(54) Title: SELF-IGNITING LONG ARC PLASMA TORCH

(57) Abstract: A plasma torch is formed from a hollow electrode forming a first gap to an isolated plasma tube, the isolated plasma tube forming a second gap with a plasma outlet tube having electrically common plasma tubes which terminate into a plasma outlet. The first gap and second gap of the isolated plasma tubes are fed by a source of plasma gas such that when a voltage is applied across the electrodes, plasmas initially form across the first plasma gap and second plasma gap. The formed plasmas spread laterally until the plasmas are formed entirely from electrode to electrode and self-sustaining. Plasma gases which are fed to the plasma torch can be metered on both sides of the electrodes to steer the plasma arc attachment axially over the extent of the hollow electrodes, thereby reducing surface wear and increasing electrode life.

Published:
— with international search report (Art. 21(3))
— before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(b))
Self-Igniting Long Arc Plasma Torch

Field of the Invention

The present invention relates to a plasma torch. In particular, the present invention is a multi-phase plasma torch for the generation of a plasma arc in excess of 0.3 meter (m) length which includes structures for the automatic initiation of the plasma arc.

Background of the Invention

Long arc plasma torches are commonly used in plasma chemistry and metallurgy, in plasma costing processes, plasma cutting and welding, and other industrial processes. Plasma torches are also used for vitrification of ceramics and hazardous wastes, in pyrolysis chambers, and in the processing of waste and generation of synthetic fuels. Plasma torches which can generate and deliver a high
temperature stream of ionized gas need to meet several
difficult requirements. One requirement is longevity of
the electrodes, which have a surface region in direct
contact with the plasma in a transient point known as the
arc attachment. One problem of high energy plasma torches
is that the high temperature arc attachment points at the
electrode surface are proximal to very high temperatures of
the reactive ionized gas, which can corrode the surface of
the electrode at the arc attachment point. This surface
corrosion subsequently leads to roughness of the electrode
surface, which then causes enhanced electric fields in the
corroded areas, which then encourages preferential plasma
formation in the corroded areas. Another problem inherent
in high energy long arc plasma torches is plasma arc
initiation. In one prior art device, an external source
introduces a plasma into the desired plasma arc extent,
after which the ionized gas of the introduced plasma forms
a plasma arc across the working electrodes of the plasma
torch. In another prior art device, a separate transformer
generates one or more areas of localized ionized gas along
the path of desired plasma formation between the working
electrode, which local plasmas combine upon application of
sufficient voltage to the working electrodes. In either
device, a separate plasma initiation structure is used at start-up time.

It is desired to provide a long arc plasma torch which self initializes and which provides improved electrode life by ensuring uniform wear of the electrode surface.

Objects of the Invention

A first object of the invention is a plasma torch having a plurality of plasma tubes, each plasma tube having a plasma outlet tube including a plasma exit aperture, the plasma outlet tube including a shared plasma outlet which is electrically common to the other outlet plasma tubes, each plasma tube also having an electrically isolated central plasma tube and an electrode termination, the electrically isolated central plasma tube forming a first gap and plasma initiation region with the adjacent electrode termination and also a second gap plasma initiation region with the commonly connected plasma outlet tube, such that the application of a voltage across the electrodes with an ionizing gas directed to the plasma exit
aperture causes a plasma to form in the first gap and also
in the second gap and thereafter fully extend to span the
electrodes of the plasma tubes, each electrode optionally
having a series of apertures for the introduction of a gas
having a circumferential velocity within the electrode for
circumferentially rotating the plasma attachment point to
the electrode, the electrode also having gas emitting
apertures on at least one end of the electrode to provide
for steering the arc attachment point axially over the
extent of the electrode, the electrode surrounded by a
coaxial coil for the generation of an axial magnetic field.
A second object of the invention is an arc attachment
control system having a hollow cylindrical electrode
carrying a plasma current and having a plasma arc
attachment on an inner surface of the electrode, the
electrode having a gas inlet port adjacent to a sealed
window axially located on one end of the electrode and a
plasma tube on the opposite side of the electrode, the
sealed window coupling optical energy from the plasma arc
attachment to an optical detector generating an electrical
response which is inversely proportional to the distance
from the arc attachment to the detector, the control system
estimating the axial distance of the arc attachment to the
electrode from the electrical response and thereafter
regulating the flow of gas into the gas inlet port to
provide for the arc spot uniformly traverse the axial
extent of the electrode.

