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Sheer et al.

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[54] METHOD OF ENERGY TRANSFER
UTILIZING A FLUID CONVECTION
CATHODE PLASMA JET

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[63] Continuation-in-part of Ser. No. 805,574, Mar. 10, 1969, abandoned.

[30] Foreign Application Priority Data

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[51] Int. Cl.....H01j 7/24, H05b 31/26

[58] Field of Search.....313/231; 315/111; 219/121 P

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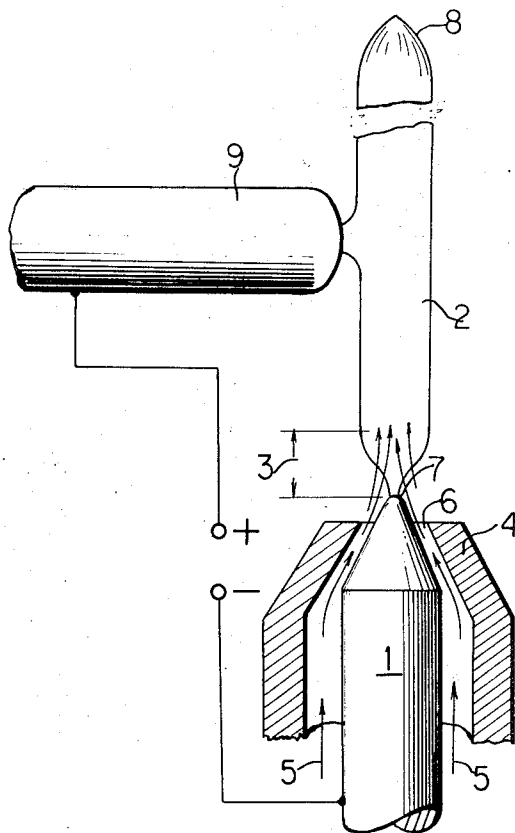
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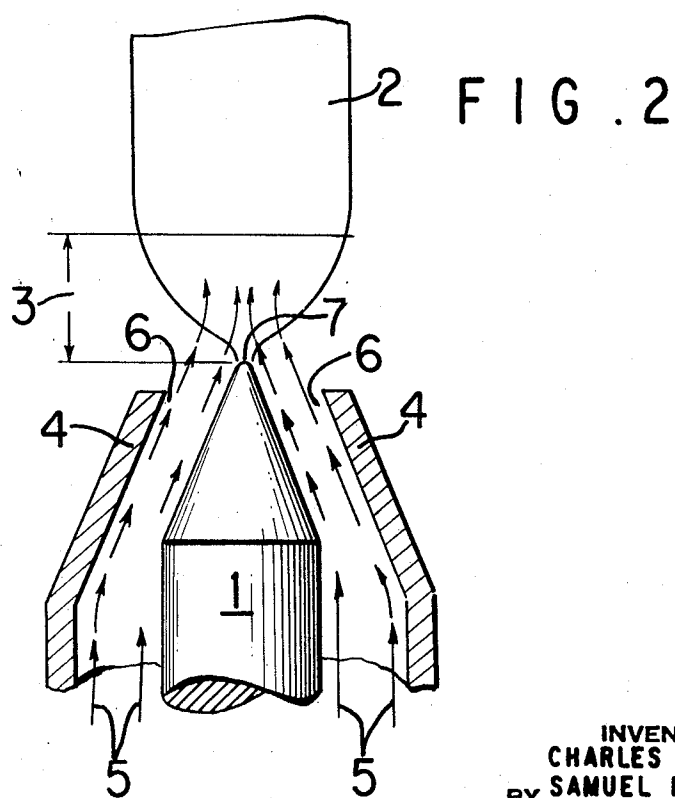
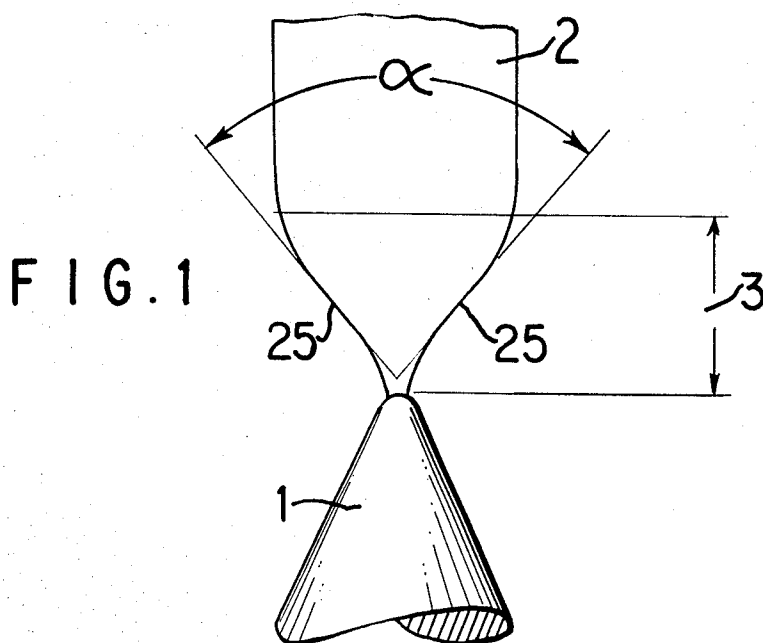
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ABSTRACT

A process of energizing a fluid medium by means of an arc discharge between an anode and a cathode having a conical tip, said arc discharge forming a contraction of the current-carrying area in the transition region in the vicinity of said cathode, the points of inflection of said contraction of the current-carrying area forming, when extended, an angle α which comprises forcefully projecting a fluid medium along said conical tip of said cathode into and through said contraction of the current-carrying area in the transition region in the vicinity of said cathode at a mass flow density at substantially constant convection rate which is at least sufficient to effect a rise in the temperature of said arc column at a constant current level, and below a total fluid medium convection rate at substantially constant mass flow density which is sufficient to reduce the angle α below 40° at a constant current level.

