Aug. 25, 1964 J. H. McGINN 3,146,371

ARC PLASMA GENERATOR

Filed July 20, 1961 4 Sheets-Sheet 1

Fig. 1

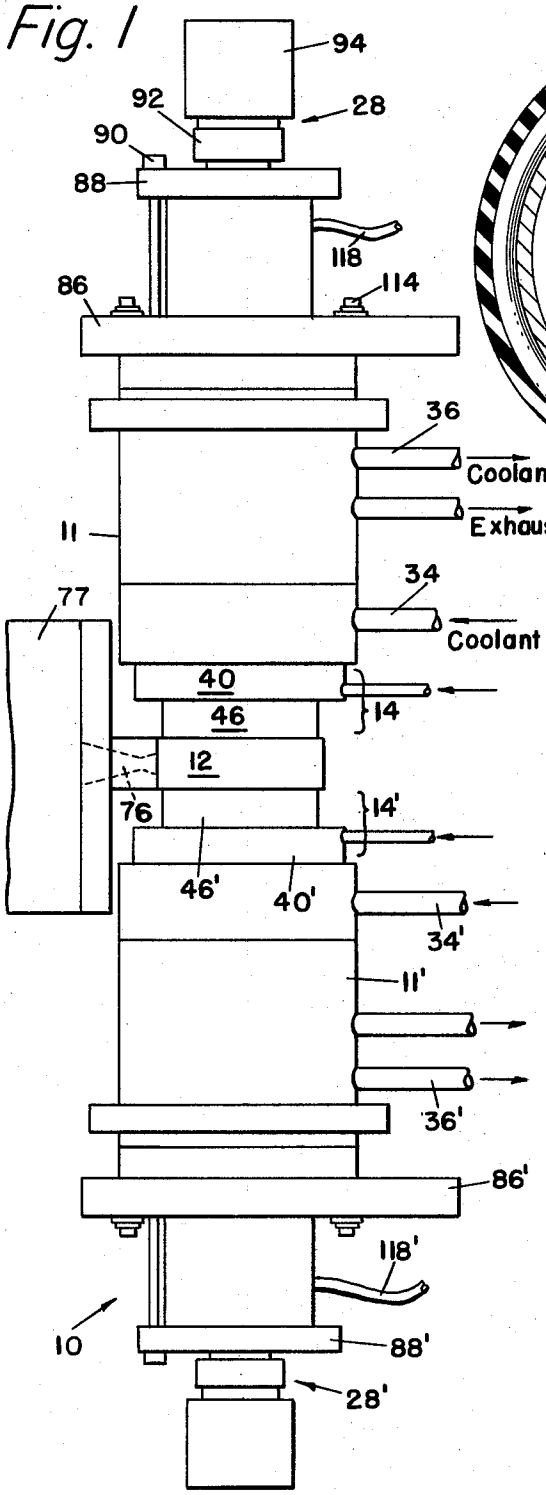
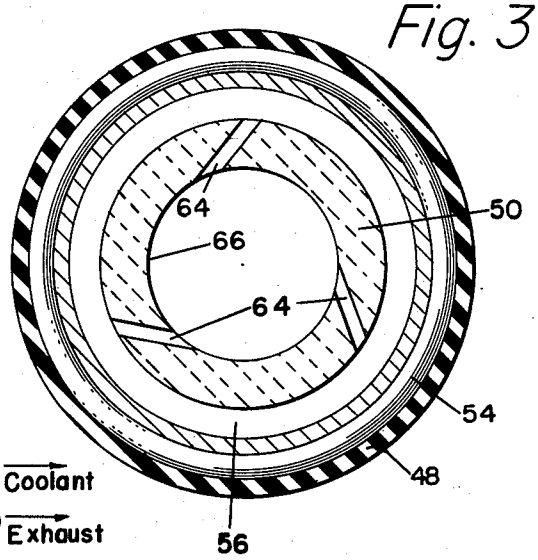