A third object of the invention is an arc attachment
control system having a hollow cylindrical electrode
carrying a plasma current and having a plasma arc
attachment on an inner surface of the electrode, the
electrode having apertures along the axial extent of the
electrode and a series of optical detectors for determining
the axial position of the arc attachment to the electrode,
the electrode also having gas inlet ports adjacent to each
ends of the electrode for the introduction of gas, the flow
of gas at each electrode end regulated to place the arc
attachment in a preferred location based on the arc
attachment determined by the optical detectors, the flow of
gas at each electrode regulated to ensure uniform electrode
wear based on the estimated position of the arc attachment
provided by the optical detectors.

A third object of the invention is a self-igniting
plasma generator, the plasma generator having a plurality
of plasma tubes, each plasma tube having an electrically
common end leading to a plasma exit aperture adjacent to
the plasma exit aperture of other plasma tubes, each plasma
tube also having a conductive but electrically isolated
center section and an electrode end having a hollow
cylindrical electrode, the center section forming a first
gap with the hollow cylindrical electrode on one end and a
second gap with the common electrode on the opposite end,
the electrode having a provision for introducing a gas
adjacent to the electrode, where voltage applied to the
electrodes of the plasma tubes causes the gas to ionize in
each of the first and second gaps, the gas flow towards the
exit apertures causing the plasma to expand in extent until
the plasma is continuous between the electrodes.

Summary of the Invention
The invention is a self-igniting plasma torch having a
plurality of plasma tubes, each plasma tube having an
electrode part having a hollow cylindrical electrode with
an electrode gas port and closed window on a first end of
the electrode and a first gap gas port on an opposite
second end of the electrode, the first gap gas port formed
by the gap between the second end of the hollow cylindrical
electrode and an electrically conductive but isolated
center plasma tube a first gap axial distance from the
second end of the hollow cylindrical electrode and thereby
forming the first gap, the center plasma tube having an
opposite end which forms a second gap with an outlet plasma
tube coupled to an exit aperture and electrically common
with other outlet plasma tubes, each of which are coupled
to a respective isolated center plasma tube having a
respective first gap and second gap and terminating in a
respective hollow cylindrical electrode. Each isolated
center plasma tube which forms the first gap and second gap
of each plasma tube is electrically isolated from other
center plasma tubes and other hollow electrodes. In a
plasma initiation mode, gas is introduced to each of the
electrode gas ports, first gap ports and second gap ports,
and a voltage is applied to each of the hollow cylindrical
electrodes of each plasma tube. The applied voltage causes
the gas at the first and second gaps to ionize, and the
direction of gas flow causes the ionized plasma to flow to
the exit aperture, where the plasma expands in extent
across each first gap and second gap until the plasma is
continuous and directly flowing from electrode to electrode
through the plasma tubes. Gas which is introduced into the
hollow cylindrical electrodes has an azimuthal velocity
component, which causes the plasma arc attachment to rotate
circumferentially within the hollow electrode.

Additionally, a coil is in series with each hollow cylindrical electrode and surrounds the hollow cylindrical electrode to generate an axial magnetic field to each hollow electrode using the plasma current, and this magnetic field causes the plasma arc attach at the electrode surface to rotate circumferentially. An axial position control system measures optical energy at each of the electrode windows, or alternatively using a linear array of sensors which estimates attach position based on apertures in the hollow electrode, to estimate the axial arc attach position over the hollow electrode extent, and the gas flow to the electrode port and the first gap gas port is regulated to cause the plasma arc attach to uniformly move over the axial extent of the inner surface of the hollow electrode to provide uniform electrode surface wear. In addition to the axial position control provided by the regulation of gas introduction between the two ends of the hollow electrode, the gas which is introduced circumferentially into the hollow electrode in combination with the axial magnetic field generated by the coil provides uniform wear of the arc attach point of the inner surface of the hollow electrode.
Brief Description of the Drawings

Figure 1 shows a perspective drawing of a plasma torch.

Figure 2 shows a cross section view of a single plasma tube.

Figures 3A, 3B, and 3C show a composite cross section view of a three phase plasma torch in a first stage, second stage, and final stage, respectively, of plasma initiation.