13 Claims, 8 Drawing Figures





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FIG. 3

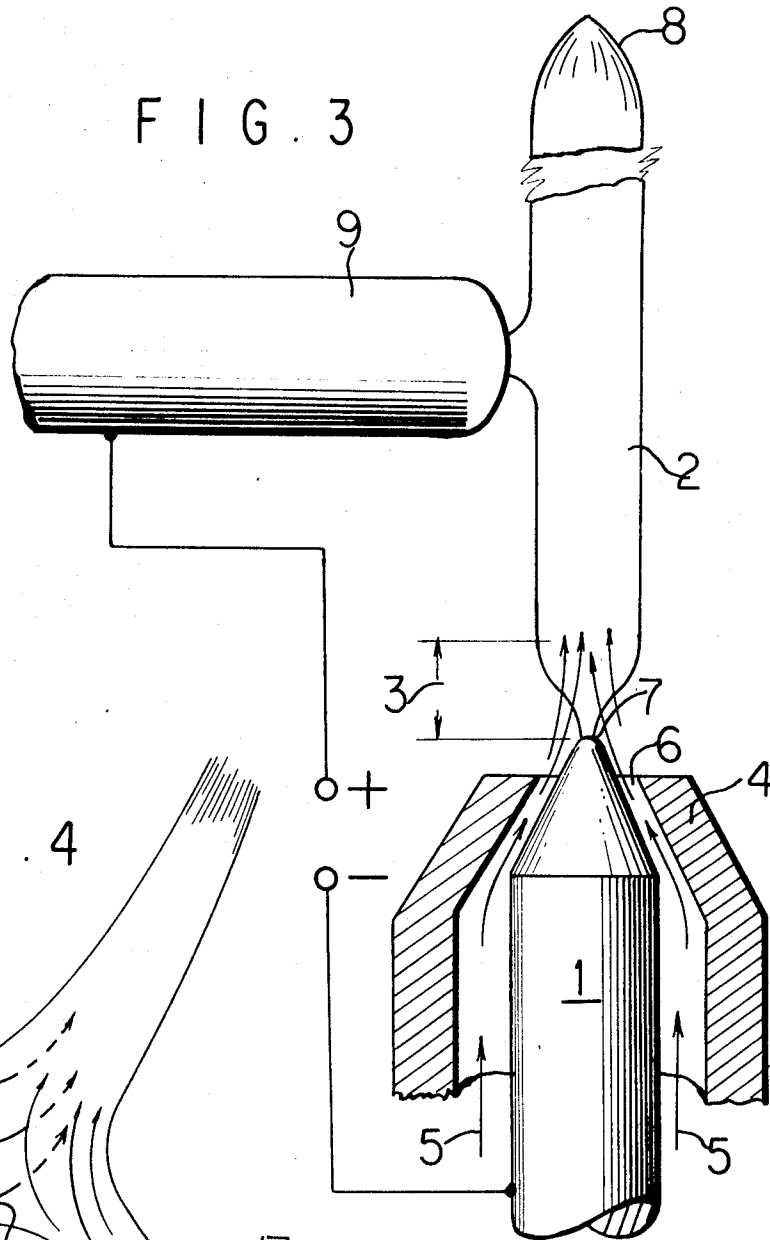
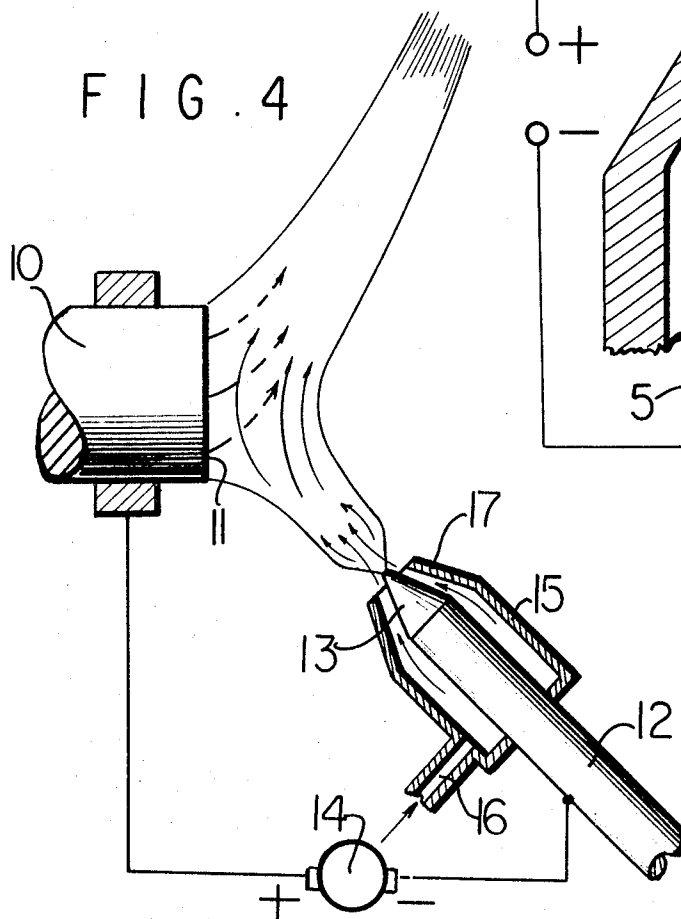


FIG. 4



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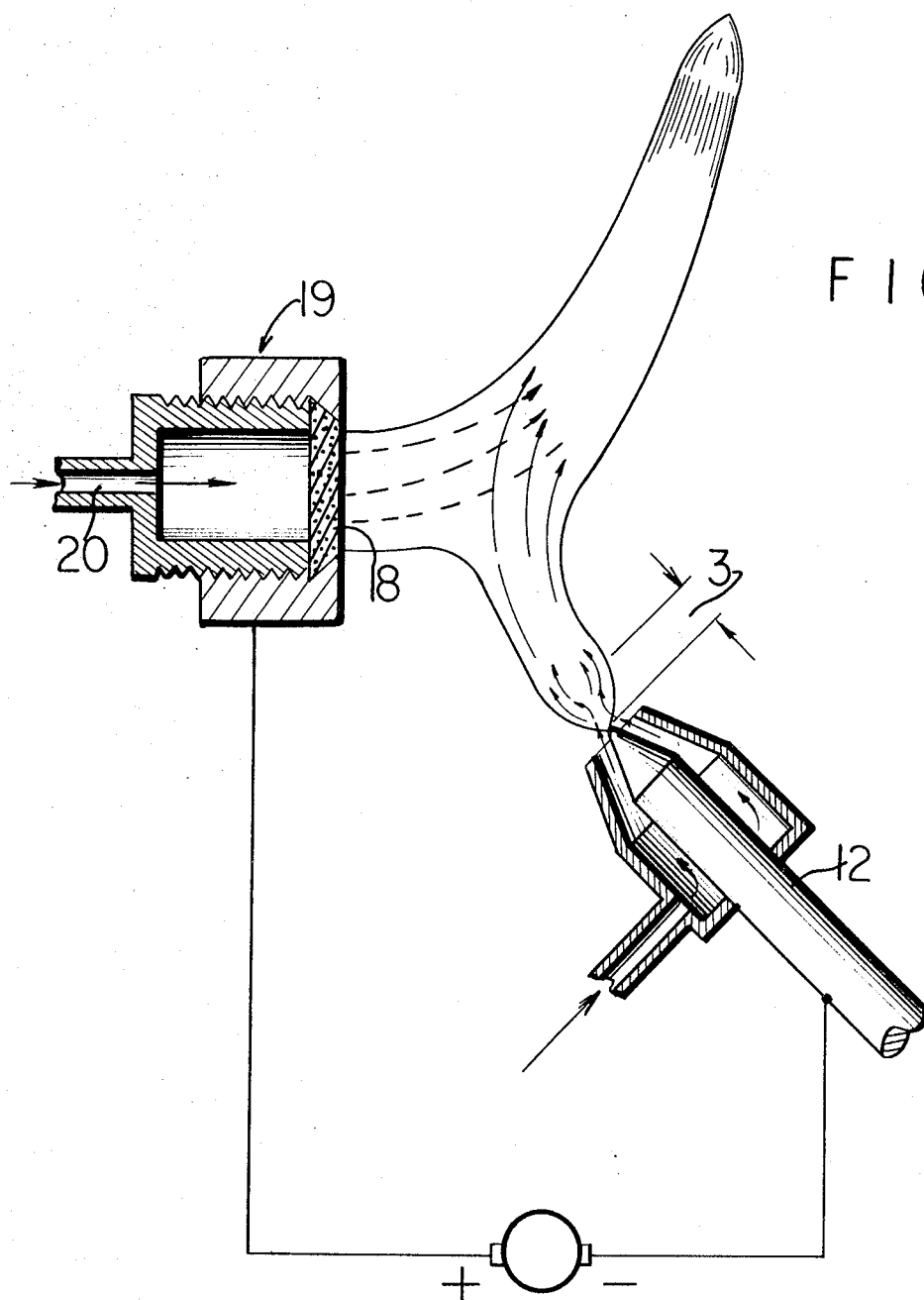