Fig. 3



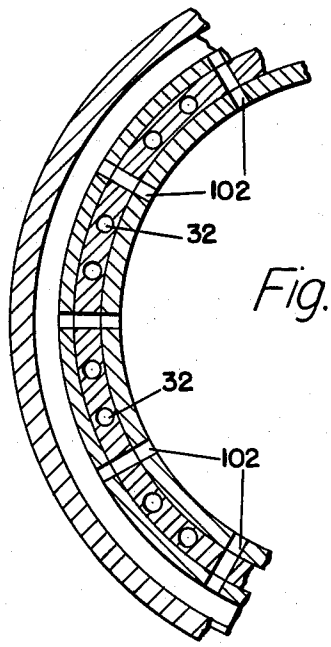


Fig. 4

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ARC PLASMA GENERATOR

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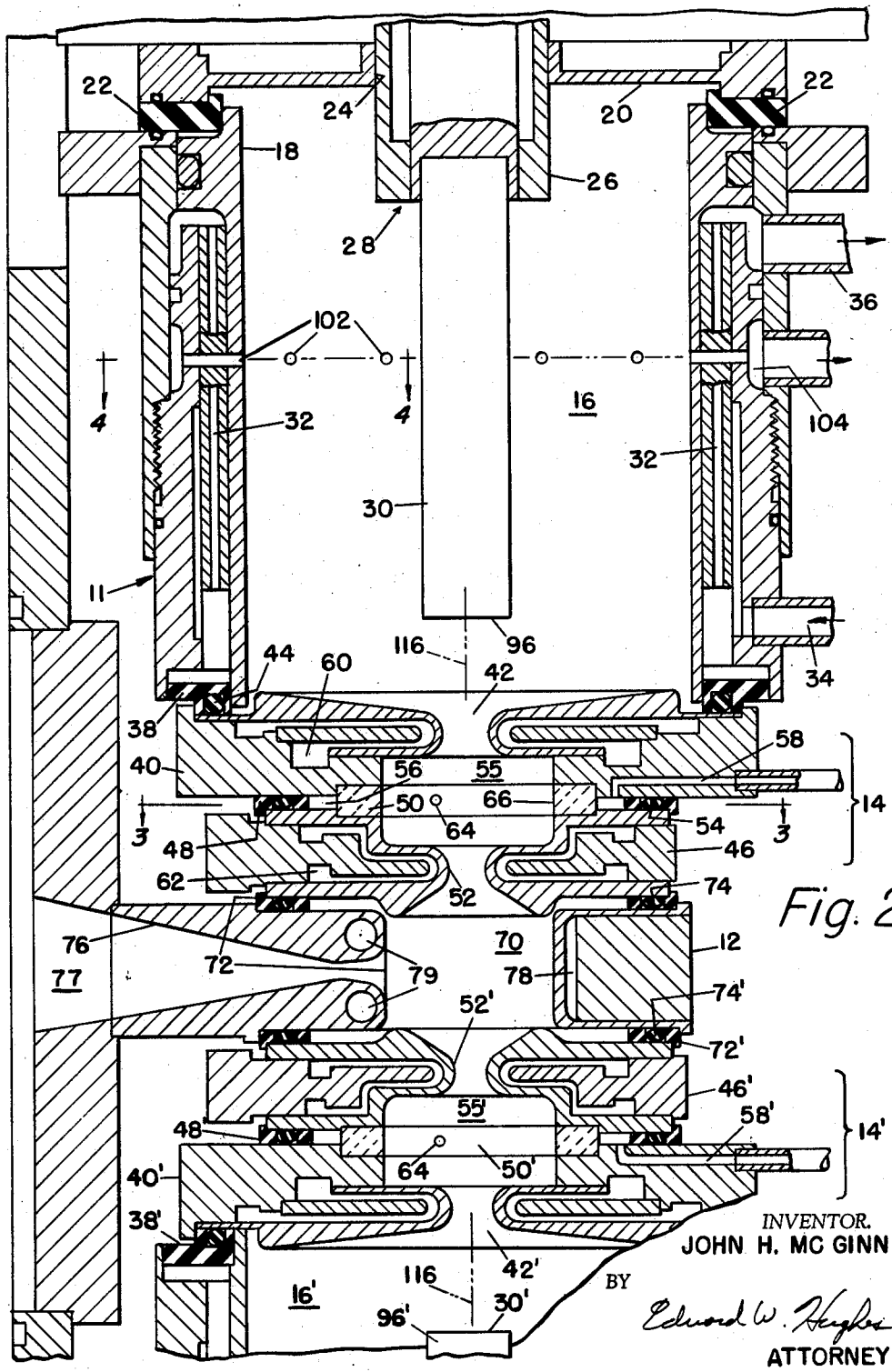


Fig. 2

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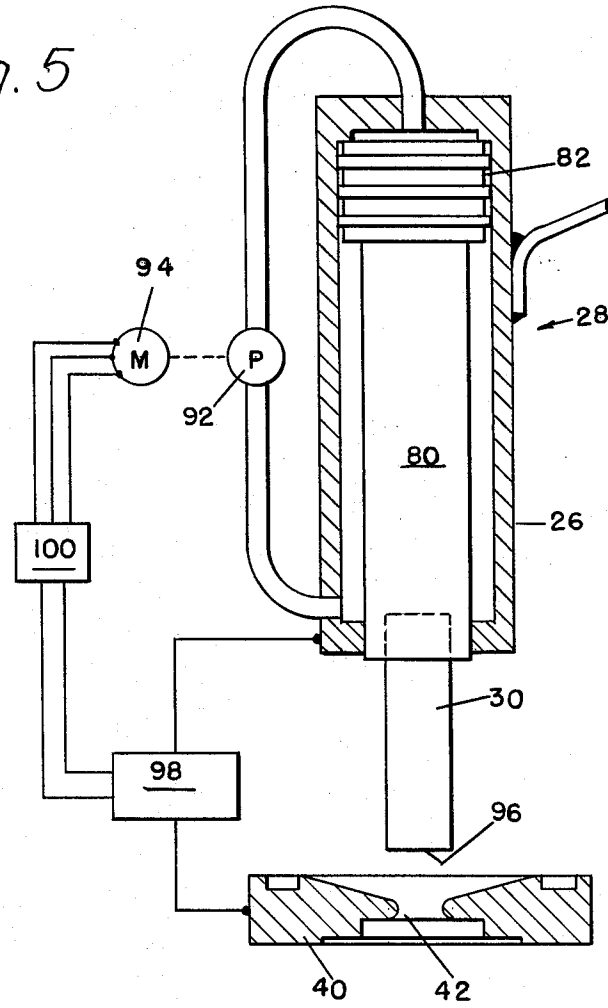
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ARC PLASMA GENERATOR

