219-121.
05-16-72 OR 3,663,792
SR

Fey

[15] **3,663,792**

[45] **May 16, 1972**

[54] APPARATUS AND METHOD OF INCREASING ARC VOLTAGE AND GAS ENTHALPY IN A SELF-STABILIZING ARC HEATER

[72] Inventor: **Maurice G. Fey,** Turtle Creek, Pa.

[73] Assignee: **Westinghouse Electric Corporation,** Pittsburgh, Pa.

[22] Filed: **Mar. 2, 1970**

[21] Appl. No.: **15,597**

[52] **U.S. Cl.** ....219/121 P

[51] **Int. Cl.** B23k 9/00

[58] **Field of Search** ....219/121 P, 75, 76; 313/231

[56] **References Cited**

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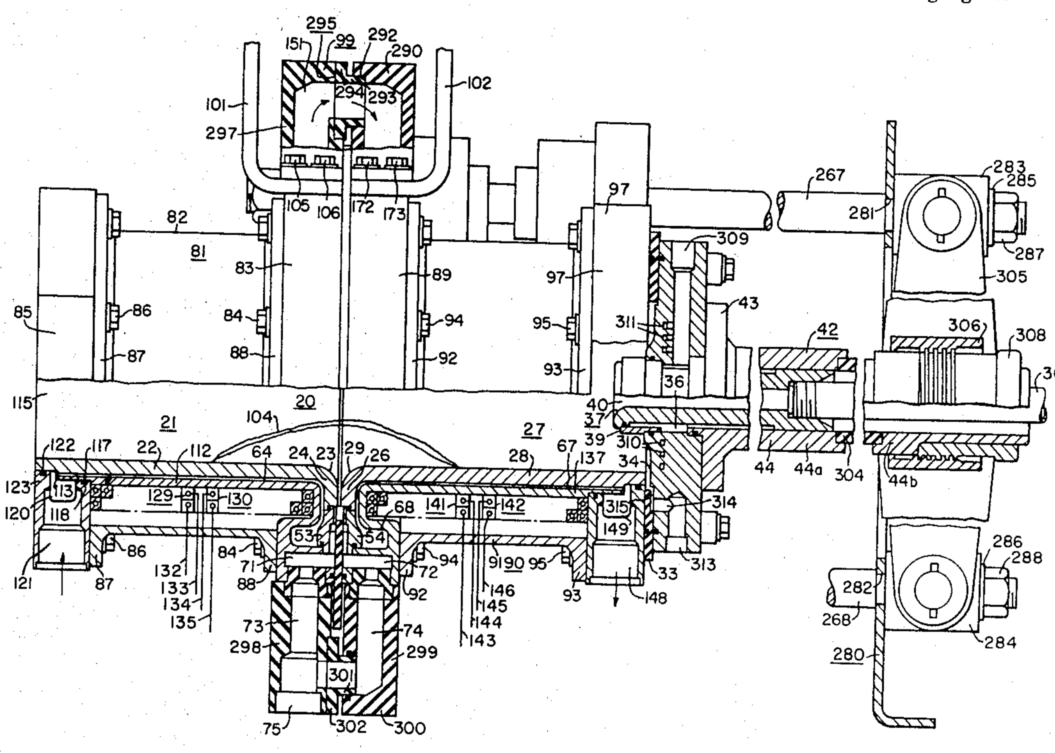
Primary Examiner—J. V. Truhe
Assistant Examiner—Gale R. Peterson
Attorney—A. T. Stratton, C. L. McHale and M. I. Hull

[57] **ABSTRACT**

The method includes admitting gas to be heated at a high velocity into an arc chamber through a narrow gap between spaced electrodes while maintaining across the electrodes a system or backup voltage sufficient at all times to cause electrical breakdown in the narrow gap between electrodes, while producing in the arc chamber a magnetic field having a preselected configuration to produce a beneficial effect or effects on the arc. The arc is periodically elongated by the high velocity gas until it attains such a length that the voltage required to sustain the arc exceeds the breakdown voltage of the gap whereupon the arc returns to the gap momentarily only to be blown out and elongated again. Gas is brought to the vicinity of the outside of the gap through a plurality of tangentially extending slots at spaced intervals around the entire periphery of the gap, whence it passes through the gap, the gas passing through the gap having a radial component and a tangential component. The high tangential flow component provides sufficiently large gas velocity to blow the arc from the electrode gap at a greatly reduced mass flow rate which may be of the order of one-fourth the flow rate which would be required if gas were admitted solely in a radial direction through the gap. The resulting decrease in the volume of gas to be heated results in an increased enthalpy imparted to the heated gas which may be of the order of five times that which can be obtained by purely radial gas admission. A higher arc voltage, results in a greatly improved power factor, and resulting decreased arc current results in an improvement in electrode lifetimes. Centrifugal effects in the arc chamber together with the influence of the magnetic field on the arc establish conditions wherein the arc column virtually follows the center line of the heater.

Apparatus is provided for bringing gas to the gap to produce the aforementioned tangential flow coponent, and generate the magnetic field.

7 Claims, 22 Drawing Figures



Patented May 16, 1972 3,663,792

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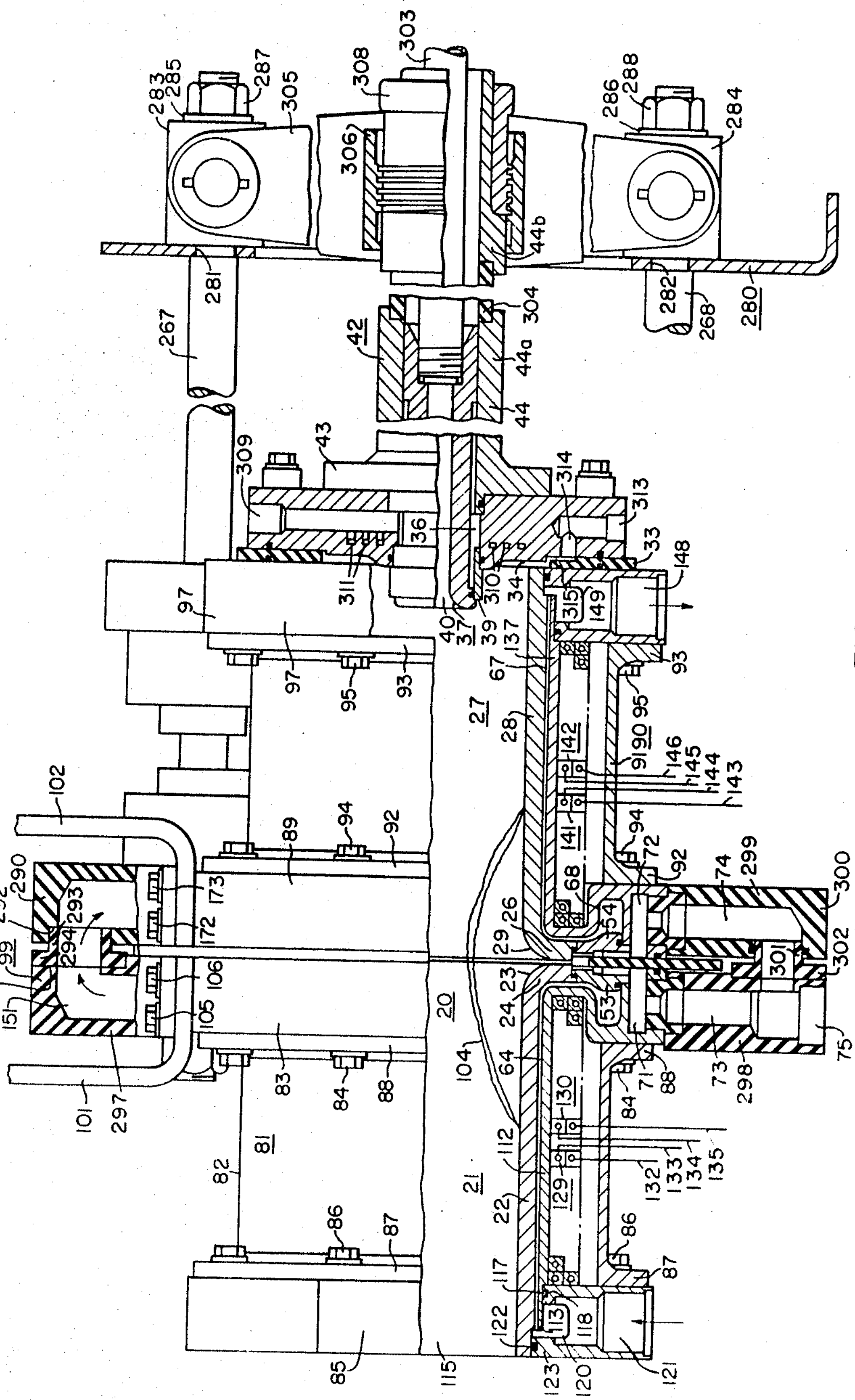


