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ELECTRODELESS PLASMA TORCH AND METHOD

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2 Sheets-Sheet 1

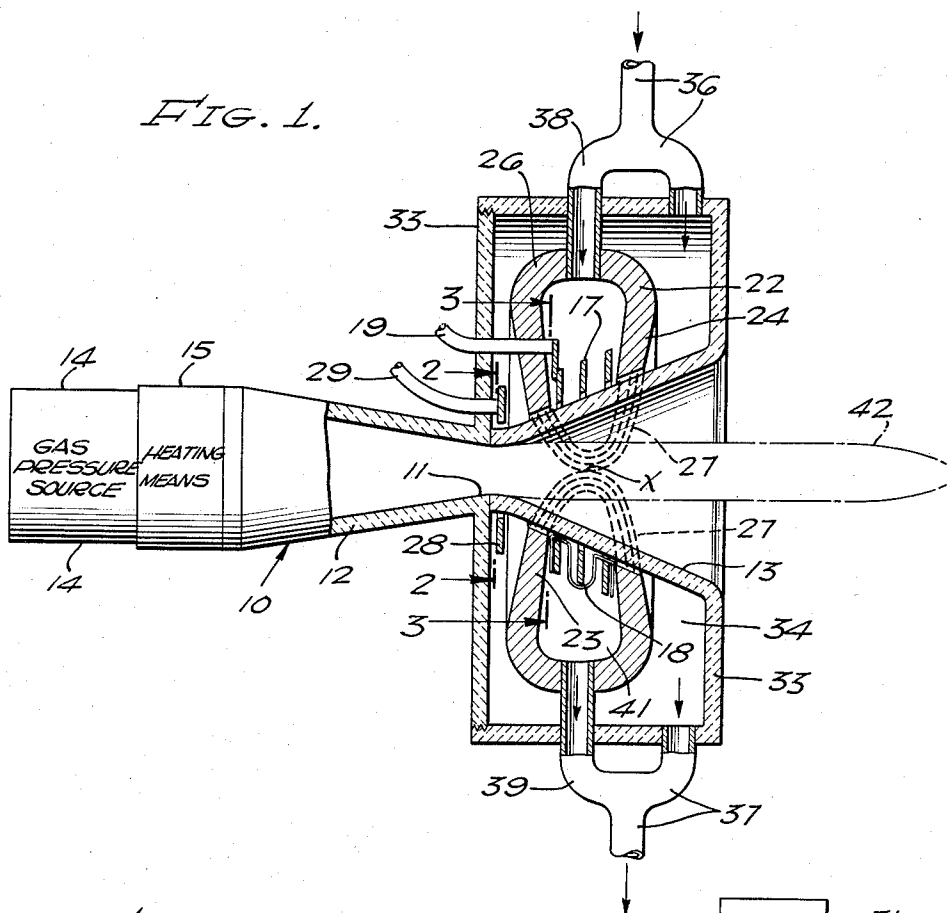


FIG. 3.

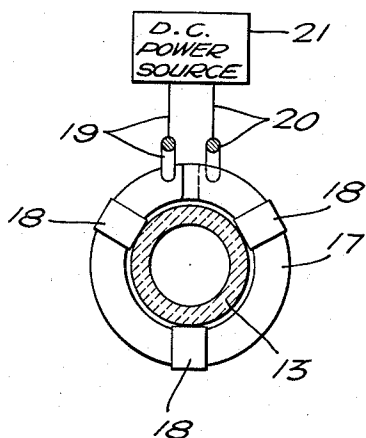
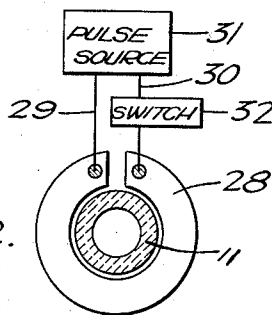


FIG. 2.