FIG. 5

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FIG. 6

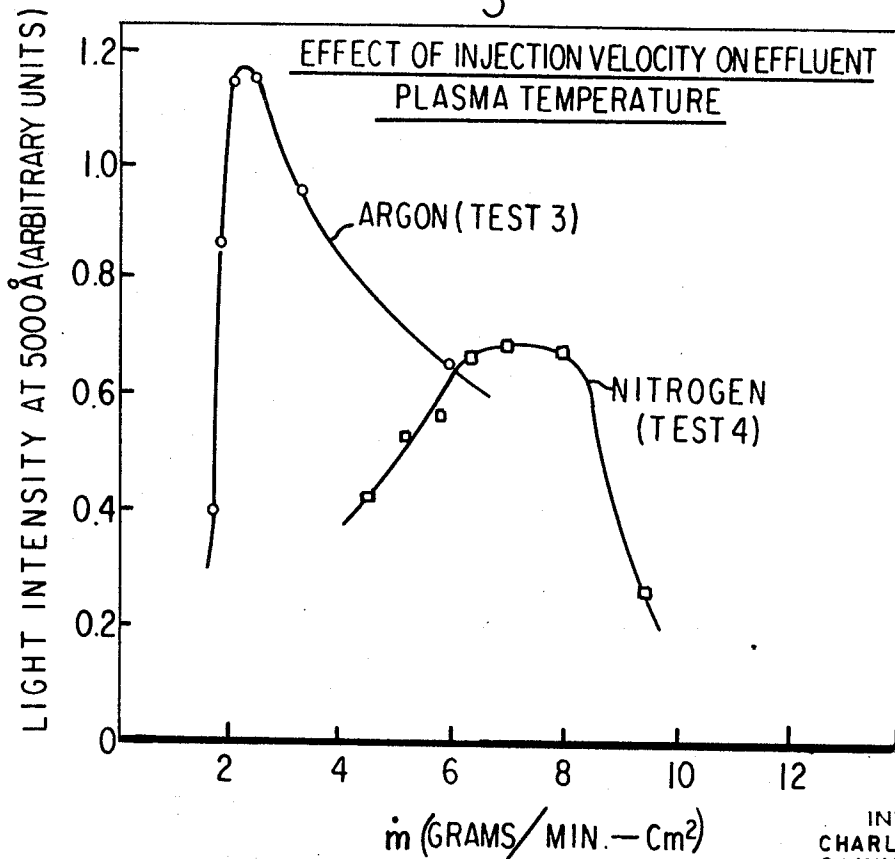
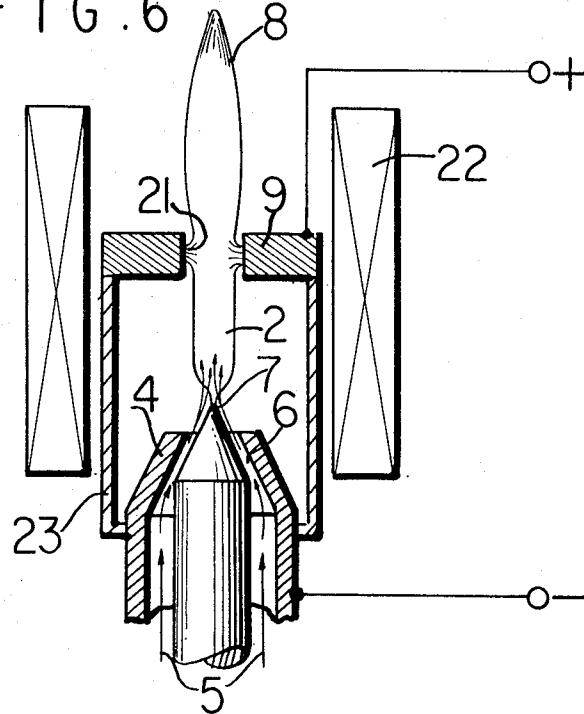
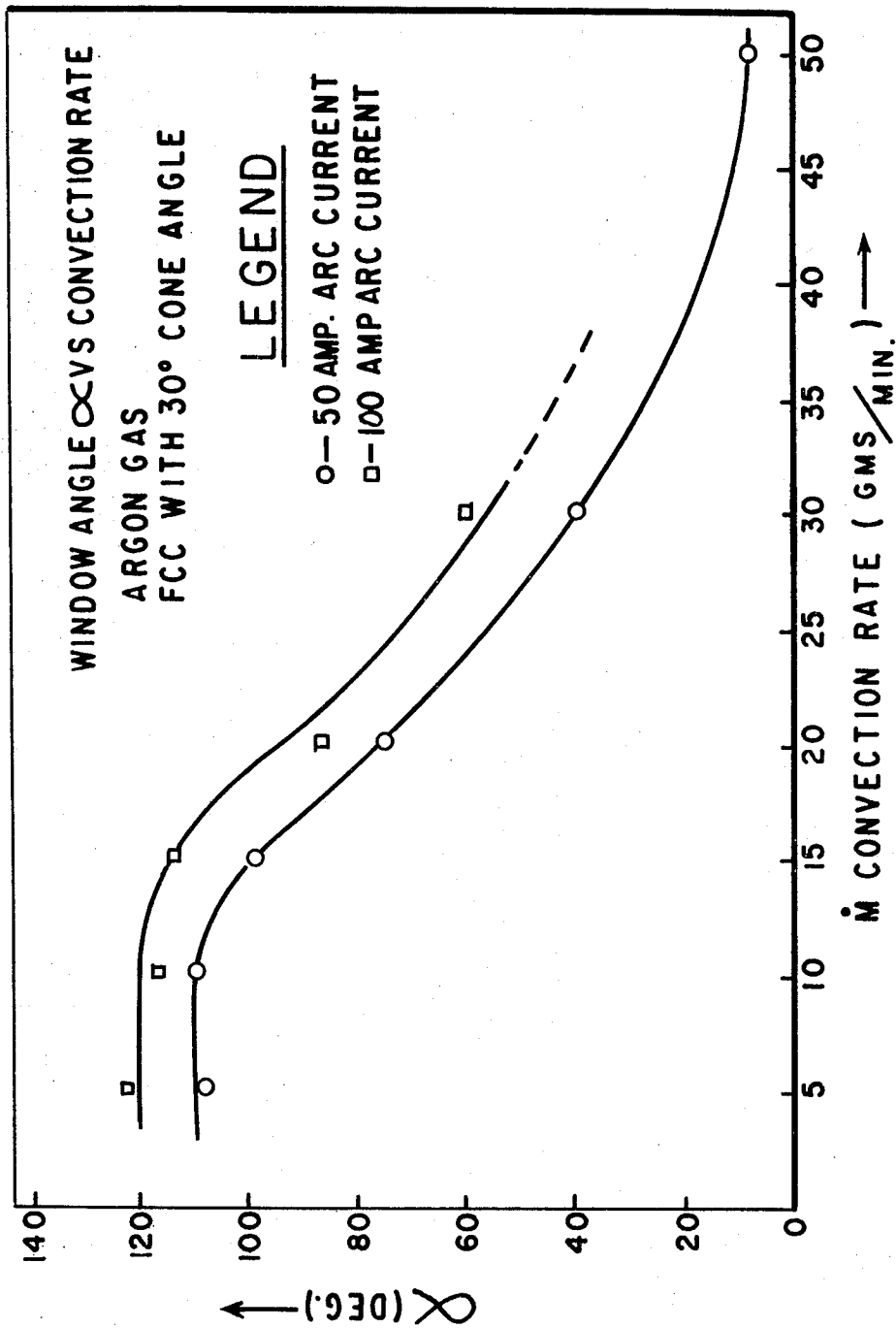


FIG. 7

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FIG. 8



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METHOD OF ENERGY TRANSFER UTILIZING A FLUID CONVECTION CATHODE PLASMA JET

REFERENCE TO EARLIER FILED APPLICATION

This application is a continuation-in-part of our copending U.S. Pat. application Ser. No. 805,574, filed Mar. 10, 1969, now abandoned.

THE PRIOR ART

As is well known, a hierarc is an electric discharge between a cathode and an anode of such intensity that the material of the anode face is vaporized and converted into a plasma jet, shooting off into space, avoiding the cathode. This is sometimes referred to as the consumable anode hierarc.

Methods and devices for transferring energy to fluid materials also by exposing said fluid material to the energy of a hierarc have been previously reported. For example, in U.S. Pat. No. 3,209,193, a novel method of exposing the fluid to the energy of an arc is disclosed, which consists of passing the fluid continuously through a porous anode so that it enters the discharge via the active anode surface, i.e., where said surface is acting as the arc terminus. That patent further discloses that unique and valuable results can be obtained if certain criteria are satisfied in operating such a device.