Figure 4 shows the cross section view of an electrode with a plasma arc and arc axial position detector.

Figure 5 shows a plot of the response of the detector of figure 4.

Figure 6 shows a plot of the axial arc position versus flow F2.

Figure 7 shows a plot of arc attach angular velocity versus gas flows.

Figure 8 shows a cross section diagram of a plasma tube indicating dimensional relationships.
Figure 9 shows a cross section diagram of a gas inlet port adjacent to an electrode.

Detailed Description of the Invention

Figure 1 shows one example embodiment of a three phase plasma torch 100. The plasma torch has a plurality of plasma tubes equal in number to the number of electrical phases driving the electrode of each plasma tube, and each plasma tube has a local axis 112-1, 112-2, and 112-3. Each plasma tube consists of a plasma tube electrode unit 110-1, isolated plasma tube 108-1, and plasma outlet tube 106-1 which is electrically connected to other plasma outlet tubes with shared plasma outlet 102. The associated structure for this particular plasma tube indicated with a "-1" suffix, and the plasma tubes for other phases are correspondingly indicated with "-2" and "-3" suffixes. The plasma tube axis 112-1, 112-2, 112-3 are separated from each other by a solid angle with respect to a central axis (not shown), such that the plasma tubes are separated from each other in a plane normal to the central axis (not shown) by an angle of 360/n, where n is the number of
phases and plasma tubes. In the three phase example of
figure 1, the plasma tubes are separated from each other by
120 degrees circumferentially, and the angular separation
from the central axis to the local axis of each plasma tube
may vary from 5 to 30 degrees, as required by the
application. As will be described in detail later,
controller 120 has an electrode control part which provides
drive voltage to each plasma tube electrode, and a gas
control part which includes an optical arc measurement for
estimating the temporal plasma arc attachment axial
location in the electrode, a gas inlet and control for the
multiple locations in each plasma tube where ionizing gas
is introduced, and coolant for each electrode. The
electrical, fluid, and gas interconnects from each plasma
tube to controller 120 are shown for simplicity as single
interconnects 122-1, 122-2, and 122-3.

The plasma generator may be used with any combination
of ionizing and non-ionizing gases, including air,
nitrogen, carbon dioxide, hydrogen, and noble and inert
gasses. The plasma generator of the present invention is
suitable for generation of high energy plasmas with arc
lengths in excess of .3m, such as arc voltages of 1KV to
6KV, any number of electrical phases (equal in number to
the number of plasma tubes), and arc currents of 30A to 500A, resulting in high energy plasma in the range of 100KW to 2500KW.

Figure 2 shows a cross section diagram for one of the plasma tubes of figure 1. Plasma outlet tube 106-1 is centered about local axis 112-1 and leads to the shared plasma outlet 102 which terminates in plasma outlet aperture 104-1, which is joined electrically and mechanically to the other plasma outlet tubes 106-2 and 106-3. Adjacent to, and electrically isolated from plasma outlet tube 106-1, is isolated central plasma tube 108-1, which is also adjacent to and electrically isolated from plasma tube electrode termination 110-1. Plasma initiation first gap 228-1 with gap extent A1 and plasma initiation second gap 230-1 with gap extent A2 are on opposite ends of the isolated plasma tube 108-1, with first gap 228-1 formed by the gap between conductive hollow cylindrical electrode 206-1 and the conductive sleeve 202-1 of isolated plasma tube 108-1. Second gap 230-1 with gap extent A2 is formed by the gap between the electrically conductive isolated plasma tube 202-1 and electrically conductive plasma outlet tube 106-1. The hollow cylindrical electrodes 206-1 may be formed from any combination of copper, copper alloy,
graphites, or formed from any conductor suitable for use in high temperature environments. Additionally, the hollow cylindrical electrodes 206-1 may include water cooling jackets (not shown) for heat removal such as with a coolant such as water, or the water cooling jacket may be isolated from the coolant using a suitable thermally conductive but electrically insulating dielectric material. The plasma outlet tube 106-1 and isolated plasma tube 108-1 may be formed from any electrically conductive material, including aluminum, copper, and copper alloys. As a rough guideline, for optimum outlet tube 106 and plasma tube 108 life, is preferred to use stainless steel for these components where the plasma current is less than 60 amps, and copper and copper alloys for currents above 60A.