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2 Sheets-Sheet 2

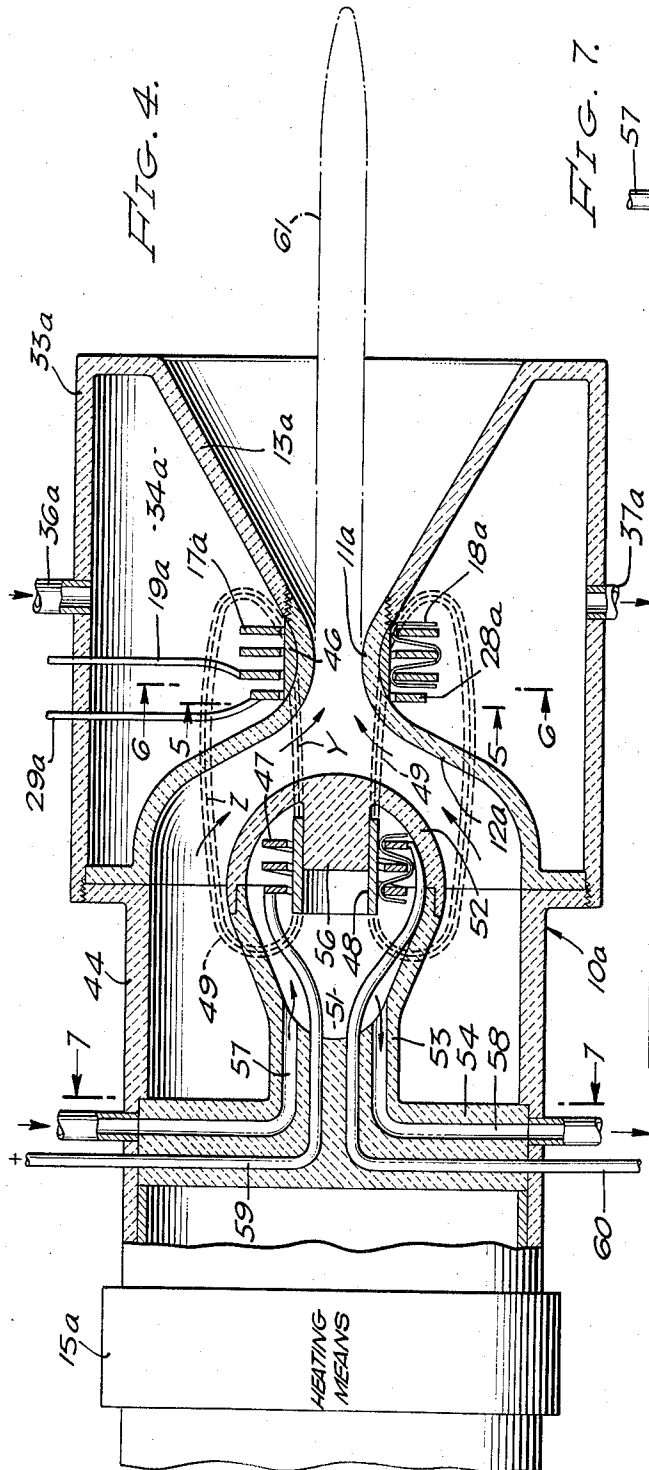


FIG. 4.

FIG. 7.

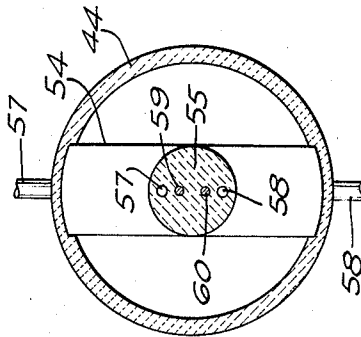


FIG. 6.

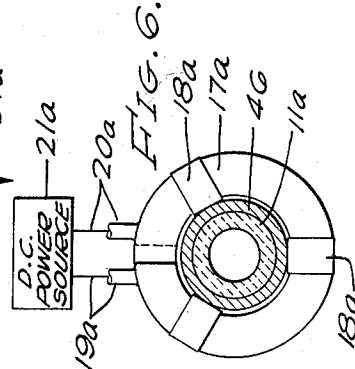
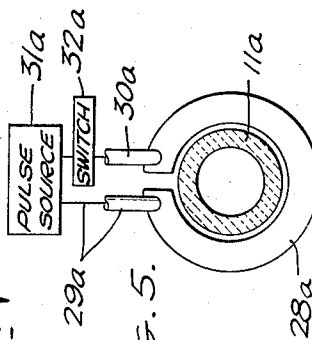


FIG. 5.



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1

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ELECTRODELESS PLASMA TORCH AND METHOD

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16 Claims. (Cl. 313—231)

This invention relates to a method and apparatus for generating a plasma flame or jet without employing electrodes.