FIG. 1A.

Patented May 16, 1972

3,663,792

7 Sheets-Sheet 2

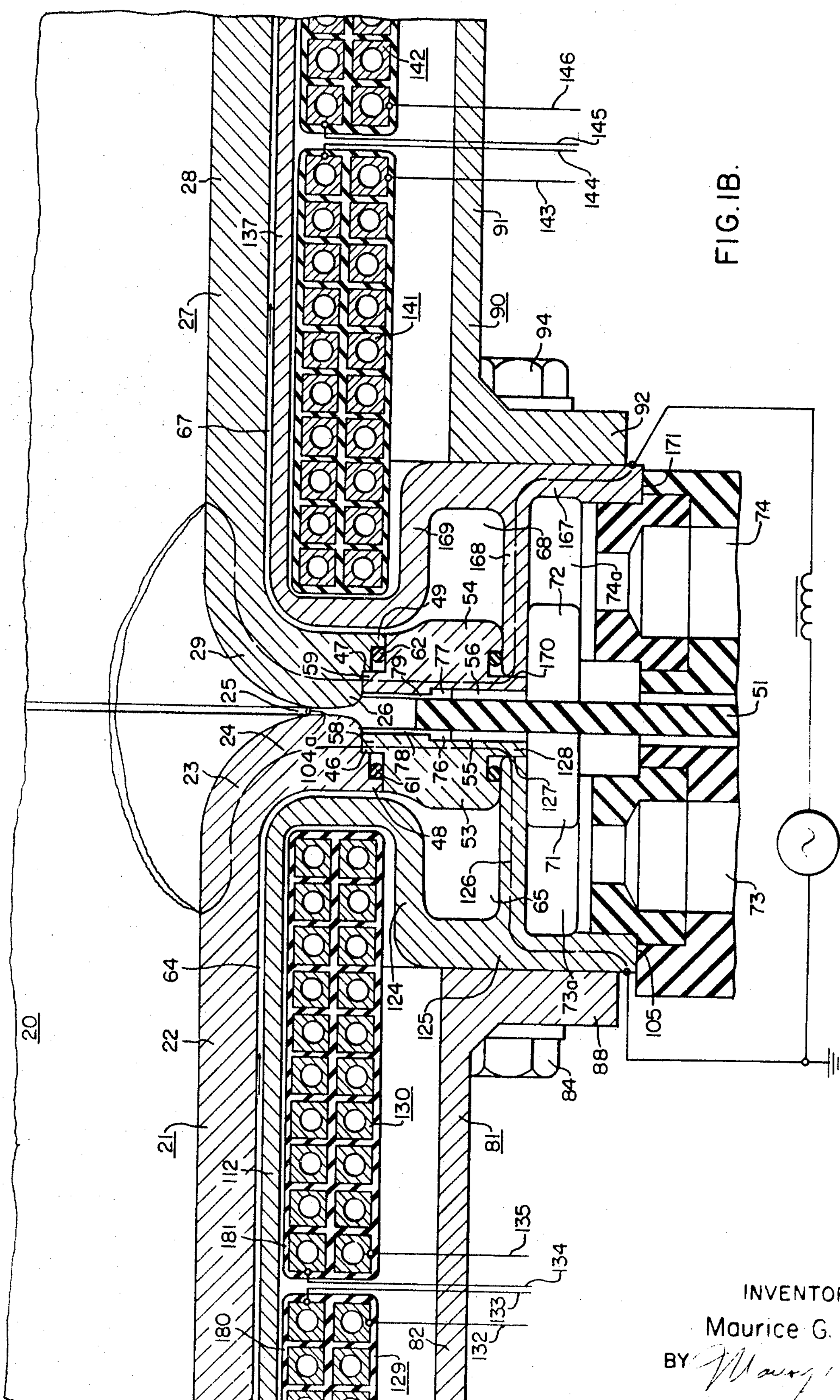


FIG. 1B.