Also located in the first gap 228-1 is a first gap gas delivery structure 236-1 which includes gas inlet port 204-1, and structure 236-1 may optionally direct the inlet gas in a circular flow perpendicular to axis 112-1 to encourage a circumferential trajectory of the arc attachment about hollow cylindrical electrode 206-1. On the opposite end of hollow cylindrical electrode 206-1 is an electrode gas port 212-1 which includes a similar structure and inlet apertures 232-1 to encourage a circumferential trajectory
of the gas introduced into the region of the hollow
cylindrical electrode 206-1, with the introduced gas having
a circular trajectory with the same sense as was provided
by first gap gas delivery structure 236-1 through first gap
228-1. Controlling the relative gas flows between first
gap 228-1 and electrode gap 232-1 allows axial control of
the arc attachment point, and the measurement of axial arc
attachment is performed with optical arc attachment
estimator 214-1, which determines the attachment point
through transparent window 216-1, which isolates the
estimator 214-1 from the plasma and also encloses the gas
and plasma volume, thereby directing the introduced gas to
the exit aperture 104-1.

Voltage is applied to hollow cylindrical electrode
206-1 through lead 210-1, which passes first through
helical wound coil 208-1, and the opposite end of the
helically wound coil 208-1 which surrounds electrode 206-1
and is then electrically connected to the electrode 206-1,
such that plasma current which passes through the electrode
206-1 self-generates an axial magnetic field parallel to
local axis 112-1, which, along with the circumferential
velocity of gasses introduced to the electrode, also
encourages circumferential rotation of the arc attachment
point across the inner surface of electrode 206-1. In this manner, the axial magnetic field generated by the plasma current causes circumferential movement of the arc attachment point, and differential control of gas flow through electrode gas inlet 212-1 and first gap gas inlet 204-1 provides axial steering of the arc attachment point over the inner surface of the hollow cylindrical electrode 206-1, with the differential gas flow rates determined from measurement of the axial arc position using optical measurement unit 214-1 through transparent circular window 216-1. Alternatively, axial arc attach position may be determined using a linear array of sensors which are positioned along the axial extent of electrode 106-1 and are optically coupled through apertures in the hollow electrode 206-1.

Second gap 230-1 also has a gas inlet port 234-1 which directs gas into the plasma tube using housing 232-1. The hollow electrode 206-1 has an axial extent L1 220-1, the isolated plasma tube 202-1 has an axial extent L2 222-1, and the plasma outlet tube 106-1 has an axial extent L3 from second gap 230-1 to outlet aperture 104-1 shown in figure 1. The extent of each of these three sections is selected in combination with first gap A1 and second gap A2.
extents and operating voltage to provide for plasma
initiation upon application of voltage to the hollow
electrodes, as can be seen in figure 3A for two electrodes.

In a first interval of plasma initiation shown in
figure 3A, a voltage such as three phase voltage in the
example range of 10kV to 20kV is applied across annular
electrodes 206-1, 206-2, and 206-3 while ionizing gas is
introduced in the three ports (electrode gas port 212-1,
first gap gas port 204-1, and second gap gas port 234-1) of
each plasma tube. If the first gap extent A1 (shown in
figure 2 as 228-1) of each plasma tube is shorter than
second gap extent 230-1 A2, the electric field density will
be highest at the first gap extent, resulting in the
ionization of gas and subsequent formation of initial
plasma 320, 322, 324, followed almost instantaneously by
initial plasma formation 321, 323, 325, as shown in the
first gap and second gap regions, respectively, of the
three plasma tubes. The initial plasmas formed across the
first gap and second gap of each plasma tube spread along
the conductive walls or electrode surface of the respective
axial extents of each plasma tube, as shown in first gap
regions 330, 332, 334 arc extent from electrode to isolated
plasma tube wall and second gap regions 336, 338, and 340
from isolated plasma tube wall to shared plasma outlet
tubes of figure 3B, and each of the plasmas grows in
lateral extent and also in the direction of the plasma
outlet tube exit apertures 104-1, 104-2, 104-3 (shown for
reference in this composite cross section view) with the
introduction of pressurized gas in the electrode gap, first
gap, and second gap regions. As the extent of the plasmas
grows and follows the gas to the exit apertures, the plasma
regions between electrodes interconnect and interact until
each electrode has a single plasma path interconnecting
each of the electrodes of the respective plasma tubes, as
shown in figure 3C plasma 340, 342, 344, and the plasma
longer has attachment points to the conductive isolated
plasma tubes 202-1, 202-2, or 202-3 or to the shared plasma
outlet plasma tubes 106-1, 106-2, or 106-3. At this point,
the plasma is now flowing directly between electrodes 206-
1, 206-2, and 206-3 and is entirely contained within the
plasma tubes and directed to the exit apertures, with no
remaining plasma in the first and second gap regions. The
plasma torch has now completed plasma initiation and enters
a steady state operational mode.