In generating electrical plasma flames or jets, the problem of electrode life has been highly critical and difficult of solution. Because of the very high current densities and temperatures present in high-temperature plasma-jet equipment, the electrodes tend to erode and otherwise deteriorate unless special procedures and apparatus are employed. Such special procedures generally include the use of an oxidation-preventing gas such as argon, helium, nitrogen, etc. Where an oxygen-containing gas such as air is passed through the torch, it has been found that electrode life is generally measured in minutes. It is therefore normally impractical to pass air and other extremely cheap gases through such torches. It is also normally impractical to pass through such torches highly-corrosive substances which will react adversely with the electrodes.

In view of the above and other factors characteristic of presently-known plasma torches, it is an object of the present invention to provide a method and apparatus for generating a plasma flame or plasma jet in the absence of any electrodes, so that the plasma need only contact ceramic or other insulating surfaces which are relatively immune to oxidation and corrosion.

A further object of the invention is to provide a method and apparatus for generating closed loops of current in a rapidly flowing gas and thereby create a plasma flame or jet.

These and other objects and advantages of the invention will be more fully set forth in the following specification and claims, considered in connection with the attached drawings to which they relate.

In the drawings:

Figure 1 is a schematic view, primarily in vertical central section, illustrating one form of apparatus embodying the present invention;

Figure 2 is a section on line 2—2 of Figure 1, illustrating the triggering or plasma-initiating means;

Figure 3 is a section on line 3—3 of Figure 1 and showing the power source to the coil which produces the magnetic field;

Figure 4 is a schematic central sectional view showing a second form of apparatus embodying the present invention;

Figure 5 is a section on line 5—5 of Figure 4 and illustrating the triggering means;

Figure 6 is a section on line 6—6 of Figure 4; and

Figure 7 is a section on line 7—7 of Figure 4 and illustrating the support for the island which contains one of the magnetic field-generating coils.

Stated generally, the apparatus of the invention includes conduit means, means for effecting flow of gas at a high velocity through the conduit means, and means to generate a strong magnetic field within the conduit means and having a substantial component perpendicular to

2

the direction of gas flow. The apparatus further includes trigger means for aiding in the initiation of the electrical discharge, and means for cooling the torch components.

Referring first to the embodiment shown in Figures 1—3, the conduit means is schematically indicated at 10 as being generally tubular or cylindrical in shape and as having a throat or nozzle portion at 11. On the upstream side of the throat 11, the conduit means 10 comprises a frustoconical section 12 which converges in the downstream direction. On the downstream side of the throat 11, the conduit means 10 comprises a frustoconical section 13 which diverges in the downstream direction and terminates in an outlet opening.

The conduit means 11, and all of the components of the apparatus excepting such elements as the current conductors, magnetic shields or cores, etc., may be formed of a suitable ceramic which is highly resistant to oxidation and corrosion. It is, however, within the scope of the invention to form the conduit means of metal, for example a water-cooled refractory such as tungsten.

The means for effecting flow of gas at high velocity through the conduit means 10 is schematically represented in Figure 1 as comprising a source 14 of gas under high pressure, and a heating apparatus 15 for pre-heating the gas as it expands (or thereafter) from source 14 into the conduit means. Source 14 may contain, under a relatively high pressure adapted to produce a high gas velocity upon expansion into the conduit means, a readily ionized gas such as argon or helium. However, it is within the scope of the invention to employ such gases as hydrogen and nitrogen and highly inexpensive gases such as air.

The heating apparatus 15 serves the purpose of increasing the flow of velocity and electrical conductivity of the gas, and also raises the temperature of the subsequently generated plasma by increasing the temperature of the gas prior to conduction of current therethrough.

The heater may be of any suitable type, for example a pebble heater, and may heat the gas to a temperature on the order of 1000° K., for example. Also, a high-frequency high-power coil may be used to heat and thus pre-ionize the gas.

The gas pressure delivered from source 14, the amount of heating in the heater 15, the degree and manner of constriction of the conduit means 10 at throat or nozzle portion 11, etc., should be such that the gas flow velocity in the region of point x, at the diverging section 13 of the conduit means, is on the order of the local speed of sound at x, or higher.

The means for creating a strong magnetic field in the conduit means is illustrated in Figure 1 to comprise a generally helical coil 17 mounted closely and coaxially around the diverging conduit section 13 radially outwardly from point x, a short distance downstream from the throat 11. The coil 17 may be shaped in the manner of a cork screw, having a relatively thick rectangular section capable of carrying extremely high currents. In order to insure against shorting of one turn relative to the next, strips of insulating material such as "Teflon" may be woven between the individual turns as indicated at 18 in Figures 1 and 3.