INVENTOR
Maurice G. Fey
BY [signature]
ATTORNEY

Patented May 16, 1972 3,663,792

7 Sheets-Sheet 3

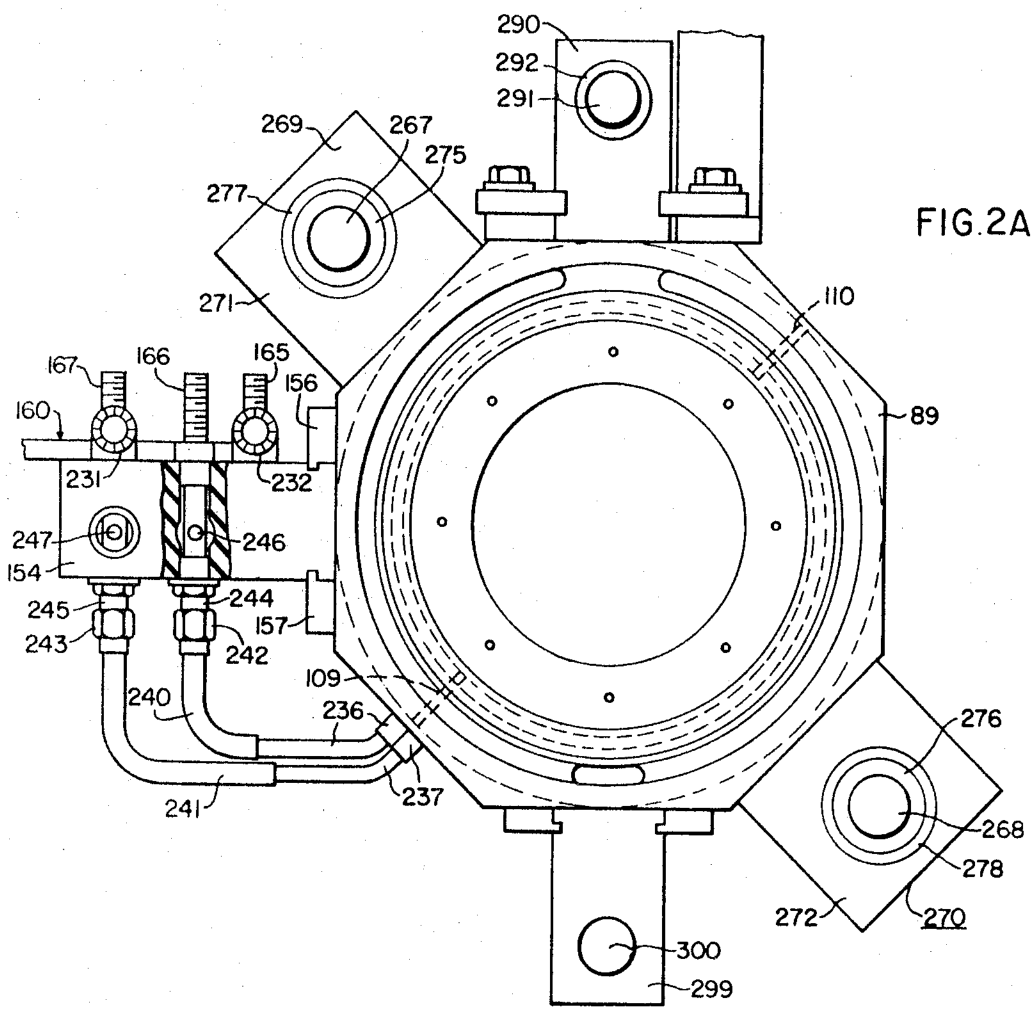


FIG. 2A.

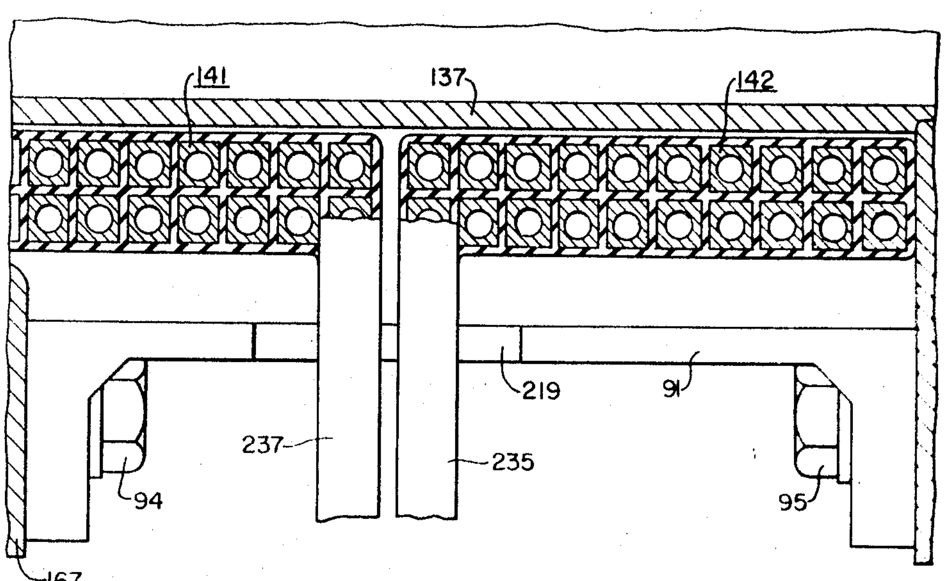
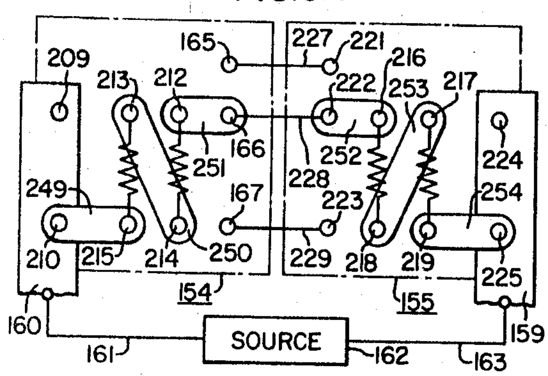


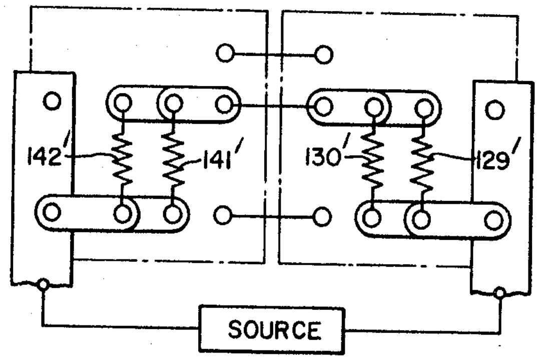
FIG. 2B.

FIG. 3A.



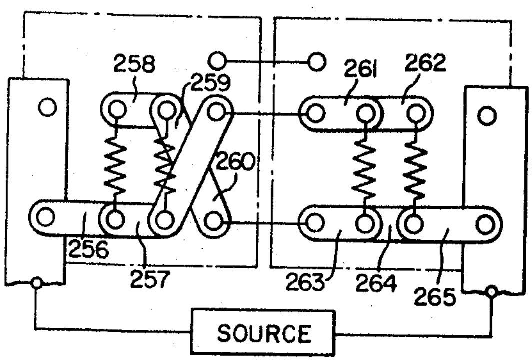
SERIES FIELD COIL CONNECTION

FIG. 3D.



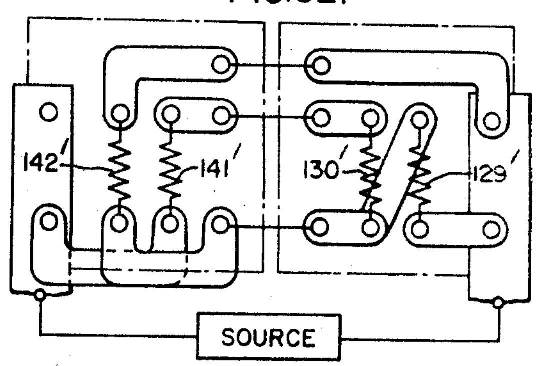
PAIRS PARELLEL
PARALLEL PAIRS IN SERIES

FIG. 3B.



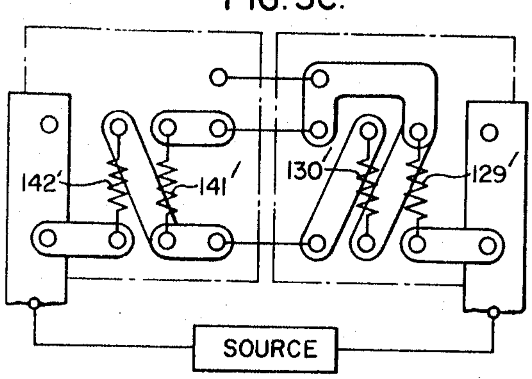
ALL COILS CONNECTED IN PARALLEL

FIG. 3E.