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Fig. 5



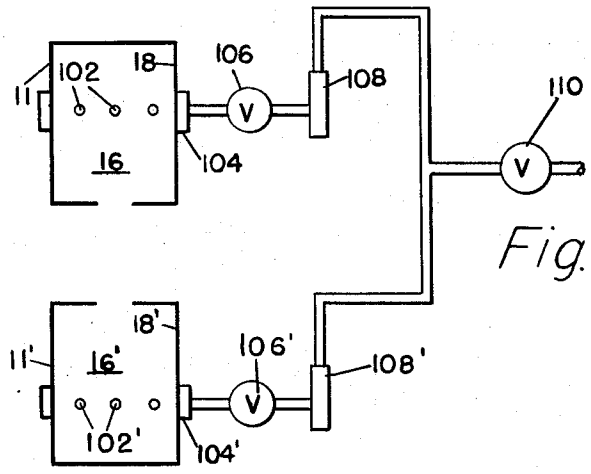


Fig. 6

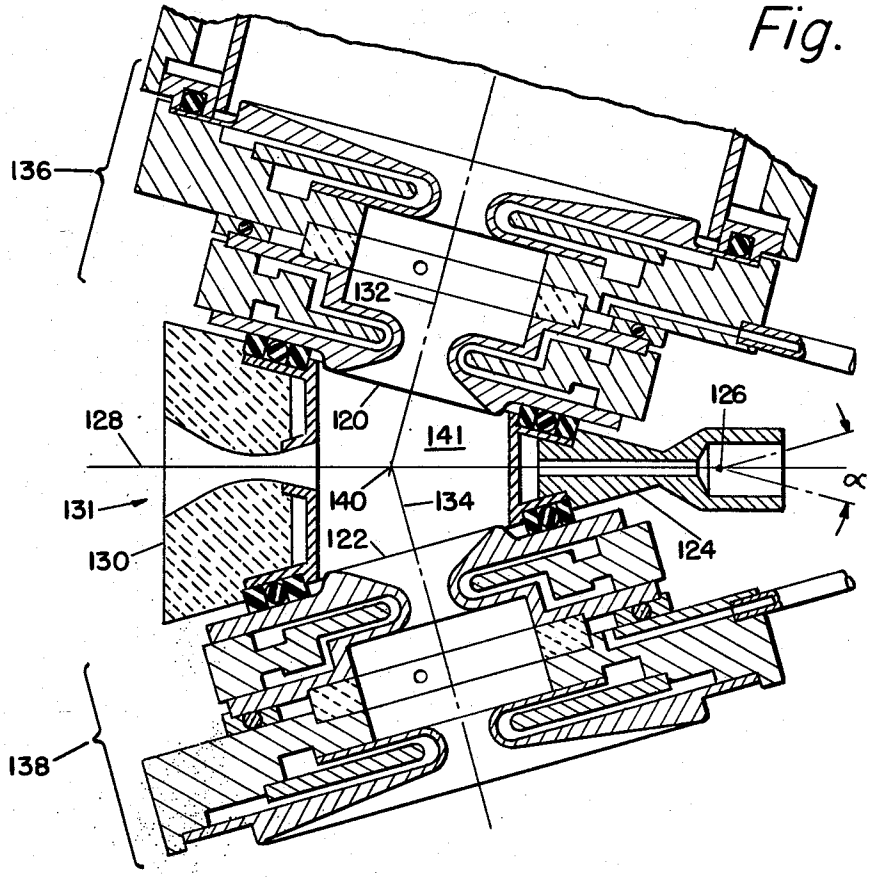
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ARC PLASMA GENERATOR

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Fig. 7



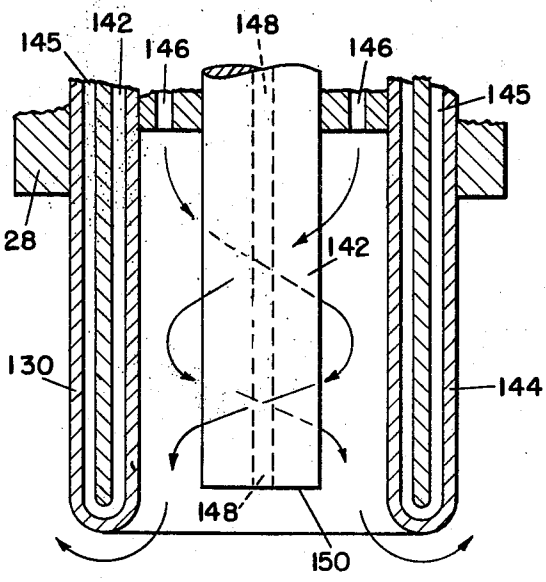


Fig. 8

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United States Patent Office 3,146,371 Patented Aug. 25, 1964

3,146,371

ARC PLASMA GENERATOR

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Filed July 20, 1961, Ser. No. 125,413
15 Claims. (Cl. 313—231)

This invention relates to improvements in arc plasma generators, and more particularly to an arc plasma generator for producing very high enthalpy plasma having substantially uniform characteristics and in which contamination of the plasma by material derived from the electrodes is minimized.

Experimental studies of plasma properties and hypersonic flow simulation require a high temperature steady state source of plasma of a precisely controlled composition. The composition of the plasma is particularly important in those situations where emissivity, electrical conductivity, and chemical interactions are involved. In such instances, it is essential that the plasma produced be pure in the sense that it does not contain detrimental quantities of electrode material. In addition to high temperature and purity, it is also desirable that variations in the temperature and velocity of the plasma be minimized as it leaves the generator. The problem of producing high temperature plasma of uniform characteristics uncontaminated by electrode derived material becomes more difficult as the enthalpy of the plasma increases.

In recent years much time and energy have been expended to develop improved arc plasma generators. The improvements sought are increasing the heat content, or enthalpy, of the plasma produced, increasing the quantity of plasma produced per unit time, decreasing contamination by electrode materials of the plasma, and increasing the efficiency of such generators. Much of this effort has been directed toward the use of cooled metallic electrodes and means for causing arcs between electrodes to move in a predetermined manner in order to distribute heat flux from the arcs over a substantial area of the electrodes. In such generators, the electrodes are largely exposed to the plasma so that it is difficult to adequately cool them without substantially reducing the enthalpy of the plasma. The electrode configuration of such arc plasma generators is often incompatible with the requirement for optimum containment and mixing of the plasma.

Plasma having enthalpies up to 15,000 calories per gram using ambient air as the working fluid is found in the central region of a plasma jet produced by a vortex stabilized plasma generator. However, since such a generator does not employ a settling or plenum chamber, the temperature, velocity, and composition of the plasma are not uniform, and the instantaneous rates of which the plasma is produced are not constant.

The present invention provides a solution to the problem of producing a higher enthalpy plasma in which the amount of contamination of the plasma by materials derived from the electrodes is minimized and in which the temperature, composition and velocity profile of the plasma produced are substantially uniform. This is accomplished by constructing the arc plasma generator so that the arc column between a pair of electrodes extends through a pair of vortex chambers and a plenum chamber located between the vortex chambers. In each vortex chamber, the working fluid is introduced and caused to rotate around and stabilize the arc column. The working fluid flows out of each vortex chamber in two opposite directions, one direction being toward an electrode and the other being toward the plenum chamber. The rate of flow of the working fluid from each vortex chamber into its adjacent electrode chamber can be such as to

prevent material from the electrodes from entering the vortex chambers in amounts detectable spectroscopically. The direction of rotation of the working fluids in the two vortex chambers are normally chosen to be in opposition so that within the penum chamber the plasma will mix thoroughly and rapidly stagnate. The dimensions of the plenum chamber are chosen to optimize the production of a plasma of substantially uniform characteristics and to minimize the heat loss from the plasma to the walls of the plenum chamber. As a result, the plasma which flows out of the plenum chamber through the expansion nozzle has a very high enthalpy. Its temperature, composition and velocity are substantially uniform and it contains no readily detectable amounts of material derived from the electrodes.

