PLASMA ARC ELECTRODES

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ABSTRACT OF THE DISCLOSURE

A plasma arc electrode assembly utilizing cathode and anode buffer electrodes is disclosed. These buffer electrodes along with structure for aerodynamically spinning the plasma adjacent the electrodes and withdrawal of the plasma from the anode region, improve stability and do not cause the destructive erosion of the electrodes to allow increases in size and operating potentials of the assembly.

This application relates to improved plasma arc electrode assemblies.

Workers in the plasma and other arts have employed cathode assemblies comprising a tapered or pointed cathode electrode surrounded by a concentric annular anode electrode, together with means to introduce a suitable feed gas into the arc region. Such electrode assemblies are used in connection with plasma torches, plasma containment devices, plasma propulsion devices, and the like. Difficulties have been experienced with this type of electrode structure in attempting to increase the size and to extend operation to voltages much in excess of 100 volts or currents much in excess of several hundred amperes. The two major difficulties encountered are an unstable and destructive cathode arc attachment and excessive erosion of the anode by high energy electrons.

It is accordingly an object of the present invention to provide an arc electrode assembly which is adapted to stable operation at higher powers and with larger dimensions than other device. This object is achieved in part through the use of buffer electrodes adjacent the cathode and anode.

It is often desired to operate at the highest possible arc voltage. Increases in size, current, and magnetic field tend to increase arc voltage, but not very much.

An additional object is to provide the provision of means and methods to increase arc voltage. Additional objects, features, and advantages will become apparent on reading the more detailed description which follows.

FIG. 1 is a longitudinal section of an arc electrode assembly according to the invention; FIG. 2 is a simplified cross section of a modified electrode assembly; and FIG. 3 is a schematic sectional view of an apparatus in which the electrode assemblies of the invention may be used.

No attempt will be made to describe or number each and every mechanical element which appears in the drawings, as such elements will be obvious to any skilled mechanic or machinist.

Referring to FIG. 1, cathode 10 is a tapered or pointed piece of metal, and like all other electrodes in the figure, will normally be axially symmetric. It is mounted in a metal heat sink 14 which, in turn, is mounted at the end of a cathode support and cooling water conduit 16 which is sealed into phenolic support block 18 by seal rings 20. A cathode cooling water inlet 22 is shown at the back of conduit 16. A cathode cooling water outlet will communicate with a cavity 24 in support block 18, that is out of the plane of the drawing and not shown. It will be understood that various other cooling water passages will not appear in the drawing for the same reason. A boron nitride insulator 26 surrounds the cathode 12 but leaves the tip portion exposed. A concentric cathode buffer electrode 28 surrounds cathode 12 and is supported with respect to the cathode and insulated therefrom by insulator 26. As shown, the cathode buffer 28 is tapered internally, and contains a chamber 40 surrounding the tip portion of the cathode and which is substantially enclosed except for an aperture 30 in the cathode buffer which is coaxial with cathode 10 and positioned slightly in front of the cathode tip. Illustratively, the diameter of this aperture may be 0.1 inch.

Cathode 12 and its heat sink 14 are bored to receive the tubular pressure tap 32 located within the cathode water conduit 16. Cathode 12 also contains one or more small channels on passages 34 which connect the pressure tap to the exterior surface of the cathode forward of the cathode insulator 26. The cathode insulator 26 is also provided with a gas passage, or preferably a plurality of circumferentially disposed passages 36 which communicate with the front face of the cathode insulator and are connected to a feed tap 38 in support block 18. Either passages 34 or passages 36 may be used to introduce a fluid to the space adjacent to the cathode, but it is generally preferable to introduce the fluid through passages 36 and to use passages 34 for measuring the pressure adjacent cathode 12.

Tungsten cathode buffer electrode 28 is attached to, and is in thermal contact with a hollow heat sink and cooling assembly 50 which is connected to an electrically conductive water inlet tube 54 which can also serve as an electrical connection to the cathode buffer. The corresponding water outlet is not shown.