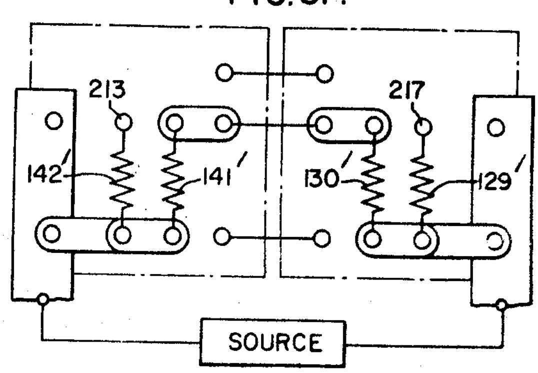
INSIDE COILS SERIES
OUTSIDE COILS PARALLEL

FIG. 3C.



OUTSIDE COILS SERIES
INSIDE COILS PARALLEL

FIG. 3F.



INSIDE COILS IN SERIES
(NO POWER TO OUTSIDE COILS)

PRIOR ART

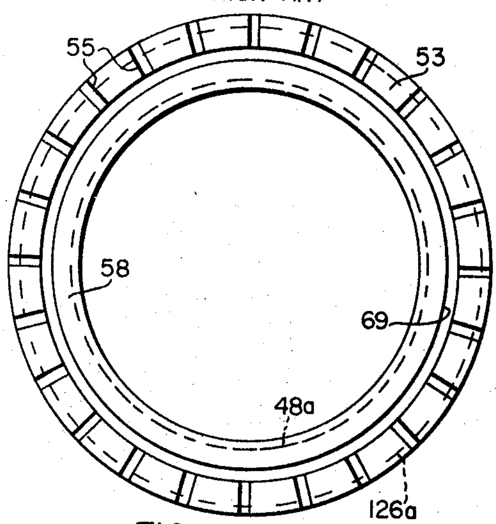


FIG. 4

FIG. 8A

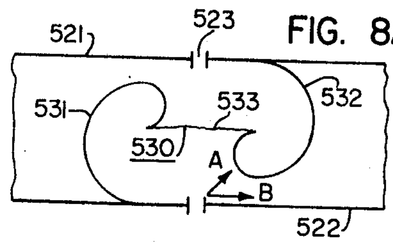


FIG. 8B

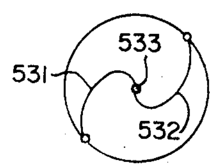


FIG. 5

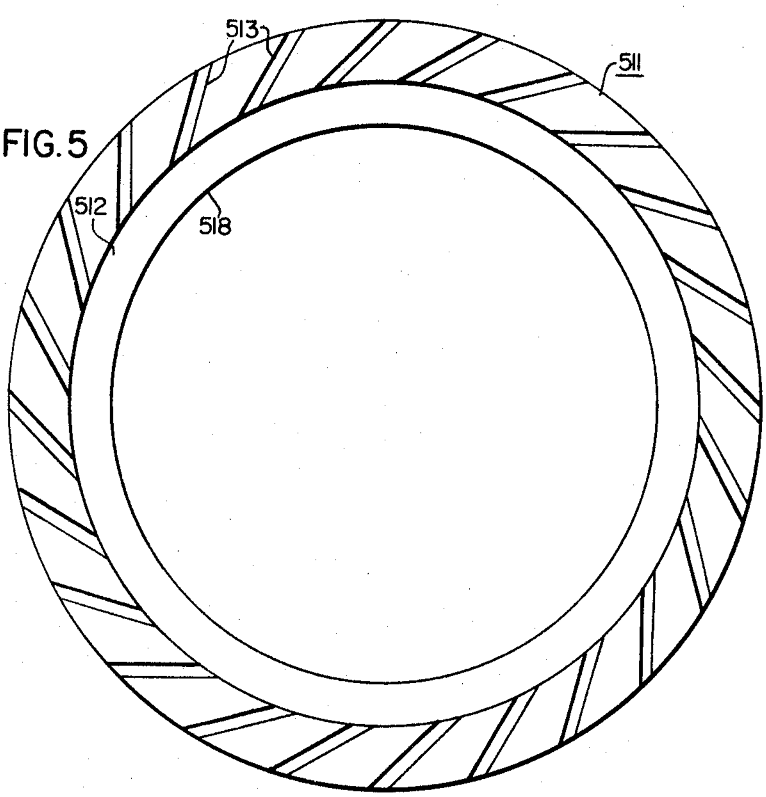


FIG. 6

Patented May 16, 1972

3,663,792

7 Sheets-Sheet 6

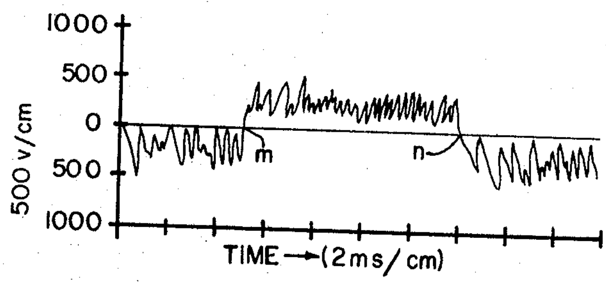


FIG. 7A

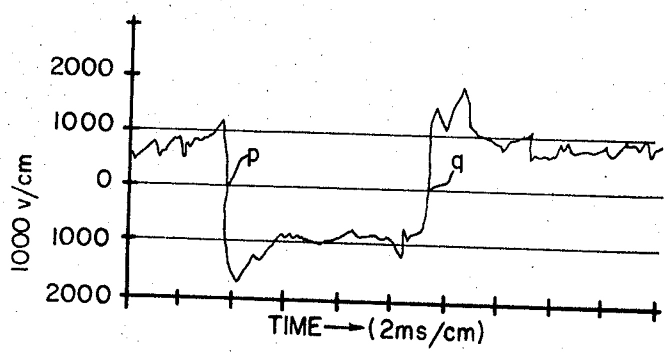


FIG. 7B

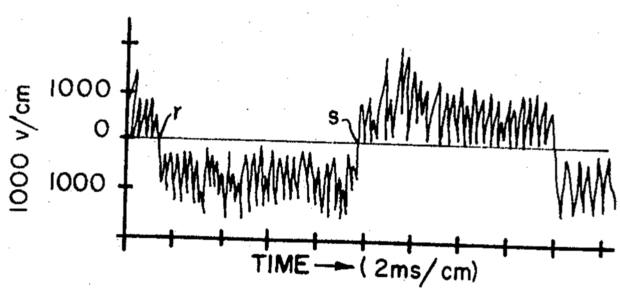


FIG. 7C

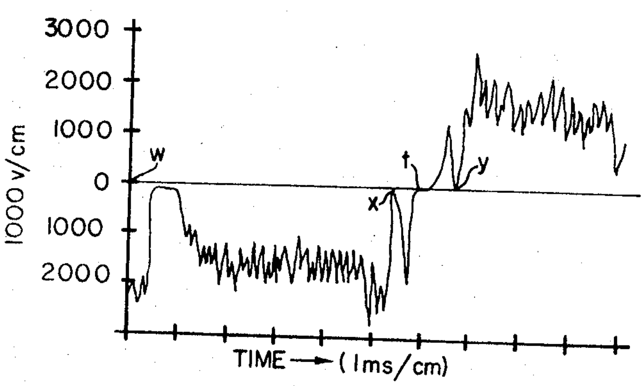


FIG. 7D

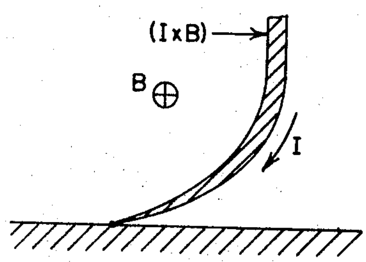


FIG. 9A.