It is, therefore, an object of this invention to provide an arc plasma generator capable of producing a plasma having substantially no contamination by materials derived from the electrodes.

Another object of this invention is to provide an arc plasma generator capable of producing a very high temperature plasma.

It is still another object of this invention to produce an arc plasma generator that is capable of producing high temperature substantially pure plasma of substantially uniform characteristics for a sustained period of time.

It is still another object of this invention to provide an arc plasma generator which does not require a ballast resistor.

Other objects and many of the intended advantages will be more readily comprehended by those skilled in the art after a consideration of the following detailed description of the drawings wherein:

FIG. 1 is an elevation on a reduced scale of a double vortex arc plasma generator.

FIG. 2 is an enlarged cross sectional view of part of the generator illustrated in FIG. 1.

FIG. 3 is a section taken on line 3—3 of FIG. 2.

FIG. 4 is a partial section taken on line 4—4 of FIG. 2.

FIG. 5 is a schematic diagram of an electrode feed mechanism and its controls.

FIG. 6 is a schematic diagram of apparatus for controlling the rate of flow of working fluid from the electrode chambers.

FIG. 7 is a section illustrating a modified plenum chamber.

FIG. 8 is a section of a modified electrode.

In FIG. 1, the general arrangement of the major components of arc plasma generator **10** is illustrated. Generator **10** is provided with a pair of electrode housing **11, 11'**. For convenience electrode housing **11** will also be referred to as the upper electrode housing and housing **11'** will also be referred to as lower electrode housing because of the symmetry of generator **10** with respect to its plenum housing **12**. Between housings **11, 11'** and plenum housing **12** there are located a pair of vortex housings, upper vortex housing **14** and lower vortex housing **14'**. As illustrated in FIG. 2, the inner will of upper electrode housing **11** which defines upper electrode chamber **16** is formed of a hollow metal cylinder **18**. Backplate **20** is secured to and closes the upper end of housing **11**, but it is electrically insulated from housing **11** by insulator ring **22**. In backplate **20** there is formed a central opening **24** through which extends cylinder **26** of the hydraulic feed motor **28** which advances upper electrode **30** to compensate for the fact that electrode **30**, which is preferably made of graphite, is consumed during operation of generator **10**. Housing **11** is provided with a plurality of passages **32** to permit a coolant, such as water, to flow from inlet **34** to the outlet **36** to limit the temperature of the material from which housing **11** is made to a value it can withstand without deleterious

effect. Backplate 20 is also cooled by the circulation of a suitable coolant. The details for accomplishing the cooling of backplate 20 are not illustrated since they are well known to those skilled in the art.

Secured to the bottom of housing 11 but electrically insulated therefrom by insulating washer 38 is the upper back orifice plate 40 of upper vortex housing 14. Opening or orifice 42 is formed in orifice plate 40. O ring 44 hermetically seals the connection between housing 11 and orifice plate 40. Between upper front orifice plate 46 and back orifice plate 40 of upper vortex housing 14, are located electrical insulating washer 48 and vortex ring 50. Orifice plate 46 is provided with a central opening 52. O ring 54 hermetically seals the connection between orifice plates 40 and 46. The orifice plates 40, 46 and vortex ring 50 define the upper vortex chamber 55.

The space between vortex ring 50, orifice plates 40, 46 and washer 48 defines working fluid manifold 56. Working fluid under pressure is supplied to manifold 56 through passage 58 formed in upper back orifice plate 40. Orifice plates 40, 46 are provided with passages 60, 62 respectively through which a coolant, such as water, is circulated, by conventional means which are not illustrated, to limit their temperature to a value at which the material from which orifice plates 40, 46 are made will not be damaged even when generator 10 is operated for sustained periods of time at high power.

Vortex ring 50, as is more clearly illustrated in FIG. 3, is a hollow cylinder which has a plurality of passages 64 substantially tangential to the inner surface 66 of ring 50 formed in it. Vortex ring 50 in a preferred example is made of alumina quartz which is an electrical insulating material.

Upper front orifice plate 46, lower front orifice plate 46' and hollow cylindrical plenum housing 12 form, or define, plenum chamber 70. It should be noted that plenum housing 12 is electrically insulated from orifice plates 46, 46' respectively by washers 72, 72'. The connection between the plenum housing 70 and the orifice plates 46, 46' are hermetically sealed by O rings 74, 74'. An expansion nozzle 76 is mounted in plenum housing 12 in order that plasma can be conducted from the plenum chamber 70 into hypersonic tunnel 77 for example. Housing 12 is provided with a passage 78 and nozzle 76 is provided with passages 79 connecting with passage 78 through which a coolant such as water is circulated, by conventional means which are not illustrated, to keep housing 12 and nozzle 76 from reaching temperatures where they can be damaged.

Referring now to FIG. 5, one end of upper electrode 30, which in a preferred embodiment is made of graphite, is removably secured to one end of piston rod 80 which in turn is secured to the piston 82 of hydraulic feed motor 28. Hydraulic motor 28 is secured to the generator base plate 86, as illustrated in FIG. 1, by hydraulic motor mounting plate 88 and bolts 90. Pressurized hydraulic fluid to actuate the motor 28 is produced by reversible pump 92 which is driven by reversible electrical motor 94. As electrode 30 is consumed, motor 94 is energized to cause the piston 82 to advance electrode 30 to maintain the gap between the end 96 of electrode 30 and orifice plate 40 substantially constant.