The opposite ends of coil 17 are connected through leads 19 and 20 to a suitable source 21 of direct current. The current source should be adapted to deliver very high steady (non-pulsating) currents, for example on the order of 10,000 amperes, although the voltage may be relatively low such as 10 volts. Such currents are required to generate a very strong direct magnetic field in a region surrounding point x, such magnetic field having an intensity of 50,000 to 100,000 gauss and higher.

In order to cause the lines of magnetic flux or force to have a substantial component perpendicular to the direction of gas flow, that is to say generally radial to the axis of the conduit portion 13, a shield 22 formed of a magnetizable substance such as soft iron is provided around the coil. More specifically, the illustrated shield is formed with upstream and downstream frustoconical portions 23 and 24, respectively, mounted coaxially around the conduit means and adjacent the opposite ends of coil 17. The frustoconical portions 23 and 24 converge towards each other and are connected at their regions remote from point x by an integral annular body portion 26. This configuration causes the lines of magnetic force or flux, indicated at 27 in Figure 1, to penetrate into the conduit means to the region of point x, and to have substantial components perpendicular to the gas flow direction as desired.

The trigger means, for aiding in the initiation of plasma generation, is represented at 28 as comprising a single-turn electrical conductor encompassing the throat 11 of the conduit means. The opposite ends of the single-turn conductor are connected through leads 29 and 30 to a source 31 adapted to deliver a high-intensity pulse of current. For example, source 31 may comprise a low-inductance capacitor having a relatively high capacity, and which may be charged from a suitable D.C. source. A suitable switch, indicated at 32, is provided in lead 30 to complete the circuit from capacitor 31 to coil 28, so that a very large pulse of current may be caused to flow momentarily through the conductor.

The cooling means for the torch may comprise wall means 33 to define an annular chamber 34 around the divergent frustoconical section 13, and in which the elements 17, 22 and 28 are disposed. Water is fed through chamber 34 by means of an inlet conduit 36 and an outlet conduit 37 located at diametrically opposite portions of the wall means 33. Branch conduits 38 and 39 are associated, respectively, with the inlet and outlet conduits 36 and 37, and communicate directly with the chamber 41 formed within the magnetic shield 22. The branch conduits may thus provide a forced and rapid flow of water around the coil 17 to effectively cool the same.

It is to be understood that the conductors 19 and 29 should be large in cross-sectional area, and may be water cooled. They may (as may elements 17 and 28) comprise hollow tubes through which water is fed. The same applies to corresponding elements in the embodiment of Figures 4-7.

Summary of the method of the invention

As previously indicated, the method comprises passing gas at a high velocity through a strong magnetic field having a substantial component perpendicular to the direction of gas flow. In accordance with Maxwell's equation, this causes a voltage to be generated in the gas and having a magnitude equal to the vector cross-product of the gas velocity and the magnetic field intensity as follows:

$$\vec{E} = \vec{v} \times \vec{B} = |\vec{v}| |\vec{B}| \sin \theta$$

where

E is the voltage gradient in the gas, in volts per meter;
v is the gas velocity in meters per second;
B is the magnetic field intensity in webers per square meter; and
 θ is the angle between the direction of gas flow and the direction of the lines of magnetic force.

Assuming a magnetic field strength of 100,000 gauss, and a gas velocity of 1,000 meters per second at right angles to the magnetic field, the above equation shows that there is a voltage in the gas of 100 volts per centimeter. Such a voltage causes currents to flow through the gas, the current flow being in closed loops through the gas since no electrodes are employed. The result

is a high-temperature plasma flame or jet which is schematically represented at 42 in Figure 1.

With the apparatus shown in Figures 1-3, the method of the invention comprises causing gas to expand from the high-pressure source 14 through heater 15 and into the conduit means 10. The gas is thus caused to flow rapidly, and increases in velocity as it enters the throat 11, so that the velocity in the region of point x is relatively high and may be in the sonic range. The rapidly moving gas flows through the lines 27 of magnetic flux or force, such lines being generated due to passage of very high direct current through the coil 17 from D.C. power source 21. In order to produce initial ionization, switch 32 (Figure 2) is closed to cause discharge of capacitor 31 (or other pulse source) through the trigger loop 28 and thus generate a rapidly changing field in the conduit means 10 at throat 11. The discharge then begins and is continued to produce the plasma flame or jet shown at 42.