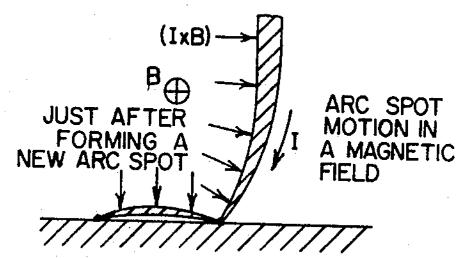


FIG. 9B.

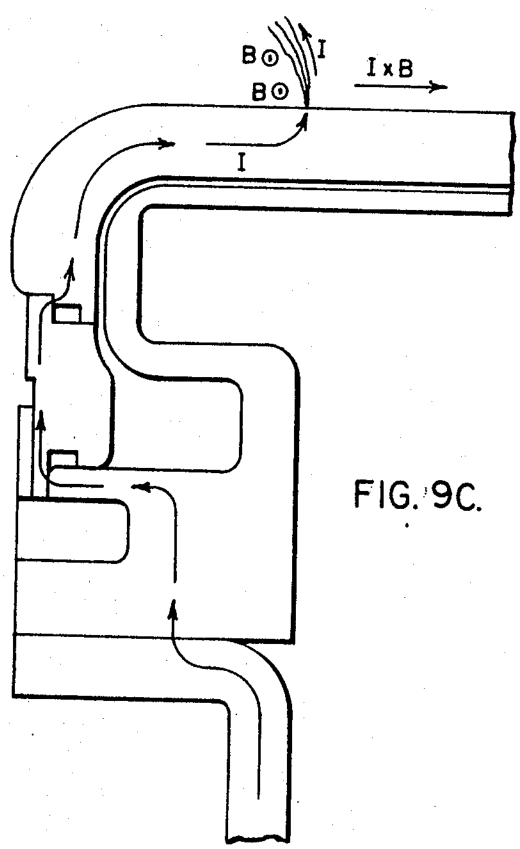


FIG. 9C.

APPARATUS AND METHOD OF INCREASING ARC VOLTAGE AND GAS ENTHALPY IN A SELF-STABILIZING ARC HEATER

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to the copending application of M. G. Fey, C. B. Wolf, F.A. Azinger, Jr., and G.A. Kemeny for "A Recurrent Arc Heating Process," Ser. No. 790,417, filed Jan. 10, 1969, the process described and claimed herein being an improvement over the process described and claimed in the afore-identified copending application; this application is also related to the copending application of C. B. Wolf and M. G. Fey for "Self-Stabilizing Arc Heater Apparatus," Ser. No. 15,446, filed Mar. 2, 1970, both of the aforementioned copending applications being assigned to the assignee of the instant invention.

BACKGROUND OF THE INVENTION

Field of the Invention

The invention lies in the field of devices for utilizing an electric arc to heat a gas or fluid and to the improvement of the prior art processes by providing increased heating efficiency, providing a process which will permit a very high enthalpy to be imparted to the heated gas, and providing a process which permits a larger or greatly improved power factor, and other matters.

Description of the Prior Art

It is old in the art to utilize an electric arc to heat a gas by passing the gas through the arc path in an arc chamber and exhausting the heated gas therefrom. A number of patents have issued in this area including fluid process and apparatus patents, the art being exemplified by U.S. Pat. Nos. 3,296,479; 3,309,550, 3,316,444; 3,343,019; 3,389,189; and 3,445,191, all of said patents being assigned to the assignee of the instant invention.

Other prior art includes U.S. Pat. No. 3,400,070 issued Sept. 3, 1968 to J.T. Naff for "High Efficiency Plasma Processing Head Including a Diffuser Having an Expanding Diameter" which shows radially extending and tangentially extending passageways for bringing gas to an arc chamber; U.S. Pat. No. 3,372,296 issued Mar. 5, 1968 to J.T. Naff for "Arc Plasma Electrode Pair Having A Venturi-Shaped Configuration;" U.S. Pat. No. 3,301,995 issued Jan. 31, 1967 to R.C. Eschenbach et al., for "Electric Arc heating and Acceleration of Gases;" and the arc heating apparatus and method described in Technical Documentary Report No. RTD–TDR–3–4055 dated February 1964, prepared by Speedway Research Laboratory, Indianapolis, Indiana for the AF Flight Dynamics Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, released to the Office of Technical Services, U.S. Department of Commerce, Washington, D.C. for sale to the general public.

In both of the aforementioned copending patent applications gas passes through the gap between electrodes in substantially a radial direction and at generally a uniform gas flow rate around the entire periphery of the annular gap.

SUMMARY OF THE INVENTION

I have discovered that by bringing gas to the vicinity of the outside of the gap substantially around the entire periphery thereof and having the gas moved in a tangential direction until it reaches a position adjacent the outside of the gap, that in addition to there being a tangential flow component of gas through the gap, there is a radial flow component with the result that a sufficiently large gas velocity to blow the arc from the electrode gap is obtained at greatly reduced mass flow rates, so that the lower limit for mass flow rate of prior art apparatus and processes is reduced; that power in the arc can be transferred to a greatly decreased volume of gas thereby raising the enthalpy imparted to the gas to a value several times as great as that previously obtainable. In my processes, I enhance the formation of an arc path having the desired location, length, and points of arc spot attachment to the electrodes by generating a carefully configured magnetic field within the arc chamber. I have further discovered that according to the process of my invention the arc may be operated at a substantially increased voltage with a corresponding decrease in the arc current, providing not only an improved power factor but increased heating efficiency and a reduction in erosion of material from the electrode.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1A, 1B, 2A, 2B, 3A to 3F, 5 and 6 are views of apparatus suitable for practicing the processes of my invention;

FIG. 4 is a view of a portion of prior art apparatus utilizing radially extending slots and a manifold ring to produce gas passage through the gap in a substantially radial direction and is included to demonstrate the contrast between prior art apparatus and the apparatus of the instant invention, particularly FIG. 5, where tangential slots are provided in a manifold ring.

FIGS. 1A, 1B, 2A, 2B, 3A to 3F, and 4 are substantially identical with the apparatus described and claimed in the aforementioned copending application of C.B. Wolf and M.G. Fey for "Self-Stabilizing Arc Heater Apparatus," Ser. No. 15,446, filed Mar. 2, 1970.

FIGS. 7A–7D are graphs illustrating the operation of the apparatus of my invention and illustrating in part processes of the invention;

FIGS. 8A and 8B are side elevational and end views of a typical arc path produced by the tangential and radial components of gas admitted according to the process of my invention; and

FIGS. 9A, 9B and 9C are illustrations of arc spot attachment under the influence of a magnetic field, according to my invention.