Figure 3C also shows the gas controller 350 component
of the controller 120 of figure 1. Gas controller 350
includes an axial arc attachment sensor 214-1, 214-2, 214-3
and associated control valves (not shown) which regulate
the flow of gas to the electrode gas port 212-1, first gap
gas port 204-1, and second gap gas port 234-1 based on the
arc attachment local axial (Z) position, which position is
modulated cyclically from front to rear of the hollow
cylindrical electrode by regulation of the ratio of gas
flows into the electrode gas port on the rear of the
electrode and first gap gas line port on the front of the
electrode to minimize the single point surface wear.
Successful control of the axial arc attach position and
circumferential rotation rate of the arc attach can provide
a large increase in electrode usable life in the range of
thousands of hours of life. The arc attachment control for
each plasma tube operates independently of the arc attach
control of the other plasma tubes.

Figures 4 and 5 show one example embodiment for a
sensor system estimating the arc axial position. Arc axial
positional estimator 214-1 may use an omni-directional
optical sensor 410 which is responsive to the intensity of
the arc, such that when the near field arc intensity is
used as a calibration point, the separation distance may be
computed using the detector output and the inverse square
law which estimates intensity at a distance, in combination
with the near field arc intensity measurement. The arc
attachment point 404 rotates circumferentially over the
inside surface of electrode 206-1 at a particular distance
406, with a high rate of circumferential rotation compared
to axial movement, so that as the arc spot 404 rotates, the
fixed circumferential distance 406 to detector 410 produces
a relatively fixed detector response at output 412. The
detector response for arc spot 404 is shown in 506 of
figure 5, with the distance response shown with the inverse
square response plot 504, such that an arc attachment at
point 402, which is a separation distance 408 from detector
410 produces the response shown in point 502. Window 216-1
provides optical coupling from detector 410 to resolve the
range of arc spot attachment from 402 to 404 while
providing mechanical and electrical isolation of the
detector from the ionized gas and plasma arc. Detector 410
may be operative in the infrared, visible, or ultraviolet
wavelengths, and window 216-1 may be constructed of a
material with matching wavelength characteristics.

One of the advantages of the present invention is the
independent control of arc attachment axial position, which
is controlled by the ratio of F2 to total flow \( F_t = F_1 + F_2 \) and
control of the arc attachment circumferential rotation, which is primarily controlled by the azimuthal velocity component of the gas jets F1 and F2 at the hollow electrode in combination with the magnetic field generated by the coil which surrounds the electrode. It is desired to be able to control these independent arc position parameters to prevent excessive heat buildup on an electrode from a stationary arc spot attachment, which would otherwise cause destruction of the electrode surface.

In one example embodiment of the invention, a flow of gas at a substantially fixed flow rate $F_t$ is divided between the front gas port 204-1 and rear gas port 212-1 of the electrode. In this embodiment, the total flow of gas is $F_t = F_1 + F_2$, where $F_1$ and $F_2$ are shown in figure 4 and the fraction of gas applied to the rear gas port of the electrode may be expressed as $F_2 = K \times F_t \ (0 \leq K \leq 1)$.

Figure 6 shows a plot for axial control of the arc attachment point using the configuration of figures 4. As was described in figure 2, electrode gas port 212-1 (shown with flow rate $F_2$) and first gap gas port 204-1 (shown with flow rate $F_1$) both support controllable gas flows, with the gas flow $F_2$ of electrode port 212-1 passing over the surface of electrode 206-1, and where the axial position of
the circumferentially rotating arc attach can be entirely
controlled by the ratio of gas flows for F1 and F2. In this
manner, the circumferential arc attachment can be varied
from 0 (arc attachment 404) to L1 (arc attachment 402)
through control of flows F2 and F1 at port 212-1 and 204-1,
respectively. This is illustrated in plot 602 of figure 6,
which shows that as flow F2 is increased from 0 to the
maximum flow rate \( F_t \), the axial position of the arc
attachment point can be varied from 0 to L1.