The flame or jet 42 may be employed for a wide variety of beneficial purposes, and does not result in rapid deterioration of the torch since there is no arcing to a solid element. As previously indicated, the torch is maintained cool by water forced through the chambers 34 and 41 by means of the conduits 36-39.

Embodiment of Figures 4-7

The embodiment shown in Figures 4-7 is adapted to generate lines of magnetic flux or force which are substantially perpendicular to gas flow at all regions of at least one cross-section of the gas flow path, so that a very high efficiency is achieved with consequent high-temperature discharge. The elements of Figures 4-7 which correspond to the elements in Figures 1-3 have been correspondingly numbered, except that the numbers in Figures 4-7 have been followed by the letter "a."

In the embodiment of Figures 4-7, the conduit means 10a has a relatively large-diameter tubular portion 44 which merges with the relatively steeply convergent section or portion 12a terminating in throat 11a. Throat 11a, in turn, merges with the divergent section 13a which terminates in the outlet opening. Portions 11a, 12a and 13a are encompassed by wall means 33a for defining an annular chamber 34a therearound, and in which is mounted a helical coil 17a coaxially around throat 11a. Direct current is fed through coil 17a by leads 19a and 20a from a D.C. power source 21a, and excessive heating of the coil due to the high currents is prevented by passing water through chamber 34a via water conduits 36a and 37a. A trigger loop 28a is located at throat 11a, upstream from coil 17a, and is connected through leads 29a and 30a to the pulse source 31a. The magnetic shield 22 of the previous embodiment is not employed, and a ring 46 of magnetizable material such as soft iron is mounted closely around the throat radially inwardly from coil 17a.

A second helical coil 47 is provided in the cylindrical portion 44 of conduit means 10a, upstream from throat 11a and coaxial with coil 17a. Coil 47 is mounted around a magnetizable ring or tube 48 which is coaxial with ring 46. The coils 17a and 47, and the rings 46 and 48, may be regarded as extensions of each other but as spaced apart so as to permit gas flow therebetween. When current is fed through the coils 17a and 47, in aiding relationship, the result is a solenoid action whereby loops or lines of magnetic force or flux 49 are set up through the combined coils 17a and 47. The inner portions of such loops traverse the space immediately upstream from throat 11a as indicated at y, and the outer portions of such loops traverse the space upstream therefrom as indicated at z.

The second coil 47 is mounted in a chamber 51 in a bulbous island or envelope member 52 which may be generally spheroidal or tear-drop shape in external configuration. Member 52 is coaxial with the conduit means

and is connected at its upstream end, through a connecting section 53, to a bridge or support member 54. The bridge or support 54 is, as best shown at Figure 7, disposed diametrically across the tubular portion 44 of the conduit means 10a, and is preferably streamlined on its upstream side in order to minimize turbulence.

An internal support portion 56 of the island member 52 is disposed within the iron ring 48 and serves to support the same. Cooling water is conducted to and from the chamber 51 in island member 52 by passage means 57 and 58, and electric current is conducted to and from the opposite ends of coil 47 via electrical conductors 59 and 60. The passage means 57-58, and the conductors 59-60, pass through the connecting portion 53 and also the bridge element 54 as shown in Figures 4 and 7.

In the operation of the embodiment of Figures 4-7, a large direct current (or separate aiding currents) is passed through the coil 47 via leads 59 and 60, and through coil 17a via leads 19a and 20a, in aiding relationship to thus set up the lines or loops of flux indicated at 49. Gas is passed from the source, not shown, through the heating means 15a and around the bridge 54 to the annular region surrounding the island member 52. In flowing around the island member 52 to the throat 11a, the gas must sequentially traverse the portions of z and y of the lines of magnetic force or flux, and at substantially right angles as indicated by the arrows. This provides very high efficiency not only because the lines of force are traversed at right angles, but also because the separate loop portions y and z of the lines of force are traversed sequentially by the gas.

Initial ionization is aided by discharging one or more pulses of current through loop 28a, by means of switch 32a, thereby resulting in a continued discharge which produces a plasma flame or jet schematically represented at 61.

Various embodiments of the present invention, in addition to what has been illustrated and described in detail, may be employed without departing from the scope of the accompanying claims.

We claim:

1. An electrodeless plasma torch apparatus, which comprises conduit means, means for effecting flow of gas through said conduit means at a high velocity, and means for generating in said conduit means a strong magnetic field having a substantial component transverse to the direction of gas flow, said gas flow velocity being sufficiently high and said magnetic field being sufficiently strong that a discharge is effected through said gas to create a plasma flame or jet in the absence of electrodes.