In FIG. 5 there is illustrated schematically one means for controlling the hydraulic feed motor 28 to assure that the position of the end 96 of electrode 30 with respect to back orifice plate 40 remains substantially constant. It has been learned that the potential difference between electrode 30 and orifice plate 40 varies inversely with the distance between them. This knowledge is used by sensing, or measuring, the potential difference between the electrode 30 and back orifice plate 40, by a conventional potentiometer 98. When the potential between electrode 30 and back orifice plate 40 exceeds a predetermined maximum value, potentiometer 98 will cause relay 100 to be energized to cause motor 94 to drive pump 92 in such a direction as to advance electrode 30 toward orifice plate 40 until the potential drop between the electrode 30 and back orifice plate 40 measured by potentiometer 98 is reduced to the desired value. When this happens relay 100 will be de-energized to stop pump 92. Obviously, there are other ways of regulating the feed of the consumable electrode 30 such as by optically observing its position through a small port in housing 11, which is not illustrated. Under such circumstances the operation of electrode feed mechanism 28 can be controlled by an operator or by a light sensing device.

The structure of lower vortex chamber 55', lower electrode chamber 16', and hydraulic feed motor 28' and its control means, are the same as those of upper vortex chamber 55, upper electrode chamber 16, and motor 28 and its control mechanism as illustrated in FIG. 5. A detailed description of this structure is not believed to be necessary to understand the invention, therefore, and has been omitted. The main difference between the upper and lower portion of generator 10 is the preferred orientation of vortex rings 50, 50'. In the preferred arrangement ring 50 is oriented to cause rotation of working fluid in vortex chamber 55 in one direction and nozzle 50' is oriented to cause rotation of the working fluid in vortex chamber 55' in the opposite direction. It also should be noted that the orientation of arc plasma generator 10 is not critical. It will operate in any orientation.

Housings 11, 11' are provided with a plurality of openings 102, 102' which are connected to exhaust manifolds 104, 104'. It is through openings 102, 102' and manifolds 104, 104' that working fluid and materials derived from the electrodes 30, 30' escape from electrode chambers 16, 16'. In FIG. 6 there is schematically illustrated means for regulating the rate of flow of gases or fluids from the upper and lower electrode chambers 16, 16'. The exhaust manifolds 104, 104' of the electrode housings 11, 11' are connected through flow valves 106, 106', to flow meters 108, 108'. From flow meters 108, 108' exhaust gas from chambers 16, 16' flows through adjustable flow valve 110 and is then vented. Since the rate of flow of working fluid into vortex chambers 55, 55' can be easily adjusted by means that are well known in the art, valves 106, 106' can be varied until the rates of flow from vortex chambers 16, 16' into plenum chamber 70 have the desired ratio which is normally 1:1, but can have any desired value. Thereafter changes in the rates of flow from electrode chambers 16, 16' can be regulated by adjustment of valve 110. It has been learned that once valves 106, 106' have been adjusted to obtain the desired ratio of flow from vortex chambers 55, 55' into plenum chamber 70, the ratio will remain substantially constant even though the total rate of flow is adjusted by changing valve 110.

The use of the double vortex arc plasma generator 10 is particularly attractive where a chemical reaction between different working fluids is desired. One working fluid of one or more chemical materials can be introduced into the upper vortex chamber 55 and a second working fluid likewise of one or more chemical materials could be introduced into lower vortex chamber 55. The rates of flow of the two working fluids into plenum chamber 70 can be independently varied in order to make certain that the materials within plenum chamber 70 have the desired ratios to facilitate the desired chemical reactions.

The metallic components of arc plasma generator 10; i.e., backplates 20, 20'; electrode housing 11, 11'; back orifice plates 40, 40'; front orifice plates 46, 46'; and plenum housing 12 are electrically insulated from one another by insulating washers 22, 22'; 38, 38'; 48, 48'; and 72, 72'. This structural arrangement prevents the arc column from being short circuited through the structure of generator 10. The vortex rings 50, 50' as pointed out earlier are also of electrical insulating material, but

they have the function of imparting an angular velocity to the working fluid in the vortex chambers in addition to that of electrically insulating the front orifice plates **46**, **46'** from the back orifice plates **40**, **40'** of vortex housings **14**, **14'**. The components of generator **10** are held together by bolts **114** extending from the upper base plate **86** to lower base plate **86'**. The O ring seals between the components of generator **10** are provided to hermetically seal electrode chambers **16**, **16'**, vortex chamber **55**, **55'** and plenum chamber **70**. Components **12**, **40** and **46**, for example, have been described as single entities; preferably they are fabricated from several smaller parts as is well known in the metal working art. The metal components of generator **10** are, in a preferred embodiment, made of copper because it is such a good conductor of heat, the insulating washers are made of glass melamine, the vortex generators **50**, **50'** are made of alumina quartz, and the O rings are made of neoprene or silicone rubber. The metallic components of generator **10** are so designed that radiation from the arc column between electrodes **30**, **30'** is not directly incident on the glass melamine insulators.

The longitudinal axes of electrodes **30**, **30'** are substantially coincident with the longitudinal axis **116** of generator **10**. Feed motors **28**, **28'** are mounted in such a manner to advance electrodes **30**, **30'** along axis **116**. The centers of openings **42**, **42'**, **52**, **52'** of the orifice plates **40**, **40'**, **46**, **46'** lie substantially on the axis **116** and the planes of these openings are substantially normal to axis **116**. Electrodes **30**, **30'** are connected respectively, preferably to a source of D.C. power, which is not illustrated, through piston rod **80**, **80'**, cylinder **26**, **26'** of motor **28**, **28'** and electrical conductor **112**, **112'**. Generator **10** will operate however when connected to an A.C. source of electrical power.