Cathode buffer electrode 28 is surrounded by a boron nitride insulator 56 and the cathode buffer heat sink 50 is surrounded by a more conventional insulator 58 which is an extension of the boron nitride insulator 56. Insulators 56 and 58 serve to insulate and support a tungsten anode buffer electrode 60, which is concentrically located about the cathode and cathode buffer, and an anode buffer heat sink and cooling assembly 62 which is fixed thereto. A water cooled copper anode assembly 70 is mounted on the outside of support block 18 and is electrically insulated from heat sink 14 and 62 by insulators 72 and 74. Anode 70 has at its forward end of a cylindrical inner surface 76 which illustratively may be 2 inches in diameter and is separated by a small annular space from a cylindrical outer surface of anode buffer 60. Illustratively, the forward surfaces of the cathode buffer 28, insulator 56, anode electrode 60, and anode 70 may lie on a common plane as shown. Insulator 74 has a plurality of circumferentially disposed and axially oriented passages 80 which communicate with the annular space 78 defined by anode 70 and anode buffer electrode 60 and which also communicate with an anode gas feed tap 82. There is also provided a radial passage 84 in anode 70 which opens to the annular space 78 and communicates with an anode pressure tap 86.

In most instances it is desirable to operate the electrode assembly in the presence of a magnetic field and accordingly a magnet coil 90 is shown which is supported from the anode 70 by an insulator 88 which surrounds the anode 70 and also covers the front face thereof. Insulator 88 also prevents arc attachment to the face of the anode, which would cause very rapid erosion. A conventional power supply 92 may be used to operate magnet coil 90. A water cooling assembly 94 is positioned so as to cool the forward portion of the magnet and also the face of the anode, each of which is likely to be exposed to high temperatures in the operation of the device. A suitable DC power supply 100 and switch 102 are connected between cathode cooling conduit 16 and cathode buffer cooling conduit.
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The arc electrode assembly of FIGURE 1 was tested in an axial magnetic field of 2000 gauss, using argon as the feed gas. At a steady arc current of 200 amperes the corresponding arc voltage was 150 volts. A conventional electrode assembly was operated under the same conditions for comparison but the arc voltage was only 40 volts instead of 150.

FIGURE 2 is a simplified sectional schematic view of a modified form of electrode assembly according to the invention. The cathode buffer electrode 28 and anode buffer electrode 60 of FIG. 1 has been supplemented by a series of alternating electrodes 120 and insulators 122. Subdivision of the cathode-anode spacing into a multiplicity of gaps in series further reduces the possibility of inter-electrode arcing in high voltage operation.

A series of passages 124 extend outward from cathode chamber 49, passing through electrodes 120 and insulators 122. These passages do not lie in planes passing through the axis of the device, but are canted to give a tangential velocity to gas issuing therefrom in a direction consistent with the magnetic field. The portion of anode insulator 74 containing passages 60 has been removed and an enlarged inlet tube 82 is connected to a vacuum pump 90. These modifications operate to increase the operating voltage of the device and therefore to increase the temperature of any plasma which is produced.

The operating voltage of a plasma electrode assembly of the type shown in FIG. 1 or 2 can be given by

$$\phi = \frac{KT}{\ln \left( \frac{\rho_a}{\rho_b} + \frac{a_b R}{R} + M_a \frac{a_b R}{R} \right)}$$

where:

- $\phi$ is the voltage,
- $T$ is the plasma temperature adjacent the electrodes,
- $\rho_a$ is the on-axis gas pressure adjacent the electrodes,
- $\rho_b$ is the ambient pressure,
- $a_b$ is the angular rotational velocity of the plasma adjacent the electrodes,
- $B$ is the magnetic field,
- $R$ is the anode radius,
- $M_a$ is the atomic (or ionic) mass of the plasma material.