2. An electrodeless plasma torch apparatus, which comprises conduit means adapted to contain a gas, means to generate a strong direct magnetic field in said conduit means, and means to effect a sufficiently high rate of relative movement between said gas and said magnetic field that an electrical discharge is effected in said conduit means solely as the result of said relative movement and in the absence of electrodes.

3. An electrodeless plasma torch apparatus, which comprises conduit means having an outlet opening, gas-flow means for effecting flow of gas at a high velocity through said conduit means and out said outlet opening, and magnet means for generating within said conduit means and adjacent said outlet opening a high-intensity direct magnetic field having a substantial component transverse to gas flow direction, thereby setting up in said gas electrical currents flowing in closed loops to generate plasma in said conduit means and discharging out said outlet opening.

4. The invention as claimed in claim 3, in which trigger means are provided for effecting initial ionization of said gas in the region of said magnetic field to thereby aid in initiation of plasma discharge.

5. The invention as claimed in claim 3, in which said gas-flow means is adapted to create a gas velocity on the order of the local speed of sound in the gas, and in which said magnet means is adapted to create a magnetic field intensity on the order of about 50,000 gauss.

6. The invention as claimed in claim 3, in which said magnet means is adapted to cause said direct magnetic field and the direction of gas flow to be generally perpendicular to each other.

7. An electrodeless plasma torch, which comprises conduit means terminating in an outlet opening and having a restricted or throat portion adjacent said outlet opening whereby to increase the flow velocity of gas flowing through said conduit means in the region of said outlet opening, means to effect flow of gas through said conduit means at a high velocity and out said outlet opening, a coil of electrically-conductive material disposed adjacent said conduit means in the region of said throat portion, means to cause flow of very high direct current through said coil to generate a high-intensity direct magnetic field in said conduit means in the region of said throat portion, and means to cause said magnetic field to be transverse to the direction of gas flow.

8. The invention as claimed in claim 7, in which means are provided to create momentarily in said conduit means and in the region of said throat portion a rapidly-varying high-intensity magnetic field to thus effect initial ionization of said gas.

9. The invention as claimed in claim 7, in which means are provided to effect cooling of said electrically-conductive material.

10. The invention as claimed in claim 7, in which means are provided to effect pre-heating of said gas on the upstream side of said magnetic field.

11. Electrodeless plasma torch apparatus, which comprises conduit means having a convergent portion which converges in a downstream direction to a throat, said convergent portion communicating with an adjacent outlet opening, means to effect flow of gas through said conduit means at a velocity at least approaching the local speed of sound in said conduit means, a generally helical coil of electrically-conductive metal mounted coaxially around said conduit means adjacent said throat, means to pass a very high non-pulsating direct current through said coil to thereby generate in said conduit means a high-intensity direct magnetic field, and magnetic shield means to cause said magnetic field to be generally perpendicular to the direction of gas flow through said conduit means, said magnetic field cooperating with said gas flow to set up in said gas closed loops of current and thus effect discharge of plasma out said outlet opening.

12. The invention as claimed in claim 11, in which heater means are provided a substantial distance upstream from said throat to effect heating of said gas prior to entry thereof into said magnetic field.

13. The invention as claimed in claim 11, in which means are provided to effect initial ionization of said gas in the region of said throat.

14. The invention as claimed in claim 11, in which a second coil of electrically-conductive metal is mounted in said conduit means in the region of said convergent portion thereof and spaced upstream from said throat, said second coil being generally coaxial with said first-mentioned coil, in which means are provided to conduct a high direct current through said second coil in aiding relationship relative to the flow of current through said first-mentioned coil whereby to create an interrupted solenoid resulting in the setting up of lines of magnetic flux or force around both said first-mentioned and second coils, and in which island or envelope means are provided around said second coil to cause said gas to flow generally radially inwardly between said island means

and the wall of said convergent conduit portion and then into said throat whereby said gas traverses said lines of magnetic flux or force generally at right angles.

15. The invention as claimed in claim 14, in which first and second annular elements of magnetizable material are mounted concentrically with said conduit means adjacent said first-mentioned and second coils.

16. The invention as claimed in claim 11, in which said magnetic shield means comprises two generally radially-extending magnetizable elements mounted adjacent opposite ends of said coil and connected at their outer extremities by a magnetizable body portion.

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