When it is desired to operate plasma generator **10**, a coolant is caused to circulate through all the passages in the metallic components of the generator **10**. The working fluid, which may be air or any other gas or liquid, is supplied under pressure through the passages **58**, **58'** at predetermined rates to the vortex rings **50**, **50'**. The arc between electrodes **30**, **30'** is normally started by having a thin striking wire connected between the electrodes **30**, **30'**. When a suitable source of electric power is connected to electrodes **30**, **30'** the striking wire will vaporize and an arc will be established. The arc column between the ends **96**, **96'** of electrodes **30**, **30'** extends through the vortex chambers **55**, **55'** and the plenum chamber **70** located between them. The working fluid is introduced tangentially into the chambers **55**, **55'** through passages **64**, **64'** in the vortex rings **50**, **50'**. The working fluid in these two chambers preferably rotates in opposite directions around axis **116**. Working fluid introduced into the vortex chambers **55**, **55'** through ring **50**, **50'** flows out of chamber **55** through openings **42** and **52** and out of chamber **55'** through openings **42'** and **52'**. There thus is an actual component of flow of the working fluid respectively from vortex chambers **55**, **55'** toward electrodes **30**, **30'**. As long as the component of flow of the working fluid through openings **42**, **42'** is greater than the ion propagation velocity of the material from which electrodes **30**, **30'** are made, detectable quantities of the material derived from the electrodes **30**, **30'** are substantially prevented from entering into plenum chamber **70**. The working fluid and the contaminants derived primarily from electrodes **30**, **30'** in the electrode chambers **16**, **16'** escape respectively through exhaust openings **102**, **102'** and the exhaust manifold **104**, **104'**. Flow valves **106**, **106'** are adjusted until the desired ratio of rates of flow of working fluid from vortex chamber **55**, **55'** into plenum chamber **70** is reached.

Rotation of the working fluid in the vortex chamber **55**, **55'** establishes a radial pressure gradient which serves to constrict the arc column between the electrodes **30**, **30'**. The relatively cool working fluid flowing through openings **42**, **42'**, **52**, **52'** reduces the heat flow from the arc column to the parts of the orifice plates **40**, **40'**, **46**, **46'** which define openings **42**, **42'**, **52**, **52'**.

Since the working fluid injected into the vortex chamber **55**, **55'** preferably rotates in opposite directions, within plenum chamber **70** it is self-stagnating which encourages mixing of the working fluid and plasma while avoiding the formation of local hot spots on the walls of the plenum chamber **70**. The arc column extends through plenum chamber **70** and adds power to the plasma within chamber **70**. The high enthalpy obtainable from the double vortex arc plasma generator is due in large measure to the substantial amount of power added while the plasma is in plenum chamber **70**.

There are two distinct modes of operation of the double vortex arc plasma generator, one in which the arc column is vortex stabilized, and the other in which the arc column is wall stabilized. The arc column is vortex stabilized when its diameter is determined by the radial pressure gradient of the working fluid with the result that a boundary layer of substantial dimension of relatively cool working fluid exists between the arc column and the walls of opening **42**, **42'**, **52**, and **52'**. The arc column is wall stabilized when its diameter is determined by the immediate cooling effect on the arc column due to the absorption of heat by the walls defining one or more of the openings **42**, **42'**, **52**, **52'**. When the arc column is wall stabilized the boundary layer of working fluid between the column and the walls of one or more openings **42**, **42'**, **52**, **52'** is so thin as to be negligible. The transition from vortex stabilized operation to wall stabilized operation is a function of the mass flow measured for example in grams/second of the working fluid and the magnitude of the current of the arc column. The transition from vortex stabilized to wall stabilized operation occurs discontinuously as the total mass flow into the vortex chambers **16**, **16'** is decreased, assuming that the current flow remains constant; or as the magnitude of the current of the arc is increased, assuming that the mass flow remains constant. When the mode of operation changes from vortex to wall stabilized flow, the flow of plasma through nozzle **76** becomes very steady. However, the amount of power loss increases due in part to the proximity of the arc column to the walls of the orifice plates **40**, **40'**, **46**, **46'** defining openings **42**, **42'**, **52**, **52'**. However, there is a significant advantage in wall stabilized operating conditions due to the fact that the cross sectional area of the arc column can no longer increase since it is limited by the diameter of one or more of the openings **42**, **42'**, **52**, **52'**. As a result generator **10** demonstrates a positive resistance characteristic; i.e., the magnitude of the electric current of the arc will increase only if there is an increase in the voltage across electrodes **30**, **30'**. Because of this positive resistance characteristic found in double vortex arc plasma generators, a condition not found in prior art vortex stabilized plasma generators, it is not necessary to include a ballast resistor in series with the power supply. The elimination of the power dissipated by a ballast resistor obviously increases the efficiency of the generator in converting electrical energy supplied by the power source into the thermal energy of the plasma.

When the arc column becomes wall stabilized, the temperature variations within the plenum chamber **70** are reduced, but the maximum temperature is some 20 percent higher than when the arc is vortex stabilized assuming that the other operating parameters remain constant. Also, the dimensions of plenum chamber **70** can be reduced because of the reduction in turbulence of the plasma.

In a preferred example, the operating conditions of the arc generator were as follows: power input ranged between 100 and 200 kilowatts, at from 290 to 360 volts and from 290 to 600 amps., with the upper value being determined by the capability of the power supply. The arc has been operated with the mass flow through nozzle **76** of from .5 to 5 grams per second. Using air as the

working fluid, the generator has produced plasma having an enthalpy of from 2000 to 9000 calories per gram at stagnation pressures varying from .5 to 11 atmospheres. The maximum temperature of the plasma that has been measured by spectrographic means has been 12,050° K. from a jet of plasma coming from the expansion nozzle of a plenum chamber having a diameter of 2.7 cm. The generator has been operated continuously for periods up to 15 minutes.

In operation, graphite electrodes **30**, **30'** are consumed at different rates, the anode being consumed at the rate of approximately ⅜ of an inch per minute and the cathode at the rate of approximately 1/10 of an inch per minute when operating at power levels in the vicinity of 200 kilowatts. The maximum operating time of generator **10** is determined by the length of the electrodes **30**, **30'** that the electrode feed mechanism **28** of the cathode is able to handle.

