main material of said electrodes being chosen from the group consisting of high-temperature resistant and corrosion-resistant steels, tungsten, molybdenum, tantalum and high-temperature alloys thereof.

6. In a plasma gun according to claim **1**, said main material of said electrodes being chosen from the group consisting of electrically conducting silicides, carbides and borides.

7. In a plasma gun according to claim **1**, said added substances of low work function being chosen from the group consisting of ThO_2, K_2O, BaO, SrO, UO_2, UC, LaB_6.

8. In a plasma gun according to claim **1**, said added substances amounting maximally to 20% by weight of said main substance.

9. A plasma gun, comprising two coaxial annular electrodes spaced from each other and forming an annular arc gap between each other, said electrodes consisting of electroconductive refractory main material having a melting point above 1200° C. and an addition of substance having a work function within 0.15 to 0.7 of that of said main material, said addition being at most 20% by weight of said main substance, alternating-current supply means attached to said respective electrodes, magnet coil means surrounding said electrodes to produce in said annular gap a transverse field for causing the arc between said electrodes to rotate along said gap, gas duct means for passing gas to be ionized through said gap, said duct means comprising cooling channels along said electrodes for maintaining their working temperature by heat exchange with substantially all of the gas flow at a value below the melting point of the electrodes and above 1000° C.

10. A plasma gun according to claim **1**, comprising direct-current supply means connected to said respective electrodes, and only the cathodic electrode containing said addition of low work function.

11. In a plasma gun according to claim **10**, said gas duct means forming separate cooling channels for the cathodic and anodic electrodes respectively.

12. In a plasma gun according to claim **1**, said two electrodes being hollow-cylindrical and axially spaced from each other to form said annular arc gap axially between each other, said gas duct means comprising gas inlets near the respective electrode ends remote from said gap so that the gas flows from said ends along the inner cylinder walls of said electrodes toward the intermediate arc gap.

13. In a plasma gun according to claim **12**, said gas duct means comprising a tubular plasma outlet duct extending from the vicinity of said annular arc gap through the interior of one of said cylindrical electrodes in substantially coaxial relation thereto.

14. Device for heating gases comprising a pair of annular electrodes consisting of current conducting refractory main substance having a melting point above 1200° C. and an addition of substance having a work function within 0.15 to 0.7 of that of said main substance, means for producing a magnetic field to rotate an arc between said annular electrodes and means for maintaining an adjusted operating temperature of said electrodes at a value below said melting point and above 1000° C., said last mentioned means comprising structure for directing substantially all of the gas to be heated into cooling relationship with said electrodes.

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