Specifically, the performance criteria required to achieve the desired results are the following:

1. The average diameter of the pores on the surface of the anode is less than the thickness of the anode fall space which is normally established in the absence of fluid flow adjacent to the active area, i.e., the fall space thickness of a conventional arc operating under noflow conditions.

2. The fluid is forced to flow through the passageways in the porous electrode so that the fluid emerges directly from the electrode surface into the fall space over the area integrally congruent with the arc terminus on the porous electrode surface, and preferably nowhere else.

3. The surface distribution of orifices, through which the fluid emerges from the electrode into the fall space, is sufficiently uniform that the individual streams of fluid from each orifice will diffuse laterally, merging with each other stream adjacent to it to form a homogeneous stream, as though it were issuing as a vapor from a solid surface, and further, the average interorifice distance on the active surface is sufficiently small that essentially complete flow homogeneity is established before the fluid penetrates an appreciable distance into the fall space.

4. For a given arc current, gap distance, and ambient pressure, the rate of fluid transpiration through the porous anode is adjusted so that it is greater than the value required to effect a transition to the hierarc mode of arc operation.

U.S. Pat. No. 3,214,623 describes an improvement to the above patent where the arc discharge has an essentially conical geometry. The cathode, porous anode and insulating supports are arranged geometrically to each other, so that the conduction column assumes the shape of an axially symmetrical conical shell.

The technique of fluid injection through a porous anode has been termed the "fluid transpiration arc" (FTA), and is a second example of the use of a hierarc to transfer energy to materials.

Several interesting features distinguish the FTA from the other forms of plasma generators and which emphasize the potential utility of this technique as an addition to the roster of high-temperature devices. One of the most striking properties of the FTA is the energy transfer efficiency (ratio of effluent jet enthalpy to power input). This results largely from the elimination of the need for thermal constriction of the arc column, which is the basic means of stabilizing the column against fluid flow in the wall-stabilized arc. In the latter device, a large fraction (e.g., 30 to 60 percent) of the power input is unavoidably lost by heat transfer to the cooling circuit of the constricting channel. In the case of the FTA, when the fluid emerging from the porous anode penetrates the anode sheath,

an overabundance of ions are created which serve to stabilize the arc, irrespective of flow rate. Hence the need for a water-cooled constricting channel, which is a major energy sink, is eliminated. An additional factor is the regeneration of heat transferred to the body of the anode, some of which is transferred to the incoming gas as it transpires through the anode and returned to the arc stream. This reduces the power lost to the cooling circuit of the anode holding structure, thus further improving the efficiency. The net result is a plasma generator which, even for the small laboratory units, operates with efficiencies in the range of 80 to 95 percent.

Another consequence of the elimination of column constriction is the quasi free-burning nature of the FTA. The only constraint involved in this device is the requirement that the working fluid penetrate the anode sheath as it emerges from the anode. Since the sheath is a thin layer contiguous to the anode surface, the column formed by the stream after it leaves the sheath is completely unencumbered. This is of interest for applications in which virtually complete accessibility of the effluent column provides an important practical advantage. Also of interest is the quasi one-dimensional character of the emergent plasma for an appreciable distance along the column. Owing to the shape and disposition of the anode sheath (thin, flat disc) through which the fluid passes, the plasma properties of the emerging column are relatively invariant in the radial direction. Furthermore, the radial invariance persists for several column diameters downstream, providing an appreciable volume characterized by only axial variation of plasma parameters. This means that a small axial increment of the column may be treated as a uniform medium, thus vastly simplifying the theoretical interpretation of diagnostic data.

One of the most interesting features of the FTA is the abnormally high-electrical conductivity of the effluent plasma, particularly in the region near the anode. Here one observes a macroscopic plasma zone characterized by a high degree of nonequilibrium. In particular, the electron temperature is much higher than the gas temperature throughout most of this region. This feature has been observed in low-pressure (<0.1 atm.) discharges, but never before at atmospheric pressure. The high-electron temperature is in itself insufficient to explain the measured electrical conductivity (two-temperature model). Spectroscopic measurements indicate a higher degree of ionization than can be correlated with the Saha equation. The high density of free electrons in a relatively dense plasma suggests an enhancement of continuum radiation and provides the basis for an efficient source of radiation.

Attempts have also been made to inject a working fluid into the interior of an arc column at other points than the anode. Many difficulties have been found in these attempts. For example, in a constricted arc column having a conventional wall-stabilized arc with a segmented, water-cooled constrictor channel long enough to assure the establishment of a fully developed column, the injected gas was forced to flow axially, concentric and parallel to the conduction column. Since the column in this device is subject to an appreciable thermal constriction, it would seem that the convected gas would be forced through the column boundary into the primary energy dissipating zone. It was found, however, that, even in the fully developed region, beyond which the radial distributions of the flow parameters remain constant, by far the major part of the flow traverses the thin, cool, nonconducting gas film adjacent to the channel wall. In fact only about 10 percent of the mass flow enters the hot core. The much higher density and lower viscosity of the cool gas in the wall layer, plus the fact that even a very thin film can have appreciable cross-sectional area near the wall, compensate for the lower velocity of the cool gas layer, and account for nearly all of the convected mass flow. It should be noted that the radial temperature across the fully developed portion of the column remains above 10,000° K. over 80 percent of the channel diameter, so that the plasma fills the channel quite well. The conclusion is that most of the working fluid does not penetrate the column and is therefore

not directly exposed to the zone of maximum energy dissipation.

The same effect is noted with other flow configurations. For example, if a stream of gas is projected at right angles to the column of a free-burning arc, the arc will be blown out at quite low-flow rates. However, the column can be stabilized by a magnetic field of suitable strength oriented normal to both column and gas flow so as to balance exactly the force of convection. Even when the balance is established at very high-flow rates, the gas does not enter the column, but is deflected around it, the column behaving much like a solid cylinder. An examination of existing arc jet devices reveals that in nearly every case most of the working fluid is not subjected to the zone of direct energy transfer. The only exception previously known is the FTA in which the working fluid is first energized in the anode sheath and then fully permeates the column in the vicinity of the anode. Even in this device, however, when used with a conventional conically tipped cathode, the natural cathode jet collides with the transpiration gas at some point between the electrodes. Hence, the injected gas permeates only the "positive column," i.e., the portion of the conduction column between the anode and the point of impingement of the two jets. The "negative column" (between the cathode tip and the point of impingement) is characterized by the flow of ambient gas which may not be the same as the injected gas.

OBJECTS OF THE INVENTION

An object of the present invention is the development of a method which enables the bulk of the fluid to be injected into the negative column extending from the cathode tip.

A further object of the present invention is the development of a process of energizing a fluid medium by means of an arc discharge between an anode and a cathode having a conical tip, said arc discharge forming a contraction of the current-carrying area in the transition region in the vicinity of said cathode, the points of inflection of said contraction of the current-carrying area forming, when extended, an angle α , which comprises forcefully projecting a fluid medium along said conical tip of said cathode into and through said contraction of the current-carrying area in the transition region in the vicinity of said cathode at a mass flow density at substantially constant convection rate which is at least sufficient to effect a rise in the temperature of said arc column at a constant current level and below a total fluid medium convection rate at substantially constant mass flow density which is sufficient to reduce the angle α below 40° at a constant current level.

These and other objects of the invention will become more apparent as the description thereof proceeds.

THE DRAWINGS

FIG. 1 is a schematic diagram illustrating the arc column contraction and the angle α in the vicinity of the cathode.

FIG. 2 is an enlarged cross section of operation of the method of the invention including the cathode.

FIG. 3 is a medial section of one embodiment of operation of the method of the invention.

FIG. 4 is a medial section of another embodiment of the operation of the invention.

FIG. 5 is a medial section of a still other embodiment of the invention.

FIG. 6 is a medial section of a yet further embodiment of the invention.

FIG. 7 is a graph of the unexpected temperature rise using the process of the invention.

FIG. 8 is a graph of the unexpected reduction in the angle α with increased convection rate at constant current level and mass flow density.