It has been found that the greatest cause of heat loss in the plenum chamber **70** is due to radiation from the plasma. In order to decrease this heat loss and to take advantage of the stable conditions occurring during wall stabilized operation of the arc plasma generator, the plenum housing can be modified as illustrated in FIG. 7. The top wall **120** and the bottom wall **122** of plenum housing **124** are at an angle with reference to one another, rather than parallel. The planes determined by walls **120**, **122** intersect at line **126**, which lies on axis **128** of nozzle **130**. The structure of generator **131** above and below plenum housing **124** is substantially unchanged in comparison with generator **10**. Axes **132**, **134**, the axes of symmetry or longitudinal axes respectively of upper portion **136** and lower portion **138** of generator **10** along which electrodes **30**, **30'** advance also intersect at point **140** on axis **128**. The angle α determined by the top and bottom walls of plenum housing **124** can have values ranging from essentially 0°, where the walls **120**, **122** are parallel to an upper limit of approximately 45°. Housing **124** and nozzle **130** are provided with passages through which a coolant is circulated.

The advantage in having the top and bottom walls **120**, **122** of the plenum housing **124** intersect at a point on the opposite side of housing **124** in which nozzle **130** is located is that it locates the arc column nearer nozzle **130** and gives the plasma a component of velocity toward nozzle **130**. This reduces the time the plasma remains in plenum chamber **141** and reduces the time during which the plasma can lose heat energy by radiation. As a result the plasma produced with angled plenum housing **124** has a higher enthalpy compared with plasma produced by plenum housing **12**.

In FIG. 8 there is illustrated a way to cool electrode **142** and to greatly decrease the rate it is consumed during the time generator **10** is in operation. Electrode **142** is surrounded by a cylinder **144** spaced a short distance from electrode **142**. Cylinder **144** is provided with a passage **145** through which a coolant such as water is circulated. An inert gas, such as argon, flows into the space between electrode **142** and cylinder **144** through openings **146**, which are angled, or canted to cause the gas to rotate in a given direction about electrode **142**. Electrode **142** is also provided with a central passage **148** through which argon flows in order that substantially all of electrode **142** will be surrounded by a protective layer or blanket of inert gas.

In operation it has been discovered that argon around electrode **142** prevents oxygen from reaching electrode **142**, with the result that the rate of consumption of electrode **142** is greatly reduced. Further it appears that the arc column originates from the argon gas at the open end of cylinder **144** rather than from the end **150** of electrode **142**. The result is that electrode **142** has a relatively long operational life. The structure illustrated in FIG. 8 reduces the rate of consumption of the electrodes made of graphite by a factor of 20 or more. For operating times up to one hour it is not necessary to provide a feed mechanism for the electrodes in order to continuously operate the arc plasma generator. Where, however, operation over a very long period of time; i.e., greater than one hour, is desired, a feed mechanism such as that illustrated in FIG. 5 may be used to advance the electrode **142** to maintain the length of the arc column substantially constant, or a water cooled metal electrode can be substituted for the graphite electrode **142**.

From the foregoing, it is believed clear that applicant's double vortex chamber arc plasma generator has solved the problem of supplying a very high purity plasma at substantially higher temperatures than was heretofore obtainable and in which the characteristics of the plasma, both in temperature and composition, are substantially uniform. The efficiency of the plasma generator is higher compared with other vortex arc plasma generators which use direct current or unidirectional pulsating current since the constriction of the arc by the openings in the orifice plates results in the double vortex arc plasma generator having a positive resistance characteristic once the arc column becomes wall stabilized.

Obviously many modifications and variations of the present invention are possible in the light of the above teaching. It is therefore to be understood that with the scope of the appended claims, the invention may be practiced otherwise than as specifically described and illustrated.

What is claimed is:

1. An arc plasma generator comprising an upper electrode housing, an upper electrode mounted within said housing, a lower electrode housing, a lower electrode mounted in said lower electrode housing, means for connecting said electrodes to a source of electrical power to establish an electrical arc column between said electrodes, upper and lower vortex housings, a plenum housing between said vortex housings, said vortex and plenum housings being mounted between the upper and lower electrode housings, means forming openings between said vortex housings and plenum housing so that the arc column can pass through said housings, means for introducing a working fluid into the vortex housings and for causing the fluid to have an angular component of velocity about the arc column, and an exhaust nozzle in said plenum housing.

2. An arc plasma generator comprising an upper electrode housing, an upper electrode mounted within said housing, a lower electrode housing, a lower electrode mounted in said lower electrode housing, means for connecting said electrodes to a source of electrical power to establish an electrical arc column between said electrodes, upper and lower vortex housings, a plenum housing between said vortex housings, said vortex and plenum housings being mounted between the upper and lower electrode housings, means forming openings between said vortex housings and plenum housing so that the arc column can pass through said housings, means for introducing a working fluid into the vortex housings and for causing the fluid to have an angular component of velocity about the arc column, the direction of rotation of said fluids in said vortex chambers being opposite to one another, and an exhaust nozzle in said plenum housing.

3. An arc plasma generator as defined in claim 2 in which the plenum housing has top and bottom walls, which walls determine an angle in the range of from 0° to 45°.

4. An arc plasma generator comprising means forming a first electrode chamber; means for mounting a first electrode in said first chamber; means forming a second electrode chamber; means for mounting a second electrode in said second electrode chamber; means forming a first vortex chamber; means forming a second vortex cham-

ber; means forming a plenum chamber; means for securing together the means forming the first electrode chamber, the first vortex chamber, the plenum chamber, the second vortex chamber, and the second electrode chamber in the order named; means forming openings between the electrode chambers, the vortex chambers and the plenum chamber so that they are interconnected; means for providing a passage for plasma to leave the plenum chamber; means for causing a working fluid to be supplied to the vortex chambers and to cause the working fluid within the vortex chambers to have a component of angular velocity; and means for connecting the electrodes to a source of electrical power to establish an arc column between the electrodes, which column extends through the vortex and plenum chambers.

5. An arc plasma generator comprising means forming a first electrode chamber; means for mounting a first electrode in said first chamber; means forming a second electrode chamber; means for mounting a second electrode in said second electrode chamber; means forming a first vortex chamber, means forming a second vortex chamber; means forming a plenum chamber; means for securing together the means forming the first electrode chamber, the first vortex chamber, the plenum chamber, the second vortex chamber, and the second electrode chamber in the order named; means forming orifices between the electrode chambers, the vortex chambers, and plenum chamber so that they are interconnected; means for providing an exhaust passageway for plasma in the plenum chamber; exhaust means for the means forming the electrode chambers for regulating the flow of exhaust gases from the electrode chambers; means for causing a working fluid to be supplied to the vortex chambers and to cause the working fluid within the vortex chambers to have components of angular velocity in opposite directions with respect to one another, and means for connecting the electrodes to a source of electrical power to establish an arc column between the electrodes which extends through the vortex and plenum chambers.