In one "open loop arc attachment control" embodiment
of the invention, the required flow rates F1 and F2 (or
alternatively the required values of K for a particular Ft)
are determined which provide control of the plasma arc
attach position over the range 0-L for a particular
electrode configuration. Once these parameters are known,
it is possible to simply vary F1 and F2 (or K) in a
cyclical manner to ensure sufficient arc attachment
circumferential rotation and axial movement, which would
thereby eliminate the need for the arc position detector
214-1 of figure 4.

Independent from the axial position control, the
circumferential rotation of the arc attachment (for a fixed
axial position) can be controlled by the circumferential
velocity components of the gas flows F1 and F2 entering the
electrode, in addition to the JxB magnetic field generated
by the coil surrounding the electrode. In the embodiment
of the invention shown in figures 4 and 7, the magnetic
field generated by coil 208-1 (which carries the electrode
206-1 feed current) interacts with the plasma to cause a
JxB axial rotational force which is proportional to gas
flow.

In one embodiment of the invention, flow-directing
vanes may be present in the structures associated with
electrode gap 232-1 of figure 2 and first gap 228-1 (and
optionally electrode 206-1) which causes the gas entering
ports 212-1 and 204-1, respectively, to have a
circumferential velocity in the same direction as the
smaller circumferential velocity generated by the JxB field
within the electrode, and these two forces together
contribute to the circumferential rotation of the arc
attachment spot on the inner surface of the electrode.
Where such structure which cause circular rotation of the
gas are present, the circumferential rotational velocity of
the arc attachment spot may be controlled, as shown in
figure 7, by the combined flow F1 and F2 which enters the
electrode port and first gap port.
In one embodiment of the invention, 10% to 50% of the
gas flow through a particular plasma tube enters through
the first gap gas port and electrode gas port (for control
of the arc attach axial position), and in another
embodiment of the invention, the second gap gas port is
responsible for 50% to 90% of the gas flow in a plasma
tube.

The number of turns on coil 208-1 of figure 2 which is
in series with the electrode lead 210-1 are chosen to
provide a magnetic field strength sufficient to ensure
optimum plasma coherency, which provides for a high current
and high temperature plasma, while also providing minimal
wear to the surface of the hollow cylindrical electrode
206-1. As current density and electrode wear are competing
parameters, a tradeoff is made between these two objectives
in the selection of the coil. Since the gas entry at
electrode gap 232-1 and first gap 228-1 provides
circumferential velocity, it is also possible in one
embodiment of the invention to control plasma rotational
velocity using gas pressure alone. In another embodiment
of the invention, the plasma circumferential rotation is
achieved using the interaction between the magnetic field
generated by coil 208-1 and the self-current of the plasma
at the arc attach point, and in another embodiment of the
invention, the magnetic field of the coil, the self-current
of the plasma, and the circumferential velocity of the gas
provide rotation of the plasma arc spot attachment to the
electrode 206-1.

Figure 8 identifies particular structures with
dimensional notations provided, and in one embodiment of
the invention, the following preferred dimensional
relationships may be used:

\[ D_1 \] - inner diameter of the hollow cylindrical
electrode, selected on the basis of electrode life, current
density, and heat dissipation (in the range 20-200mm in one
embodiment);

\[ L_1 \] - hollow electrode length, in the range of 2*D1 to
10*D1;

\[ L_2 \] - isolated plasma tube electrode length, in the
range of 5*D1 to 30*D1;

\[ D_2 \] - isolated plasma tube electrode inner diameter, in
the range of 0.5*D1 to D1;

\[ H_1 \] - in the case where a vortex is used (where the
intermediate tube has a diameter D2 less than hollow
electrode diameter D1) H1 may be in the range of 20mm-
300mm;

L3 - plasma outlet tube length, in the range of 5*D1
to 40*D1;

A1 - first gap extent in the range 1mm to 10mm;

A2 - second gap extent in the range of 1mm to 10mm.