DESCRIPTION OF THE INVENTION

It has long been known that when an arc is struck between an anode and a cathode having a conical tip, as illustrated in FIG. 1, there occurs a contraction of the current-carrying area

in the transition region between the cathode 1 and the column proper 2. This contraction is indicated as the contraction zone 3. This contraction of the current-carrying area in the transition region between the cathode 1 and the column proper 2 may also be defined as the angle α which is determined by extending lines tangent to the column boundary at the points of inflection 25 of the contraction. This contraction causes the natural cathode jet effect as explained in the following.

Referring to FIG. 1, the current density and, therefore, the self-magnetic field due to the arc current, increases toward the cathode as a result of the contraction. This nonuniform magnetic field exerts a body force on the conductive plasma, propelling it in the direction of maximum decrease in magnetic field, i.e., along the arc axis away from the cathode tip. The streaming of plasma away from the cathode tip decreases the local pressure in the immediate vicinity of the cathode tip and causes the arc to aspirate gas from the surrounding atmosphere. This mechanism establishes the well-known natural cathode jet, which has been observed to flow along the axis of the column away from the cathode tip in all arcs characterized by a contraction zone adjacent to the cathode.

We have now discovered that this contraction zone 3 can serve as an "injection window" across which a fluid medium in the form of a gas may be injected directly into the arc column 2 at flow rates in excess of what can be forced across the cylindrical column boundary of the arc. Gas flow rates of a magnitude much greater than that aspirated naturally can be injected into the column without disturbing the stability of the arc when the gas is forced to follow the conical configuration of the cathode tip. However, the increase in gas convection rate does effect the angle α and if the angle α is reduced below 40° , no substantial amounts of addition gas can be injected into the arc column 2. The effect of the forced convection is to increase the voltage gradient in and near the transition region, thereby increasing the volume rate of energy dissipation and making available the additional energy needed to heat the increased quantity of gas introduced to the column temperature. In short, the injection window is not only possible but actually increases the heat transfer effectiveness of this part of the arc, as long as it does not exceed the convection rate which will reduce the angle α below 40° .

The boundaries of the gas which is forced to follow the conical configuration of the cathode tip are on one hand the surface of the cathode, and on the other hand a line parallel to the surface of the cathode which intersects the cathode column at the outermost limit of the contraction zone 3. Preferably, the gas is forced to follow the conical configuration of the cathode tip in such a manner that its essential entirety enters the contraction zone at its region of maximum convergence. This region can be determined by trial.

In this application a "cone" with reference to the cathode is defined as a converging segment which may be a true cone having a circular cross section or may be pyramidal in shape, comprising a number of converging planar surfaces whose cross section is a polygon of any convenient number of sides. The term "cone angle" shall refer to the vertex angle of the converging segment.

Although many arc systems have been used in which the working fluid is convected to the arc via an annular passage concentric to the cathode, the effect described above has not previously been noted due to the special conditions of gas injection of the present invention which is required to produce the maximum effect. For this purpose, the gas to be injected must be projected in a high-velocity layer along the conical cathode surface.

By proper adjustment of the gas velocity and cone angle of the cathode, the gas can be made to cross the column boundary in essentially the same general direction as would the aspirated ambient gas stream in the absence of forced convection. The optimum cone angle for this purpose appears to be between 45° and 60° .

The cone angle is an important parameter. Variations in cone angles of from 20° to 135° may be employed depending

partially on the material of the cathode, and type of fluid material injected, and the work purpose of the device. We prefer to use a cone angle in the range of 30° to 60°, and more particularly, have used angles of 45° to 60° with good results.

A second critical parameter is the injection velocity. This can be varied without altering the total mass flow (convection) rate by varying the area of the annular orifice and changing the inlet gas pressure as required to maintain a fixed flow rate. It has been observed, for example, that as the injection velocity (mass flow density) is varied, the column temperature passes through a peak, with the maximum temperature rising to two or three times that obtained when the velocity is several times higher or lower than its optimum value. It should also be mentioned that the creation of a high-velocity gas layer flowing along the surface of the cathode is effective in regenerating some of the heat lost by thermal conduction back from the cathode tip.

A third critical parameter is the total mass flow of the injected fluid medium. As the total mass flow of the injected fluid medium is varied at substantially constant current levels and mass flow density, an alteration of the shape of the contraction zone 3 occurs. When the total mass flow or convection rate of the injected fluid medium is increased from zero, little or no change in the shape of the contraction zone 3 is observed and substantially all of the injected fluid enters the arc column through the injection window. However, as the total mass flow of the injected fluid medium is increased further, at a point depending on the medium injected, the contraction zone begins to elongate thus decreasing the space rate of contraction of the arc column diameter. This space rate of contraction may be called the window angle and is depicted in FIG. 1 as the angle α . When the angle α is sufficiently reduced, that is, to about 40° or less, the major portion of the flow of the fluid medium does not enter the arc column.

The above technique of injecting the working fluid into the contraction region of the column will be henceforth termed the "forced convection cathode" arc (FCC). Excellent operational stability is achieved without energy-wasting thermal constraints, providing the basis for excellent efficiency along with a high degree of accessibility to the primary energy transfer zone. Together with the FTA it provides a means whereby the working fluid can be made to penetrate significantly all portions of the conduction column, from anode to cathode, absorb otherwise unavailable energy in the electrode transition zones, and regenerate some of the heat normally lost to the electrodes.

By the use of the FCC many chemical and physical reactions may be conducted in a practical manner. For example, a gas such as nitrogen, argon or hydrogen can be introduced into the "injection window" and in a highly energized condition is projected so as to contact an anode. The emerging plasma jet may be utilized to heat other materials, for example, in cutting and welding.

In particular, however, a reactive gas, such as nitrogen or hydrogen, can be introduced as above into the "injection window" to form a highly energized plasma jet which is projected into the jet of plasma vapor issuing from the anode of a consumable anode hierarc. If such an anode is a carbon anode, and hydrogen is introduced through the FCC, the mixture of the two jets is favorable to the production of hydrocarbons. Further, where the consumable anode contains a metal or metalloid, then if hydrogen or nitrogen is injected through the FCC, the gases so projected will unite with the plasma of the hierarc to form the corresponding nitride or hydride of the metal of the anode.

In addition, by the use of a combination of the FCC and the FTA, two different gases may be introduced into the cathode "injection window" and the anode fall space, respectively, to perform such operations as the synthesis and reformation of organic compounds and inorganic compounds such as ammonia.

The device can also be employed in other fields as in the case of the FTA.

We have also found that, in addition to a homogeneous stream of one or more gases, it is possible to inject a heterogeneous stream consisting of a carrier gas in which is entrained liquid droplets or solid particles, and that said liquid or solid particulates will be carried through the injection window along with the carrier gas to mingle thoroughly with the column and be exposed to the high temperature environment therein more effectively and at greater material throughput rates than any prior art device operating at equivalent power levels. A number of highly useful applications are derived from this capability. For example, using an inert gas such as argon, virtually any powdered material, including metals, oxides, etc., may be passed through the arc at such a rate relative to the power level that the material is melted, but not appreciably vaporized, during its transit through the column and effluent jet. When allowed to condense, following emergence from the jet, such materials will congeal in a spherical form, which is useful in powder metallurgy and other applications. By allowing the molten droplets to impinge on a substrate, the familiar process of flame spraying may be achieved with greater material application rates and better quality coatings than otherwise possible.

Also by reducing the rate of material throughput relative to the power level, the entrained particulates can be made to vaporize during their passage through the arc zone. Upon emerging from the jet, the vapors will recondense into extremely fine particles in the submicron range, thus providing an efficient process for the comminution of coarser powdered materials.