DESCRIPTION OF APPARATUS SUITABLE FOR PRACTICING THE PROCESSES

Particular reference is made to FIG. 1A. The arc chamber generally designated 20 is seen to be enclosed by a downstream electrode generally designated 21 having a cylindrical portion 22 of substantial length, a curved portion 23, and a radially extending portion 24 separated by short gap 25 from the radially extending portion 26 of an upstream electrode generally designated 27 having a cylindrical portion 28 and a curved portion 29. An end plate generally designated 32 closes the upstream end of the arc chamber and may be electrically insulated from the upstream electrode by the insulating or metallic disc member 33, there being a space 34 extending around the entire circumference of the adjacent end of electrode 27 and between it and the wall of the end plate 32 for the admission of an additional gas or fluid if desired, in a manner which will become hereinafter more clearly apparent. The end plate 32 has a generally centrally disposed bore or aperture 36 therein through which passes a feed stock tube 37 especially suitable for bringing a particulate solid into the arc chamber 20 but also for bringing a suitable additional gas or fluid. A spacer tube 39 controls the axial position of the admission of the secondary feed stock through passageway 40, it being understood that in practice a number of spacer tubes 39 of different lengths are provided and kept available so that the axial position at which feed stock material is brought in through passageway 40 can be adjusted by substituting a spacer tube of one length for a spacer tube of a different length. Secured to the end plate 32 is a feed tube housing or assembly generally designated 42 having a flange portion 43 formed integrally with an elongated tubular portion 44 composed of portions 44a and 44b separated and electrically insulated from each other by insulating portion or insulating sleeve 304, the flange portion 43 being secured to end plate 32 by peripherally spaced bolts, the bolts not being shown for convenience of illustration.

It is seen that the radially extending portions 24 and 26 of electrodes 21 and 27 are not of uniform thickness throughout. The electrodes have annular shoulders 46 and 47 extending therearound formed by radially extending lips 48 and 49 respectively. The spacing between the electrodes generally designated 21 and 27 and the width of the aforementioned gap 25 are maintained at their desired dimensions by a gap insulating ring 51 composed of electrically insulating material having mounted on each side thereof one of the slotted manifold rings 53 and 54 respectively, each of the manifold rings having a plurality of radially extending slots 55 and 56 thereacross respectively, a view of the slotted manifold rings being shown in FIG. 4 to which particular attention is directed, where for example, slotted manifold ring 53 is shown in elevation having slots 56 therein. It is seen, FIG. 1B, that each of the slotted manifold rings 53 and 54 has an annular ridge or extended portion 58 and 59, respectively, which annular ridge portions 58 and 59 extend to the aforementioned annular shoulders 46 and 47 of the electrodes generally designated 21 and 27, preventing the electrodes 21 and 27 from undergoing axial movement toward each other. A pair of O-rings 61 and 62 provide sealing engagement between the electrodes and the manifold rings, it being recalled that gas or other fluid enters the arc chamber 20 through the slots in the manifold rings and a cooling fluid flows through passageway 64 back of the wall portion 22 which forms the arcing surface of electrode 21 and thence into fluid headers 65, and a cooling fluid such as water flows in passageway 67 back of the wall forming the arcing surface of electrode 27, the passageway 67 for the flow of cooling fluid to conduct heat flux from the arcing surface communicating with the water or fluid header 68 in the upstream electrode assembly in a manner which will be described hereinafter in greater detail.

It is also seen that the slots in the slotted manifold rings extend to and communicate with a pair of chambers 71 and 72 which extend around the entire arc heater and which have gas under pressure supplied thereto through passageways 73 and 74 to be described hereinafter in greater detail, passageways 73 and 74 communicating with a single gas inlet 75 as shown, (FIG. 1A).

Slots 55 and 56, FIG. 1B, do not extend radially across the entire manifold rings, but terminate in fluid heater portions 76 and 77.

From fluid headers 76 and 77 gas or fluid passes through very narrow annular gaps 78 and 79 respectively into the space outside the electrode gap 25, and thence through the electrode gap.

It will be understood, and it will be explained more fully hereinafter, that the structures forming and enclosing passageways 73 and 74 are separable from each other when the arc chamber 20 is opened, without the necessity of doing anything more than slipping one piece out of another, as will be seen.

Generally speaking, the aforementioned downstream electrode generally designated 21 may be considered part of a downstream electrode assembly generally designated 81 including a field coil case 82 generally semi-cylindrical in shape and having at the ends thereof flange portions 87 and 88, flange portion 87, FIG. 1A being secured to a polygonal plate 85 by peripherally spaced bolts 86, flange portion 88 being secured to polygonal plate 83 by peripherally spaced bolts 84, FIG. 1A, and the upstream electrode generally designated 27 may be considered part of an upstream electrode assembly generally designated 90, having a field coil case 91 which it is understood is formed in two semicylindrical sections, the field coil case 91 having flange portions 92 and 93 at the ends thereof secured by peripherally spaced bolts 94 and 95 to polygonal plates 89 and 97 respectively.

Paying particular attention to the insulated quick disconnect manifold generally designated 99, FIG. 1A, which will be described in greater detail hereinafter, the quick disconnect manifold, or more specifically the passageways thereof, pass through holes in the plates 83 and 89. The terminal connections 101 and 102 are provided for bringing current to the electrode which forms the arc 104 therebetween and shown in an elongated form FIG. 1A such as that which might occur shortly before the arc became so elongated that breakdown occurs in the narrow gap between electrodes. From terminal 101 a current path to electrode 21 is provided as follows: it is seen, FIG. 1B, that back of the electrode 21 and spaced from the outside wall (of larger diameter) thereof to define fluid flow passageway 64 is an additional cylindrical member 112 composed of electrically conductive material and which forms part of the electrode assembly, member 112 having a U-shaped portion 124 with a radially extending flange portion 125 terminating in edge or surface 105, and an axially extending annular flange portion 126 the end or edge 127 of which is in firm electrical contact with slotted manifold ring 53. As previously stated, manifold ring 53 is in firm electrical contact with electrode 24 where annular lip or ridge portion 58 engages shoulder 46 of the electrode. Surface 105 is tightly clamped against terminal 101 by bolts 105 and 106, FIG. 1A. The current path to the arcing surface of electrode 21 then, is through terminal 101, radially extending flange portion 125, axially extending flange portion 126, manifold ring 53 including lip portion 58 thereof, to radially extending portion 24 of the electrode.

In like manner, bolts 172 and 173, FIG. 1A, firmly clamp terminal 102 against the edge 171 of radially extending flange portion 167 of electrically conductive member 137 of the upstream electrode assembly; thence current flows through aforementioned flange portion 167, through axially extending flange portion 168, through the firm electrical contact at 170 between portion 168 and manifold ring 54, through the ring 54 including the annular lip portion 59 thereof, to the radially extending lip portion 26 of electrode generally designated 27.

It will be understood that the structure defining gas inlets 73 and 74 does not extend around the entire arc heater, the circumferentially extending gas headers 71 and 72 opening into all the slots in the two manifold rings, so that clamping the terminals 101 and 102 against surfaces 105 and 171 respectively as described above at another position around the circumference of the heater as indicated in FIG. 1A may be conveniently accomplished. It will be further understood that when the two electrode assemblies are clamped together to seal the arc chamber in a manner to be hereinafter described, further tightening of contacting electrically conducting surfaces may occur.

As previously stated, both of the manifold rings 53 and 54, are annular, extend around the entire perimeter of the arcing chamber and are in firm electrical contact with the adjacent end of the electrodes respectively at substantially every point around the entire perimeter of the electrodes, providing an ample current path for the arc current which may attain a value of several thousand amperes.