The first term represents essentially a temperature times a pressure gradient, the second term represents a counter EMF generated by the interaction of a plasma rotation and an axial magnetic field, and the third term represents a centrifugal force. At the vicinity of the electrodes, $T$ is relatively low. Therefore, the voltage drop may be raised by increasing the value of $a_b$ and the third terms of the of the voltage equation.

Injection of gas from passages 124 can give rise to a linear gas velocity near the electrodes of about 2000 meters per second at a radius of 3 cm. At a magnetic field of 5000 gauss this gives rise to a counter EMF term of about 90 volts.

Vacuum pump 126 also helps raise the operating voltage by drawing plasma out of the space in front of the electrode assembly and through an annular space 78. This plasma will ordinarily have a high rotational velocity due to the torque provided by the interaction of the radial arc current with the axial magnetic field. As this plasma is drawn out through space 78 it imparts, by viscous drag, some of its angular momentum to the gas immediately adjacent to the electrodes and further increases the rate of rotation of this gas and the counter EMF resulting therefrom.

Vacuum pump 126 has still a further beneficial effect on the operation of the device of FIG. 2. It is desirable to have a relatively high mass flow of gas through cathode chamber 49 and passages 124 in order to assist in cooling the electrodes. However, this gas must be somehow removed from the chamber containing the apparatus in order to permit continuous operation. Much less energy is expended in removing this gas at the relatively high pressure encountered as passage 78 than at the relatively lower pressure encountered in the chamber.

54 and a similar DC power supply 104 and switch 106 are connected between cathode cooling conduit 16 and anode assembly 70. In operation, the electrode assembly is preferably placed in an evacuated space or chamber, not illustrated. Magnet supply 92 is turned on if a magnetic field is desired and cooling water is supplied under pressure to the various cooling passages. The pressure tap 32 and anode pressure gauge, and a feed gas such as hydrogen is introduced through feed tap 38. Power supply 100 is energized and switch 102 closed in order to start an arc between cathode 12 and cathode buffer electrode 28. After this arc is established it may optionally be introduced through feed tap 32 or inlet tube 82 and power supply 104 is energized and switch 106 closed to draw the arc from cathode 12 to anode 70. Thereafter, switch 102 may be opened and power supply 100 may be de-energized. As is known in the art, the power supplies may be adapted to provide higher than normal operating voltages in order to initially strike the arc.

Generally speaking, in the absence of a magnetic field the arc will propagate in a reasonably straight line from the anode to a localized spot on the anode where destructive erosion will take place. Application of a magnetic field causes the arc attachment to rotate about the anode or extend entirely around the anode and also causes the arc to bend away from the electrodes. The higher the ambient pressure the greater is the magnetic field required for satisfactory operation. Operation may even be extended to atmospheric pressure if the magnetic field is increased to a value in excess of about 30,000 gauss. The magnetic field may also be provided by magnet means distinct from the electrode assembly.

Continual introduction of feed gas through feed tap 38 is desirable in order to maintain a nondestructive plasma forming arc and the introduction of gas through inlet tube or feed tap 82 may optionally be continued. Gas feed rate may typically vary in the range from about .01 to about .1 gram per second.

It is believed that a higher than ambient pressure is formed in cathode chamber 49 surrounding the cathode 12 and that operation of the cathode in this high pressure environment prevents unstable or destructive arc attachment and promotes a stable, diffuse, nondestructive attachment of the arc to the cathode tip. The electrically floating character of the cathode and anode buffers causes the buffers to operate at an appropriate potential so that the arc extends directly from the anode and moves toward the cathode buffer or anode buffer. At the same time, the electrically conductive and thermally conductive character of the cathode buffer facilitates starting the cathode arc and prevents erosion of the cathode buffer under normal conditions. Further, introduction of the feed gas through a confined space surrounding the cathode tip permits the gas to more effectively cool the cathode tip.