Various chemical uses of this device are also available. For example, the powder of a stable refractory ore, not directly amenable to chemical attack by conventional reagents, may be entrained in an appropriate carrier gas and passed through the device at a predetermined rate relative to the power level, so that the ore particles are rendered chemically unstable. Depending on the type of ore, this may or may not require heating the particles above their melting point, and the optimum throughput rate for a given power level for a given ore is best determined empirically. In any case, after the heat treatment the particles are rendered amenable to chemical attack by ordinary reagents for the economic recovery and separation of the ore values.

In other chemical applications of the device, a reactive gas such as hydrogen may be used as the carrier gas to entrain powdered coal so as to produce a mixture of active hydrogen and carbon vapor, from which acetylene and other hydrocarbons may be condensed. Alternatively, droplets of liquid hydrocarbons may be entrained in the hydrogen for hydrocarbon reformation. Similarly, metals or metalloid powders may be entrained in hydrogen or nitrogen to produce hydrides or nitrides. The introduction of metal oxides with hydrogen to produce metals, or with ammonia to produce nitrides, may also be accomplished. Many other similar applications of the device for chemical processing are possible in which greater efficiency and higher yields are obtainable from the use of this device than can be obtained from other methods of treatment. When a particulated solid is introduced through the annular orifice, we have found that no difficulties in flow occur as long as the size of the particles is less than the width of the annular orifice, preferably one-third to one-fourth the width of the annular orifice.

With reference to FIGS. 2 to 6, the invention can be practiced and the high energization of the gas introduced at the cathode can be achieved in the following manner.

FIG. 2 is a cross section of a cathode nozzle 4 designed to optimize a gas injection 5 into the arc column 2 via the injection window at the contraction zone 3 at the end of the cathode 1. For this purpose, the nozzle 4 forms a narrow annular orifice 6, upstream of the conical cathode tip 7, directing the gas 5 to flow in a high-velocity layer along the conical cathode surface.

The construction shown in FIG. 3 shows the apparatus for conducting the process by means of which the cathode gases

are energized to form a plasma jet which contacts a water-cooled solid anode. The construction shown in FIG. 4 shows the apparatus for conducting the process with a consumable solid anode from which, in addition to the cathode plasma jet, the anode plasma jet is to be generated. FIG. 5 shows a similar construction in which the material of the anode jet is in the form of a gas, which is caused to transpire through the porous refractory anode block.

Referring now to FIG. 3 the cathode 1 and cathode nozzle 4 are depicted as in FIG. 2. The arc column 2 emitting from the cathode tip is directed to and contacts a water-cooled solid anode 9, such as a water-cooled copper block. The plasma jet 8 flows away from the anode.

In FIG. 4, the numeral 10 represents a consumable rod electrode of the material to be converted, having an active face 11. Spaced from the face 11, but not directly in front of it, is a cathode 12 of a refractory material such as tungsten, in the form of a rod having a conical end 13. This rod 12 is negatively charged from a suitable source 14, the positive terminal of which is the rod 10.

The active conical end 13 of the cathode 12 is surrounded closely by a preferably nonconducting box 15 having an opening 16 for the gas to be added. The box 15 has a conical end 17 surrounding the pointed end 13 of the cathode 12, but terminating before reaching the point of the cone.

With this construction the gases admitted to the box 15 must leave the box by sliding down the conical end 13 of the cone, moving past the point of the conical end of the cathode. The gases then enter the arc column through the "injection window." The cathode assembly is so situated that its arc jet will project against the active face 11 of the refractory anode 10.

The velocity of the gas may be readily controlled by the pressure exerted on it at 16 and by adjusting, in a known manner, the cathode 12 within the nozzle formed by the conical end 17 of box 15.

The construction shown in FIG. 5 shows how the process may be applied to the treatment of a material in fluid or gaseous form. In this construction the refractory anode 11 of FIG. 4 is replaced by an anode box 19 having an inlet 20 for the reaction gas, and having on the opposite face a porous block 18 through which the material is forced, exposing the fluid material to the jet from the cathode 12 in a fixture which is identical with that shown in FIG. 3. Thus, by this manner, the effluent gas streams are caused to interact at high temperatures while the anode box, itself, is held at a more moderate temperature.

The device depicted in FIG. 6 is similar in effect to that of FIG. 3. The cathode 1 and its nozzle 4 are identical to that described in FIG. 3. The anode 9 in this embodiment is a flat circular water-cooled anode. The anode spot 21 is made to rotate around the circular anode 9 by means of a magnetic field introduced through the solenoid winding 22. A gastight housing 23 encloses the arc column 2. The effluent plasma jet 8 emerges from the circular anode 9.

The voltages employed to carry out the process are determined by the result achieved.

The principle by which this cathode gas stream is employed is illustrated in FIG. 2, in which is shown a conical cathode 1 over which the cathode gas 5 is caused to flow over the conical surface of the cathode 1 and beyond the tip 7. With such a construction, some of the heat energy from the body of the cathode 1 has been found to be transmitted to the gas stream 5 when the gas stream is mechanically caused to hug the conical cathode 1 by means of the annular nozzle 6.

The following examples illustrate the device of the invention and its use. They are not to be construed, however, as limitative in any respect.

EXAMPLES

In order to illustrate the operation of the method several examples are cited in which actual tests are described.

EXAMPLE I

The simplest form of the operation of the method is shown diagrammatically in FIG. 3. It consists of a tungsten rod three-eighths inch in diameter having a conical tip with a 60° cone angle as the cathode. Surrounding the cathode is an enveloping nozzle 4 having a conical section whose inside surface also has a cone angle of 60° so that it mates with the conical cathode surface. The conical section of the nozzle is truncated so that it terminates several millimeters behind the cathode tip 7, and thus forms an annular orifice 6 about the cathode. The annular passage between the nozzle and cathode is effective in directing the flow of input gas 5 in the form of converging conical layer flowing close to the cathode surface, finally impinging on the arc column 2 largely on the injection window of the contraction zone 3.

For a given orifice area, the mass flow rate of gas can be controlled by adjusting the inlet pressure, and, for the experiment being described, was varied from as little as 2 grams per minute of argon gas to over 50 grams per minute.

The nozzle itself was initially fabricated of boron nitride ceramic, although, owing to its proximity to the arc, in later tests it was found expedient to make the nozzle out of a metal such as brass and provide it with a separate water-cooling circuit to prevent overheating. However, in the latter case, care was taken to insulate the nozzle electrically from the cathode to avoid the formation of undesired secondary arcs.

The orifice area of the cathode nozzle is made variable by moving the nozzle section relative to the cathode in the axial direction. This is done by mounting the nozzle itself on a micrometer screw. Rotation of the nozzle in either direction thus, causes the latter to move horizontally relative to the stationary cathode, opening or closing the nozzle orifice. In the present examples various nozzle orifice areas were used varying from 1.00 to 4.5 square millimeters, corresponding to annulus widths of 0.18 mm. to 1.16 mm.

The anode 9 of the arc in this apparatus is composed of a 1-inch-diameter copper tube with one-eighth inch thick wall, closed at one end with a rounded cap which serves as the current-receiving area. The interior of the tube is fitted with water passages and the anode is vigorously water cooled to inhibit erosion of the surface during operation. Provision is made to change the position of the anode with respect to the cathode, thus effectively varying the arc gap. It was also found convenient for starting the arc to provide means for altering the angle as well as the position of the anode rod with respect to the cathode axis. The procedure used for igniting the arc is as follows.

The anode is rotated about 45° and raised so that the rounded end of the anode points toward the cathode tip, and the cathode axis intersects the anode rod near its center. Simultaneously, the anode rod is brought close to the cathode tip, to leave a gap of about 5 mm. After adjusting the cathode nozzle orifice area to a suitable value, usually about 3 square millimeters, a moderate flow of gas is turned on. For argon, a startup flow of 10 to 15 grams per minute was usually used. The arc is then ignited, using a momentary high-frequency spark to form a conductive path between the electrodes with the main power supply turned on, following which a rapid spark to arc transition occurs. This technique of arc ignition is well known in the art.