In further detail, the downstream electrode assembly generally designated 81 includes the field coil case 82 which as aforementioned is in two semicylindrical sections, the break between sections being shown at 109 and 110 in dashed lines in FIG. 2A. The aforementioned fluid passageway 64 in electrode 21 is as aforementioned located between the wall portion of the electrode 22 which forms the arcing surface and an additional metallic member 112 having the shape shown in FIG. 1A with a portion 113 of reduced outside diameter at the end thereof near the exhaust opening 115, where heated gas exits from the arc chamber 20. The outside surface of portion 113 makes close fitting engagement with an adjacent inner cylindrical surface of the aforementioned polygonal plate 85. O-rings seated in an annular groove provides fluid tight seals where needed. One such O-ring 122 seated in annular groove 123 provides a fluid tight seal between the inner cylindrical surface of the plate 85 and the adjacent outside wall of electrode portion 22. The aforementioned fluid passageway 64 communicates at the upstream end thereof with a fluid header 120 which in turn communicates with fluid inlet 121.

As aforementioned, the end of the member **112** in the area of the gap **25** between electrodes is seen to have a generally U-shaped portion **124**, having a radially extending flange portion **125** which in turn has the radially spaced and axially extending flange portion **126** which closely abuts against and snugly fits an extending rim or flange portion **128** of the aforementioned slotted manifold ring **53**, firmly securing the manifold ring against movement. Within the cylindrical space between member **112** and the wall **82** of the field coil case there are disposed two magnetic field coils, each of the coils consisting of a number of turns of hollow conduit, the coils of the downstream electrode being designated **129** and **130**, the coil and coil leads being completely encompassed by electrically insulating material, the insulation, not being shown for convenience of illustration in FIG. 1A but the coil housing being shown at **180** and **181**, FIG. 1B. The coil **129** in FIGS. 1A and 1B has leads **132** and **133** symbolizing means for making electrical connection thereto which should be considered with FIGS. 3A–3F inclusive, but it will be understood that the current to the field coil flows through conduit extensions, which are not only connected to fluid outlet and fluid inlet means but by way of the terminal arrangements of FIGS. 3A–3F to selected terminals of a source of potential. The coil generally designated **130** has leads to the ends thereof designated **134** and **135** provided to assist in describing the electrical connection of the coil, but it will be understood that the field coil **130** is composed of turns of hollow conduit; the conduit extensions serve not only for bringing cooling fluid to and from the coil, but provide electrical connections for bringing an energizing current to the field coil, as will be seen more clearly hereinafter in connection with a description of FIG. 3A–3F.

The upstream electrode assembly designated **90** is similar to the downstream electrode assembly, the fluid passageway between the aforementioned wall portion **28** of electrode **27** and the member of electrically conductive material **137** being shown at **67**. Within the upstream electrode assembly **90** there are two field coils generally designated **141** and **142**; conduit extensions to both the coils bring cooling fluid to and from the coils and supply energizing current thereto, but to assist in understanding the invention, coil **141** is shown as having symbolic leads **143** and **144** to the ends thereof and coil **142** has symbolic leads **145** and **146** to the ends thereof.

Cooling fluid for both electrodes enters through fluid inlet **121** and header **120** which it is understood extends around the entire electrode structure from thence through the cylindrical fluid passageway **64** in the downstream electrode, thence into fluid header **65** which passes around the entire downstream electrode assembly, thence through the passageway **151** in the quick disconnect manifold generally designated **99** and following the path of the arrows therein, thence into fluid header **68** which extends around the entire upstream electrode assembly, thence through passageway **67** in the upstream electrode, thence into fluid header **149** which extends around the entire upstream electrode, fluid from fluid header **149** passing through the fluid outlet **148**.

Particular reference is made to FIG. 2A. Each electrode assembly has an axially extending block of insulating material secured to the polygonal plates at the ends of the electrode assembly, the matching plate for the downstream electrode assembly not being shown for simplicity of illustration, but it will be understood that it extends between polygonal plates **85** and **83**. In FIG. 2A, the insulating block **154** for the upstream electrode assembly is shown, block **154** being secured to polygonal plate **89** by two retaining blocks **156** and **157** at the end thereof, centrally disposed along the axis of the electrode, it being understood that retaining blocks **156** and **157** are secured to the octagonal plate **89** by bolts, not shown for convenience of illustration. The other end of the block of insulating material **154** is likewise secured to polygonal plate **97**, FIG. 1A, by two retaining blocks similar to **156** and **157**, but not shown for convenience of illustration, and having bolts, not shown, which pass therethrough into threaded bores in the polygonal plate **97**.

Particular reference is made to FIGS. 3A–3F where plan or side elevational views of the blocks for both the upstream and downstream electrode assemblies are shown, the apparatus being suitable for mounting in either position. In FIGS. 3A–3F the insulating block for the upstream electrode as aforementioned is **154** and the insulating block for the downstream electrode assembly is **155**. It is seen that each of the blocks has an electrical terminal strip secured thereto, the terminal strip for block **155** being shown at **159**, FIG. 3A, and the terminal strip for block **154** being shown at **160**, FIG. 3A, and in FIG. 2. Terminal strip **160** is connected by lead **161** to a terminal of one polarity of a source of potential shown in block form at **162** for energizing the field coils the terminal of other polarity of the source **162** being connected by lead **163** to the aforementioned terminal plate **159** of block **155**. The studs shown as extending from terminal plate **154** it is understood are illustrative and includes studs **165**, **166** and **167**, all also shown in FIG. 2A, as well as, FIG. 3A, studs **212**, **213**, **214**, **215**, **209**, and **210**.

The studs on insulating block **155** include **221**, **222**, **223**, **216**, **217**, **218**, **219**, **224** and **225**. It is seen that the latter two studs **224** and **225** are connected to terminal plate **159**, whereas studs **209** and **210** of insulating block **154** are connected to the electrical terminal strip **160**.