Figure 9 shows a cross section diagram of the gas
inlet structures adjacent to the hollow electrode, such as
through section A-A of figure 8. Each gas inlet admits a
gas through an inlet port 902, where it encounters a series
of vane structure 906 or other structures which direct the
flow of the gas in a tangential circumferential flow 912,
as shown by flow trajectory 910. In a preferred
embodiment, the vanes 906 terminate outside the extent 908
of the hollow electrode so as to not interfere with plasma
initiation or generation, and the vanes 906 may be
fabricated from an insulating material to avoid
interference with the plasma initiation.

In one alternative embodiment of the plasma generator,
the individual outlet apertures of the shared plasma outlet
are collected together into a single plasma port for
transfer and delivery of the generated plasma. In another
embodiment of the invention, the electrodes are coupled to
a voltage source which provides alternating current (AC),
or the electrodes are coupled to a coil wound around the
hollow electrode, or to an alternating current voltage
source with series inductors which limit the plasma
current, or any combination of these. Additionally, the
example shown may be adapted to operate on any number of
electrical phases, although three phases is shown. In
other example embodiments for a single phase application,
there may be two plasma tubes, or alternatively, four
plasma tubes may be connected with same-phase electrodes
adjacent to each other and with 90 degree separation from a
common central axis.

Additionally, the controller 350 of figures 3A, 3B,
and 3C or the controller 120 of figure 1 may estimate axial
position of the arc attachment using an optical sensor, or
it may regulate gas flows such as F1 and F2 of figure 4
(G1_gas and E_gas, respectively, in figures 3A, 3B, and 3C)
for axial control based on device characteristics in
combination with the measurement of current and voltage
applied to each electrode, where the characterization also
indicates the amount of F1 and F2 gas flows required for
satisfactory operation and axial movement to achieve
uniform electrode wear. Similarly, the measurements of electrode voltage and current may be used to regulate the flows of E_gas, G1_gas, and G2_gas shown in figures 3A, 3B, and 3C.
I claim:

1) A plasma torch comprising:

an outlet aperture formed by a plurality of plasma
outlet tubes which join to form a plurality of plasma
outlets;

a plurality of isolated plasma tubes, each having a
first gap end and a second gap end;

a plurality of hollow electrodes, each placed a first
gap distance from an associated end of said isolated plasma
tube first gap end, thereby forming a first gap;

each said isolated plasma tube second gap end placed a
second gap distance from an associated said plasma outlet
tube, thereby forming a second gap;

each said hollow electrode having a first gap gas
inlet surrounding said first gap, an electrode gas inlet on
the opposite end of said hollow electrode, and a second gap
gas inlet surrounding said second gap;

a plasma gas which enters said electrode gas inlet,
said first gap gas inlet, and said second gap gas inlet;
at least two said hollow electrodes energized with a
voltage from a voltage source sufficient to ionize said
plasma gas.

2) The plasma torch of claim 1 where said voltage is
a three phase voltage and the number of said plurality of
hollow electrodes and said plasma tubes is three.

3) The plasma torch of claim 1 where said first gap
distance and said second gap distance are selected to
initially ionize said plasma gas across said first gap and
said second gap, the plasma thereafter flowing directly
from one said hollow electrode to another said hollow
electrode.

4) The plasma torch of claim 1 where said electrode
gas inlet and said first gap gas inlet have a plurality of
vanes to cause circumferential gas flow across the inner
surface of said hollow electrode.
5) The plasma torch of claim 1 where at least one of said electrode gas inlet or said first gap gas inlet generates a circumferential gas flow adjacent to said hollow electrode.

6) The plasma torch of claim 1 where said hollow electrode includes a coil wound around the outer diameter of said hollow electrode, said coil generating a substantially axial magnetic field.

7) The plasma torch of claim 1 where said hollow electrode includes a coil wound around the outer diameter of said hollow electrode, said coil in series with said voltage source and said electrode.

8) The plasma torch of claim 1 where said voltage source is a three phase alternating current (AC) voltage source.

9) The plasma torch of claim 1 where said voltage source is current limited by a series inductance.
10) The plasma torch of claim 1 where said electrode gas inlet includes an adjacent transparent aperture for the examination of the axial location of a plasma arc attachment within said hollow electrode, and the flow of gas into said electrode gas inlet and said first gap gas inlet is controlled to cyclically move an arc attachment point over the axial extent of said hollow electrode.