Once the arc is ignited, generally with a starting current of about 50 amperes, the arc gap is increased to its desired value by withdrawing the anode. The anode is rotated to a convenient lateral position, preferably normal to the arc axis, and retracted so that the end cap is just below the plasma stream. In this configuration the effluent jet leaves the conduction column in essentially the axial direction. For high-flow rates care must be taken to keep the end of the anode sufficiently close to the column to prevent the arc from being blown out.

The device has been operated in this relatively simple configuration in a stable and continuous manner. The following are the ranges of the pertinent operating parameters which were observed during the testing of this device, using argon as the working fluid:

Arc current	50 to 300 a.
Arc voltage	35 to 165 volts
Arc gap	1 to 12 centimeters
Total mass flow of argon	2 to 50 grams per minute
Cathode nozzle orifice area	1.00 to 4.5 square mm.

These figures refer to ranges of parameter which were observed during actual test to permit stable operation and to not necessarily represent the limits of operability of the device. Some of the parameters are dependent on others, particularly the arc voltage, which increases with arc current, arc gap and total mass flow. Also for a given mass flow the voltage will increase or decrease as the cathode nozzle orifice area is changed, the increase occurring when the area is small (high-velocity flow) and the decrease when it is large (low-velocity flow).

To illustrate further, the following are two sets of specific parameters for two separate tests of this device, using argon gas:

Parameter	Test 1	Test 2
arc current	50 a.	200 a.
arc voltage	38 volts	62 volts
arc gap	1.5 cm.	2 cm.
total mass flow	15 g./min.	57 g./min.
cathode nozzle orifice area	3.1 mm. ²	4.3 mm. ²

EXAMPLE II

FIG. 6 shows an alternative configuration of the device wherein the cathode 1 and its nozzle 4 is identical to that described in FIG. 3, the main difference being the type of anode 9 used. Here, instead of a rod-shaped anode, a flat circular copper anode 9 is used, about ½ inch thick and 2 inches in diameter, with a ½-inch diameter hole in the center. The interior of the ring is fitted with water passages for rapid cooling of the cylindrical surface of the hole during operation. This surface serves as the attachment area for the anode spot 21.

When using the ring-shaped anode, it is useful to rotate the anode spot on the inside cylindrical surface. This may be done by placing the device inside a solenoid winding 22 which establishes an axial magnetic field. If sufficient magnetic flux is generated, the anode spot will rotate very rapidly, spreading out essentially into a continuous ring. This reduces anode erosion by distributing the heat transferred to the anode over a larger area. In the present illustration, a magnetic field of 2,400 gauss, measured on the axis midpoint of the solenoid was found to be effective. This is a technique well known in the art for increasing the thermal loading capacity of arc devices.

In carrying out the purposes of this invention it is often convenient to enclose the column in a gastight housing 23, as shown in FIG. 6. This will prevent contamination of the effluent stream by the atmospheric ingredients, or conversely, prevent leakage to the atmosphere of process materials. It is also useful in shielding the operator from the radiation of the arc column. The housing may be constructed of any convenient material. However, because it must absorb a considerable amount of radiation from the arc column, it is convenient to fabricate the housing from a metal, such as brass, and provide it with its own water-cooling circuit to prevent overheating. In such a case, care must be taken to provide adequate electrical insulation where the housing is attached to the anode and cathode structures. The dimensions of the housing are not critical except that the internal dimensions must be large enough so that the housing walls exert a negligible influence on the arc column. This preserves the "free-burning" character of the FCC arc and represents an important distinction from prior art devices in which the arc column housing consists of a water-cooled channel in close proximity to the column. In such devices, the housing serves to constrict

the column and represents an appreciable thermal constraint essential to their operation.

The arc in this configuration may be ignited in the same manner as described for the configuration shown in FIG. 3. However, if a housing is used, the capability of changing the arc gap involves a complexity of construction which it is desirable to avoid in many applications where a fixed gap may be employed. If a fixed gap is used, the application of a high frequency spark to ignite the arc would require an inordinately high voltage for the spark generator with consequent complications in the form of high-voltage insulation. For such cases, an alternative procedure of arc ignition is desirable. This consists of using an auxiliary "striker" rod, which may consist of a long narrow graphite rod, which is inserted through the hole in the ring anode and made to contact both cathode and anode, while the arc power supply is connected. Rapid withdrawal of the rod through the anode hole then results in a fully established arc.

The tests presented in this example are described to illustrate an important and unexpected feature of this invention which concerns the existence of an optimum injection velocity. Using the configuration of the device shown in FIG. 6, the operating and performance data of two typical tests are given below. In both tests the total mass flow of injected gas was held constant, together with the arc current and arc gap. A conventional constant-current arc power supply was used to furnish electric power to the device having an open circuit voltage two to three times the operating voltage required by the arc. This ensures that the power supply can provide whatever voltage is required by any particular combination of operating parameters encountered in the experiment.

In both tests the cathode nozzle orifice area was varied to change the injection velocity, the total quantity of gas injected per unit time being maintained constant. The effect of variation of injection velocity on the column was observed by observing the intensity of radiation emitted by the first centimeter of the plasma jet emerging from the ring anode. The light from this segment of the jet was focused on the entrance slit of a prism monochromator. The latter was adjusted to pass a bandwidth 100 angstroms in the neighborhood of 5,000 angstroms. For the gases used, this lies in the so-called "continuum" range of the spectrum and, under the conditions of the experiment, the intensity of the light in this spectral region increases with the temperature of the source and vice versa. Thus, by recording the intensity of the light output from the monochromator, an indication of the temperature of the effluent plasma jet is obtained. This is accomplished by a suitable photomultiplier, amplifier and recorder, following well-known techniques.

As stated above, the quantity which was adjusted to obtain variation in injection velocity was the area of the cathode nozzle annular orifice. This is based on the following well-known formula:

$$\rho v = \dot{M}/A$$

where ρ = density of the gas at the orifice

v = velocity of the gas at the orifice

$\dot{M}$ = total mass flow of gas through the orifice

A = area of the orifice

By adjusting the axial position of the nozzle it is clear that the orifice area, A , will change. It is a simple matter to maintain the mass flow, $\dot{M}$, constant by adjusting the inlet pressure and observing the flow rate with a flowmeter. This, therefore, provides variation in the quantity, ρv , which is in effect the momentum per unit volume of the gas stream emerging from the orifice and is equal to the mass flow density referred to the nozzle orifice. This is actually the fundamental parameter governing the effect being illustrated. However, we have found that under most conditions under which this device is operated, including those of these experiments, the changes in head pressure required to maintain $\dot{M}$ constant were very slight so that there is very little change in the density, ρ , during

the experiment. The mass flow density is, therefore, a very good indication of gas velocity at the nozzle orifice, and, because of its close proximity, the velocity with which the gas enters the injection window. However, since the measured quantities are $\dot{M}$ and A , we shall define

$$\dot{m} = \dot{M}/A$$

and present the results of each test as a plot of $\dot{m}$ versus the intensity of the monochromator output. The results are presented in FIG. 7 where $\dot{m}$ is shown in grams/second/cm.². Both curves clearly show a peak verifying the existence of an optimum injection velocity. The specific performance data for these tests are as follows:

	Test 3	Test 4
Gas	Argon	nitrogen
arc current	100 a.	100 a.
arc voltage	44 volts	118 volts
arc gap	2 cm.	3 cm.
total mass flow	4.5 g./min.	13 g./min.
magnetic field intensity	2400 gauss	2400 gauss

EXAMPLE III

The apparatus of Example I was utilized in this example; however, the cone angle of the cathode was 30°. In this test, the total mass flow or convection rate $\dot{m}$ was varied at constant arc current and mass flow density $\dot{m}$ utilizing argon as the fluid medium. The configuration of the arc column 2 in the contraction zone 3 was visually inspected as the total mass flow $\dot{M}$ was varied.