6. An arc plasma generator as defined in claim 5 in which the means for mounting the first and second electrodes include means to maintain the length of the arc column substantially constant.

7. An arc plasma generator as defined in claim 5 in which the means for mounting the first and second electrodes includes means for substantially surrounding each electrode with an inert gas.

8. An arc plasma generator as defined in claim 5 in which the means for mounting the first and second electrodes comprises a cooled metallic cylinder spaced from each electrode and extending beyond the end of each electrode, passages between each electrode and said cylinders for introducing an inert gas in the space between each electrode and its surrounding cylinder and for causing the gas to rotate around each electrode, a passage through each electrode, and means for supplying inert gas through the passages to the end of each electrode.

9. An arc plasma generator as defined in claim 7 in which the inert gas is argon.

10. An arc plasma generator comprising means forming an upper electrode chamber, means for mounting an electrode within said upper chamber, means forming a lower electrode chamber, means for mounting a lower electrode in said lower electrode chamber, means forming an upper and lower vortex chamber, means forming a plenum chamber between said vortex chambers, an exhaust nozzle in said means forming a plenum chamber, means for mounting said vortex and plenum chambers so that they are between the upper and lower electrode chambers, and means forming openings in said vortex and plenum chambers so that they communicate with one another and the electrode chambers, means for introducing a working fluid into the vortex chambers, said means causing the working fluid to rotate within their respective vortex chambers, means for connecting the electrodes to a source of electrical power to establish an arc column between the electrodes which extends through the vortex chambers and the plenum chamber, said means forming said upper and lower electrode chambers each having means for removing material therefrom.

11. An arc plasma generator comprising a hollow cylindrical plenum housing within which is located a plenum housing, said housing having upper and lower walls, a nozzle mounted in the plenum housing, a first vortex housing forming a first vortex chamber, a first vortex ring mounted in said first vortex housing for admitting working fluid under pressure and causing the working fluid to rotate within the first vortex chamber, a second vortex housing forming a second vortex chamber, a second vortex ring mounted in said second vortex housing for admitting working fluid under pressure and for causing the working fluid to rotate within the second vortex chamber in a direction opposite to that of the working fluid in the first vortex chamber, said plenum chamber and first and second vortex chambers being mounted so that the plenum chamber is between the two vortex chambers, an electrode housing forming a first electrode chamber secured to the first vortex chamber, first electrode feed means attached to said first electrode housing, a first electrode connected to the first electrode feed means, a second electrode housing forming a second electrode chamber secured to the second vortex housing, second electrode feed means attached to said second electrode housing, a second electrode connected to the second electrode feed means, means for connecting a source of electrical power between the two electrodes to establish an arc column through the vortex chambers and the plenum chamber, and means to regulate the feed means to maintain the length of the arc column between the electrodes substantially constant.

12. An arc plasma generator as defined in claim 11 in which the upper and lower walls of the plenum housing define planes which intersect on the side of the plenum housing opposite that in which the nozzle is located.

13. An arc plasma generator as defined in claim 11 in which the angle determined by the upper and lower walls of the plenum housing is in the range of from 10° to 45°.

14. An arc plasma generator comprising a first electrode housing, a first back plate hermetically secured to the housing but electrically insulated from it, a first back orifice plate hermetically secured to the other end of the first electrode housing but electrically insulated therefrom, a first front orifice plate hermetically secured to the first back orifice plate but electrically insulated therefrom, a plenum housing hermetically secured to but electrically insulated from the first front orifice plate, a second front orifice plate hermetically secured to but electrically insulated from the plenum housing, a second back orifice plate hermetically secured to but electrically insulated from the second front orifice plate, a second electrode housing hermetically secured to but insulated from the second back orifice plate, and a second back plate hermetically secured to but insulated from the electrode housing, a first vortex ring made of an electrical insulating material mounted between the first front and first back orifice plates, a second vortex ring made of an electrical insulating material mounted between the second front and second back orifice plates, the first electrode housing and the first backplate and the first back orifice plate forming a first electrode chamber, the first front and first back orifice plates and first vortex ring forming a first vortex chamber, the first and second front orifice plates and the plenum housing forming a plenum chamber, the second front and second back orifice plates and second vortex ring defining a second vortex chamber, and the second back orifice plate, the second electrode housing and the second back plate forming a second electrode chamber, a nozzle mounted in the plenum housing and communicating with the plenum chamber, a first electrode feed mechanism extending through the upper back plate, a first

electrode secured to the first feed mechanism, one end of the first electrode being located in the first electrode chamber, a second electrode feed mechanism extending through the second back plate, a second electrode secured to the second feed mechanism, one end of the second electrode being located in the second electrode chamber, means for supplying working fluid through the vortex ring into the vortex chambers, said rings being mounted to cause working fluid to rotate in opposite directions within the vortex chambers, an exhaust manifold in the first electrode housing and an exhaust manifold in the second electrode housing, said manifold being in communication with the upper and lower electrode chambers respectively,

means for regulating the rate of flow of gases from the electrode chambers, means for connecting the first and second electrodes to a source of electrical power, and means for cooling the electrode housings, the back plates, the back orifice plates, the front orifice plate and the plenum housing.

15. An arc plasma generator as defined in claim 14 in which the first and second electrode feed mechanisms are responsive to the difference in potential between the electrodes and the back orifice plates nearest each electrode to maintain the length of the arc column between the electrodes substantially constant.

No references cited.

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,146,371 August 25, 1964

John H. McGinn

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 11, line 12, for "manifold" read -- manifolds --.

Signed and sealed this 8th day of December 1964.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

EDWARD J. BRENNER
Commissioner of Patents

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