The arc penetrates at least partially into annular space 78, which is a region of increased pressure, and terminates on the inner surface 76 of anode 70. Annular space 78 is a region of negligible axial electric field and the arc electrons accordingly lose much of their energy to the gas in space 78 before striking anode 70. This obviously minimizes erosion of the anode. The presence of anode buffer electrode 60 adjacent to anode 70 helps to carry away the heat imparted to the gas in space 78, even though the arc does not attach to the anode buffer. The cylindrical geometry of anode 70 and buffer 60 presents a large area for effective heat transfer. Any gas introduced at feed tap 32 will serve to increase the pressure in annular space 78, to flush the electrically heated gas out of the passage and to provide additional generation of plasma. The cathode and anode buffers need not be insulated from each other and may even comprise a single piece of metal. The use of separate buffer electrodes is not essential, but serves to reduce the likelihood of an arc attaching to the buffer electrodes rather than passing directly between cathode and anode.
a cathode electrode having a tip, an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip, an annular anode electrode disposed around said cathode and cathode buffer and having an electron receiving area, an electrically insulated anode buffer electrode positioned adjacent said electron receiving surface of said anode and defining a channel therewith, means to introduce an ionizable gas between said cathode and said anode, and are maintaining power supply means connected between said cathode and said anode.

4. A shielded radial plasma arc electrode assembly comprising:
a cathode electrode having a tip, an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip, an annular anode electrode disposed around said cathode and cathode buffer and having an electron receiving area, an electrically insulated anode buffer electrode positioned adjacent said electron receiving surface of said anode and defining a channel therewith, means to introduce an ionizable gas between said cathode and said anode, are maintaining power supply means connected between said cathode and said anode, and means to create an axial magnetic field at said electrode assembly.

5. A radial plasma arc electrode assembly comprising:
a cathode electrode having a tip, an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip, an annular anode electrode disposed around said cathode and cathode buffer and having an inwardly facing annular electron receiving area, an electrically insulated anode buffer electrode positioned within said electron receiving surface of said anode and defining a channel therewith, and means to introduce an ionizable gas adjacent to said cathode.

6. A radial plasma arc electrode assembly comprising:
a cathode electrode having a tip, an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip, an annular anode electrode disposed around said cathode and cathode buffer and having an inwardly facing annular electron receiving area as the sole area accessible to an electric arc, an electrically insulated anode buffer electrode positioned within said electron receiving surface of said anode and defining a channel therewith, and means to introduce an ionizable gas adjacent to said cathode.

7. A radial plasma arc electrode assembly comprising:
a cathode electrode having a tip, an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip, an annular anode electrode disposed around said cathode and cathode buffer and having an inwardly facing annular electron receiving area, an electrically insulated anode buffer electrode positioned within said electron receiving surface of said anode and defining a channel therewith.
means to introduce an ionizable gas adjacent to said cathode,
insulating means covering all of said anode accessible to an arc except said electron receiving surface,
arc initiating power supply means connected between said cathode and said cathode buffer, and
arc maintaining power supply means connected between said cathode and said anode.

8. A radial plasma arc electrode assembly comprising:
a cathode electrode having a tip,
an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip,
an anode electrode disposed around said cathode and cathode buffer and having an inwardly facing annular electron receiving area,
an electrically insulated anode buffer electrode positioned within said electron receiving surface of said anode and defining a channel therewith,
means to introduce an ionizable gas adjacent to said cathode,
insulating means covering all of said anode accessible to an arc except said electron receiving surface,
arc initiating power supply means connected between said cathode and said cathode buffer,
an arc maintaining power supply means connected between said cathode and said anode, and
means to generate an axial magnetic field at said electrode assembly.