When $\dot{M}$ is increased from zero at a constant $\dot{m}$, little or no change in shape of the contraction zone 3 was observed and virtually all of the injected fluid enters the column via the injection window. As $\dot{M}$ is increased further, at some point the contraction zone 3 begins to elongate, decreasing the space rate of contraction of the column diameter. This rate of contraction is measured by the "window angle" which is pictorially defined in FIG. 1 and is designated as "α."

In summary, we have found that as $\dot{M}$ increases, α decreases and that as α decreases, the effectiveness of the window in admitting the convected fluid into the column is reduced. When α is sufficiently reduced, to about 40° or less, the major portion of the flow does not enter the column and the value of the device as a heat transfer device becomes severely limited.

An example of the effect of $\dot{M}$ on α is shown in FIG. 8. In this figure two curves are drawn, for 50 amps, and 100 amps, respectively, showing the variation of α with $\dot{M}$. These results indicate that the maximum total argon gas throughput rate that can be energized by injection into the arc column in the manner described, when a cathode with a 30° cone angle is used operating at 50 amps arc current, is about 30 grams of argon per minute. This is obtained from the 50 amp curve of FIG. 8 where α=40° as a minimum. The value for $\dot{m}$ was 4.5 g./sec./cm.² Similarly, at 100 amps of arc current the same value of α shows the maximum $\dot{M}$ is increased to about 36 grams per minutes. The value for $\dot{m}$ was 4.5 g./sec./cm.².

This effect is relatively independent of $\dot{m}$, which is the mass flow density referred to the annular nozzle orifice 6. This is given by the ratio $\dot{M}/A$ where A is the orifice area, and can be shown to be approximately proportional to the injected gas velocity (see Example II). The following table illustrates the effect of $\dot{m}$ on α for a fixed arc current of 150 amps and a fixed total mass flow $\dot{M}$ of 12 grams per minute utilizing argon.

$\dot{m}$ (g./sec./cm. ²)	α (degrees)
2.5	83°
5.0	86°
20.0	85°

Within experimental error the value of α can be taken as having remained unchanged for a nearly tenfold increase in $\dot{m}$.

Thus when $\dot{M}$ is held below the maximum value for efficient injection, it is possible to adjust $\dot{m}$ to its optimum value for maximum energy transfer to the gas without changing α, i.e., without disturbing the degree of penetration of the feed into the arc column.

EXAMPLE IV

A further example, in which the FCC is used to energize a stream of fluid which is then mixed with a vapor stream emerging from a vaporizing refractory solid anode, in accordance with the drawing of FIG. 4, is illustrated by the following two tests.

1. An arc was struck between a cathode and nozzle assembly, constructed as in FIG. 4, and a graphite rod, serving as a consumable anode. The graphite rod in this example was 1 inch in diameter and 18 inches long. During operation it was fed forward between slidable contact brushes at a rate equal to the vaporization rate at the anode crater, so as to maintain a constant arc gap. The brushes are used to join current from the power supply to the anode. It is also convenient to rotate the anode so as to maintain uniform consumption of the anode.

The arc configuration used in this experiment was one in which the anode and cathode axes are inclined at 45° to each other. This, however, is not critical and we have operated at angles ranging from 0° to 150°. It is, however, preferable, when streams of plasma are energized at both anode and cathode, to incline the axes of the two electrodes so that the two jets merge smoothly into a single jet of mixed fluids.

The gas injected via the cathode nozzle was nitrogen so that the effluent stream contained carbon and nitrogen, chemically combined.

In the second test of this modification the anode consisted of a solid rod, 1 inch in diameter and 20 inches long, consisting of a mixture of 34 percent carbon and 66 percent boric oxide. These ingredients had previously been mixed with a binder, extruded, and baked to form a hard, homogeneous electrically conducting rod, in accordance with well-known procedures. The gas injected via the cathode nozzle was nitrogen, so that the effluent jet consisted initially of a mixture of boric oxide vapor, carbon vapor and nitrogen, from which issued boron nitride and carbon monoxide.

The operating parameters for both of these tests were as follows:

	Test 5	Test 6
Cathode gas	nitrogen	nitrogen
Anode composition	100% carbon	34% carbon + 66% boric oxide
Arc current	200 a.	50 a.
Arc voltage	120 volts	160 volts
Arc gap	3 cm.	2 cm.
Nitrogen flow rate	15 g./min.	12 g./min.
Anode feed rate	1 inch/min.	1 inch/min.
Anode rotation rate	1 rev. per. sec.	1 rev. per. sec.

EXAMPLE V

In place of the vaporizing anode of Example IV an arrangement using the porous anode assembly (FTA) in conjunction with the FCC has also been operated successfully for heating gases with high efficiency. The arrangement used is shown in the drawing of FIG. 5. Here also the configuration involving a 45° angle between electrodes is shown, although the device has been operated at all angles between 0° and 135°.

The porous anode used in these tests was fabricated by hot-pressing spherical tungsten powder having a size range of 170 to 200 mesh, and sintered to a density approximately 70 percent of the density of solid tungsten. The procedures used are well known.

The tests were run, using argon gas injected through both cathode nozzle and porous anode, both streams merging to form a single argon plasma jet.

The following tabulation shows the ranges of operating parameters for which stable continuous operation was demonstrated.

arc current	50 to 300 a.
arc voltage	30 to 180 volts
arc gap	1 to 15 cm.
cathode gas mass flow rate	0.5 to 40 g./min.
cathode nozzle orifice area	2.1 to 4.8 mm. ²
anode gas mass flow rate	10 to 80 g./min.

The values of the parameters in the above list are those actually measured in the tests and do not represent limits of operability.

A specific list for a typical test is the following:

	Test 7
arc current	200 a.
arc voltage	48 volts
arc gap	3 cm.
cathode gas mass flow rate	15 g./min.
cathode nozzle orifice area	3.2 mm. ²
anode gas mass flow rate	40 g./min.

The preceding specific embodiments are illustrative of the practice of the invention. It is to be understood, however, that other expedients known to those skilled in the art may be performed without departing from the spirit of the invention.

We claim:

1. A process of energizing a fluid medium by means of an arc discharge between an anode and a cathode having a conical tip, said arc discharge forming a contraction of the current-carrying area in the transition region in the vicinity of said cathode, the points of inflection of said contraction of the current-carrying area forming, when extended, an angle α , which comprises establishing an arc discharge between said anode and said cathode, forcefully projecting a fluid medium along said conical tip of said cathode into and through said contraction of the current-carrying area in the transition region in the vicinity of said cathode at a mass flow density at substantially constant flow rate which is at least sufficient to effect a rise in the temperature of said arc column at a con-

stant current level and below a total fluid medium convection rate at substantially constant mass flow density which is sufficient to reduce the angle α below 40° at a constant current level and recovering said energized fluid medium.

2. The process of claim 1 wherein the essential entirety of said fluid medium is projected into said arc column through said contraction zone in its region of maximum convergence.

3. The process of claim 1 wherein said fluid medium is chemically reactive.

4. The process of claim 1 wherein said fluid medium is a single gaseous medium.

5. The process of claim 1 wherein said fluid medium is a mixture of at least two gases.

6. The process of claim 1 wherein said fluid medium is a mixture of at least one liquid dispersed in at least one gas.

7. The process of claim 1 wherein said fluid medium is a mixture of at least one finely divided solid dispersed in at least one gas.

8. The process of claim 1 wherein said fluid medium is a mixture of at least one finely divided solid and at least one liquid dispersed in at least one gas.

9. The process of claim 7 wherein said fluid medium is a mixture of a finely divided solid selected from the group consisting of oxides of metals, and metalloids, dispersed in a gas-containing ammonia.

10. The process of claim 7 wherein said fluid medium is a mixture of finely divided carbon, and a finely divided solid selected from the group consisting of oxides of metals and metalloids, dispersed in a gas-containing nitrogen.

11. The process of claim 1 wherein the anode furnishes a second fluid material energized in the portion of said arc column extending from the anode.

12. The process of claim 11 wherein said second fluid material is projected through a porous anode.

13. The process of claim 11 wherein said second fluid material is generated by vaporization of the anode.

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