11) A plasma torch having:

   a plurality of hollow electrodes, each said hollow electrode having an electrode gas inlet port and a first gap gas inlet port on the opposite end from said electrode gas inlet port;

   a plurality of isolated plasma tubes, each said isolated plasma tube placed a first gap distance from said hollow electrode, thereby forming a first gap having a first gap plasma initiation region, each said isolated plasma tube having a second gap end opposite said first gap plasma initiation region;
a plurality of electrically connected plasma tubes,
each said electrically connected plasma tube placed a
second gap distance from an associated isolated plasma tube
second gap end, thereby forming a second gap having a
second gap plasma initiation region, the opposite end of
said electrically connected plasma tubes having a plasma
outlet aperture which is adjacent to other electrically
connected plasma tubes and thereby forming a plasma outlet;
whereby upon the application of a gas to said
electrode gas inlet, said first gas inlet, and said second
gas inlet, and the application of an electrical voltage to
said electrodes, said first plasma initiation region and
said second plasma initiation region form localized plasmas
across said first gap and said second gap which join to
form a single plasma across said hollow electrodes.

12) The plasma torch of claim 11 where said electrode
gas inlet and said first gas inlet have respective gas
flows which are cyclically varied.
13) The plasma torch of claim 11 where said electrode has a plurality of tangentially formed apertures which cause the circumferential flow of said plasma gas.

14) The plasma torch of claim 11 where said gas includes an ionizing or non-ionizing gas.

15) The plasma torch of claim 11 where said gas includes at least one of nitrogen, carbon dioxide, hydrogen, noble, or an inert gas.

16) The plasma torch of claim 11 where said hollow electrode includes a co-axially wound coil which is in series with said electrode and said voltage source for said electrode.

17) The plasma torch of claim 11 where said electrode gas inlet and said first gap gas inlet are fed with gasses having a flow rate which is controlled based on axial arc attachment position within an associated electrode.
18) The plasma torch of claim 11 where said electrode
gas inlet and said first gap gas inlet are fed with
substantially constant gas flow rate which is cyclically
varied proportionally between said electrode gas inlet and
said first gap gas inlet sufficient to move an arc
attachment location axially over said electrode surface.

19) The plasma torch of claim 11 where said source of
electrical voltage is a three phase alternating current
(AC) voltage.

20) The plasma torch of claim 19 where said source of
electrical voltage is current limited by a series inductor.
**Figure 1**
Plasma Torch

**Figure 2**
Plasma Tube Cross Section

Electrode Drive (Out)
Optical Arc Meas (In)
Gas Inlet (F, R)
Coolant (In, Out)
Figure 4

Figure 5
Axial Arc estimation

Figure 6
Axial arc position control using flow F2

Figure 7
Arc attach angular velocity vs gas flow

Arc attach angular velocity proportional to BxJ

Ft = F1 + F2
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - B23K 10/02 (2012.01)
USPC - 219/121.48
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
IPC(8): B23K 10/02 (2012.01)
USPC: 219/121.48

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8): B23K 10/02 (2012.01)
USPC: 219/121.48,121.52,121.55; 373/18

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST; PGDB, USPT, EPO, JPAB; Google Scholar; Google Patent; Search Terms: Plasma ion hollow tube electrode swirl gap inlet gas argon noble poly-phase three-phase alternating current voltage inductance coil wound magnet micro-wave torch material hollow chamber three third 120 equidistant jet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>US 4,517,495 A (Piepermeier) 14 May 1985 (14.05.1985) col 3 ln 14 to col 6 ln 65. Fig. 1-4.</td>
<td>1-20</td>
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<td>Y</td>
<td>US 2004/0256365 A1 (DePetrillo et al.) 23 December 2004 (23.12.2004) para. [0022]-[0025], [0029], [0035]-[0045], Fig. 1</td>
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<td>Y</td>
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<td>A</td>
<td>US 3,578,943 A (Schournaker) 18 May 1971 (18.05.1971) entire document</td>
<td>1-20</td>
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</table>

Further documents are listed in the continuation of Box C.

* Special categories of cited documents:
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Date of the actual completion of the international search
29 November 2012 (29.11.2012)

Date of mailing of the international search report
19 DEC 2012

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Form PCT/ISA/210 (second sheet) (July 2009)