9. A plasma arc electrode assembly comprising:
a cathode electrode having a pointed tip,
a cathode buffer electrode surrounding said cathode insulated therefrom by an annular insulator, defining with said insulator a chamber substantially enclosing said cathode and having an aperture aligned with and in front of said cathode tip,
an annular anode electrode disposed adjacent said cathode coaxially therewith and having an inner cylindrical electron receiving area coaxial therewith,
an electrically insulated anode buffer electrode positioned within said anode and having an outer cylindrical surface adjacent the inner cylindrical electron receiving surface of said anode and defining an annular passage therewith,
cooling means to cool said cathode, said cathode buffer, said anode and said anode buffer,
first gas supply means including channels in said annular insulator opening into said chamber,
second gas supply means including at least one channel in said cathode opening into said chamber,
third gas supply means including channels opening axially into said annular space,
fourth gas supply means including at least one channel discharging perpendicularly through the inner surface of said anode into said annular space,
arc initiating power supply means connected between said cathode and said anode.

10. A plasma arc electrode assembly comprising:
a cathode electrode having a pointed tip,
a cathode buffer electrode surrounding said cathode insulated therefrom by an annular insulator defining with said insulator a chamber substantially enclosing said cathode, and having an aperture aligned with and in front of said cathode tip,
an annular anode electrode disposed adjacent said cathode coaxially therewith and having an inner cylindrical electron receiving area coaxial therewith,
an electrically insulated anode buffer electrode positioned within said anode and having an outer cylindrical surface adjacent the inner cylindrical electron receiving surface of said anode and defining an annular passage therewith,
cooling means to cool said cathode, said cathode buffer, said anode and said anode buffer,
first gas supply means including channels in said annular insulator opening into said chamber,
second gas supply means including at least one channel in said cathode opening into said chamber,
third gas supply means including channels opening axially into said annular space,
fourth gas supply means including at least one channel discharging perpendicularly through the inner surface of said anode into said annular space,
arc initiating power supply means connected between said cathode and said anode.

11. A radial plasma arc electrode assembly comprising:
a cathode electrode having a tip,
an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip,
an anode electrode disposed around said cathode and cathode buffer and having an inwardly facing annular electron receiving area,
an electrically insulated anode buffer electrode positioned within said electron receiving surface of said anode and defining a channel therewith,
means to introduce an ionizable gas adjacent to said cathode and,
a plurality of gas passages extending outward from said cathode chamber to a region between said cathode and anode and oriented to impart a swirling motion to gas discharged therefrom.

12. A radial plasma arc electrode assembly comprising:
a cathode electrode having a tip,
an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip,
an anode electrode disposed around said cathode and cathode buffer and having an inwardly facing annular electron receiving area,
an electrically insulated anode buffer electrode positioned within said electron receiving surface of said anode and defining a channel therewith,
means to introduce an ionizable gas adjacent to said cathode and,
means to remove gas at said anode.

13. A radial plasma arc electrode assembly comprising:
a cathode electrode having a tip,
an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip,
an anode electrode disposed around said cathode and cathode buffer and having an inwardly facing annular electron receiving area,
an electrically insulated anode buffer electrode positioned within said electron receiving surface of said anode and defining a channel therewith,
means to introduce an ionizable gas adjacent to said cathode and,
a plurality of gas passages extending outward from said cathode chamber to a region between said cathode and anode and oriented to impart a swirling motion to gas discharged therefrom,
and means to remove gas at said anode.

14. A radial plasma arc electrode assembly comprising:
a cathode electrode having a tip,
an electrically insulated cathode buffer electrode substantially enclosing said cathode tip and having an aperture aligned with and in front of said cathode tip,
an anode electrode disposed around said cathode and cathode buffer and having an inwardly facing annular electron receiving area,
means to introduce an ionizable gas adjacent to said cathode, insulating means covering all of said anode accessible to an arc except said electron receiving surface, arc initiating power supply means connected between said cathode and said cathode buffer, an arc maintaining power supply means connected between said cathode and said anode, means to generate an axial magnetic field at said electrode assembly and, a plurality of gas passages extending outward from said cathode chamber to a region between said cathode and anode and oriented to impart a swirling motion to gas discharged therefrom, and means to remove gas at said anode.