As previously stated, the chamber of the arc heater is adapted to be opened by moving the upstream electrode on ball bearings away from the downstream electrode. Lead connection **227**, FIG. 3A, between studs **165** and **221** symbolizes a permanent electrical connection therebetween, while lead **228** between studs **166** and **222** symbolizes a permanent electrical connection therebetween for completing the electrical circuit, and lead **229** symbolizes a permanent electrical connection between studs **167** and **223** for completing an electrical circuit therebetween. In actuality secured to terminals **221**, **222** and **223** are rigid conduit portions extending substantially parallel to the longitudinal axis of the arc heater, which conduit portions are engaged by contact finger assemblies secured to terminals **165**, **166** and **167** respectively, two of these conduit finger assemblies being shown at **231** and **232**, FIG. 2A. Finger assembly **231** engages conduit extension **229** while finger assembly **232** engages **227**. As previously stated, whereas for convenience of illustration the four field coils shown in FIG. 1 are shown as having symbolic electrical leads thereto so that the electrical circuit for energizing the coils can be traced, in actuality extensions of the conduit which forms the field coils serve for bringing current to the coils as well as for bringing cooling fluid. Two of these conduit ends or extensions are shown in FIG. 2A at **236** and **237**, the conduit portions adjacent the electrode assembly being electrically insulated. The coil housings for the two electrode assemblies are each in two semicylindrical sections with gaps therebetween shown at **109** and **110**, FIG. 2A, one of the gaps also being shown in FIG. 2B. At about the axial center of the cylindrical coil housings at the gap, there are symmetrical cutaway portions on the adjoining edges of each of the semicylindrical portions, one of the cutaway portions being shown at **219**, FIG. 2B, to provide sufficient space for the passage of four conduits representing extensions of the two field coils of the electrode assembly, two of the conduit extensions being shown at **237** and **235**, FIG. 2B. The conduits **236** and **237**, FIG. 2A, may correspond electrically to the leads **143** and **144** respectively, FIG. 1A. By extensions **240** and **241** respectively which are also composed of electrically conductive material, threaded connections are made at **242** and **243** respectively to the ends of two tubes **244** and **245** respectively which extend through the block of insulating material of the upstream electrode assembly, the block as aforementioned being designated **154**. A portion of the block is shown broken away to show fluid manifolds at **246** and **247** for bringing a cooling fluid into the coils for circulating therein and for exhausting cooling fluid from the coils generally designated **141** and **142** after the fluid has circulated therethrough. The manifolds **246** and **247** extend through the block for fluid connections to both of the aforementioned coils. It will be understood that where substantially pure water is used as the cooling fluid the electrical conductivity is very low and since the block is composed of electrically insulating material, no further insulation is necessary. The two additional conduits connected to the inner and outer turns at the left-hand end of field coil 142, FIG. 1A these conduit extensions outside of the arc heater not being shown for convenience of illustration, as well as opening into manifolds 246 and 247 also have the ends thereof extending in the form of threaded terminal studs from the insulating block 154. In FIG. 2A, the three threaded studs shown 165, 166 and 167 are provided for electrical connection to three threaded studs 221, 222 and 223 respectively on the insulating block of the downstream electrode assembly and it will be understood that none of the threaded studs 167, 166 and 165 are electrically connected by means other than the terminal board to either of the conduits which form the coil extensions, that is, conduits 236 and 237. In FIG. 3A, studs or terminals 213 and 215 represent direct electrical connections to the conduits from the field coil generally designated 142, and threaded studs 212 and 214 represent direct electrical connections to the two conduit extensions which form the ends of field coil generally designated 141, both field coil 141 and coil 142 being part of the upstream electrode assembly. Accordingly, since a view of FIG. 2A is a view at the downstream end looking toward the end plate at the far end of the upstream electrode assembly, threaded studs 212 and 214 would lie back of studs 166 and 167 which appear in the drawing of FIG. 2A and threaded studs 213 and 215 would lie back of the aforementioned studs 212 and 214, with the threaded studs 209 and 210 which are secured to electrical terminal plate 160 lying still further back at a more remote axial position along the length of the electrode assembly.

The aforementioned terminal block 155 for the downstream electrode assembly as aforementioned has three threaded studs 221, 222, and 223 substantially radially aligned with corresponding three studs on insulating block 154. In addition, insulating block 155 has threaded studs 216, 217, 218 and 219 which represent direct electrical connections to the conduit extensions which form the ends of the field coils generally designated 129 and 130, of the downstream electrode assembly. Terminals 216 and 218 are directly connected electrically to the conduit extensions emerging from the leftmost inner and outer turns of field coil 130, and for the purpose of tracing the electrical circuit, terminal 216 may be thought of as corresponding to lead 135, FIG. 1, and terminal 218 may be thought of as corresponding to lead 134, FIG. 1. In like manner, terminals 217 and 219 on insulating block 155 are directly connected to the conduit extensions from the field coil generally designated 129 of the downstream electrode assembly, and for the purposes of following the electrical circuit, terminal 217 may be thought of as corresponding to lead 132, FIG. 1A, and terminal 219 may be thought of as corresponding to lead 133, FIG. 1A. As previously stated, the insulating block 155, FIG. 3A, also has threaded studs 224 and 225 extending from the electrical terminal strip 159 connected to a terminal of one polarity of source 162.

The link arrangement of FIG. 3A shows all four field coils of the two electrode assemblies connected in series, with link 249 interconnecting terminals or studs 210 and 215, link 250 interconnecting studs 213 and 214, link 251 interconnecting studs 212 and 166, link 252 interconnecting studs 222 and 216, link 253 interconnecting studs 218 and 217, and link 254 interconnecting studs 219 and 225, completing an electrical circuit wherein all of the coils are connected in series between terminal plate 160 and terminal plate 159.

Particular reference is made to FIG. 3B wherein links effectively connect all four coils in parallel across the source of potential 162. Where links cross each other, spacer washers, not shown, are used to displace one link in height from the other so that electrical contact will be avoided. It will be understood that nuts secure the various links in the various figures to the various threaded studs. In FIG. 3B, link 256 connects stud 215 to stud 210, whereas link 257 connects stud 215 to stud 214, and link 259 connects stud 214 to stud 166. Link 258 interconnects studs 213 and 212, while link 260 interconnects studs 212 and 167. Link 261 interconnects studs 222 and 216, whereas link 262 interconnects studs 216 and 217. Link 263 interconnects studs 223 and 218, link 264 interconnects studs 218 and 219, and link 265 interconnects studs 219 and 225. It is seen that an electrical circuit is formed in which all of the coils are interconnected in parallel with the full voltage from source 162 applied across each one of the magnetic field coils.

Particular reference is made to FIG. 3C wherein an electrical circuit is shown in which the outside coils of the two electrode assemblies symbolized by 142′ and 129′ are connected in series and the inside coils of the two electrode assemblies symbolized by 141′ and 130′ are connected in parallel. The term "outside coil" as employed herein refers to that field coil of the two field coils of each electrode assembly which is most remote from the gap between electrodes.

In FIGS. 3C through 3F, the threaded studs all have positions which correspond to the studs described hereinabove in detail with respect to FIG. 3A and FIG. 3B, and the result of the link arrangement shown in each of the drawings 3C–3F is indicated in the drawing legend showing the resulting connection of the coils, so that it is believed the connections will be clear to one skilled in the art and the electrical circuits will be readily apparent from the studs and the link connections shown.

The purpose of the terminal boards in which the connections of the coils may be altered to provide a wide variety of connections including connections in which one coil of each pair is not energized at all, is to permit maximum versatility in adjusting the magnetic field strength and magnetic field configuration within the arc chamber to insure rotation of the arc at the desired speed whatever the nature of operating conditions in the arc chamber, including rotation of the arc no matter how extended it becomes and how remote the points of arc spot attachment are from the gap between electrodes, and also, for example, to permit adjustment of the force or forces exerted on the arc by the magnetic field as a particulate solid is admitted through the feed opening 40 in the feed tube extending through the end plate which closes the upstream end of the electrode. It will be understood that a particulate solid admitted through this feed tube has the effect of increasing the density of the gas in the arc chamber or increasing the viscosity, which increase may result in a slowing of the arc rotation below that which would normally be obtained in the absence of a particulate solid introduced into the arc chamber, and that it may be desirable to adjust the magnetic field strength of the field or fields which exert forces on the arc to cause the proper movement thereof.

Adjustment of the magnetic field or fields may also be desirable where a switch is made from a direct current arc to an alternating current arc. In general, where direct current supplies the arc, the cyclic process of arc elongation and breakdown in the gap may occur many times per second, whereas when alternating current supplies the arc, the return of the arc to the gap may occur once per alternation following current zero, and where the power supply frequency is 60 cycles per second, the arc may return to the gap 120 times per second. Depending upon the velocity and to some extent on the mass flow rate of gas admitted through the gap, the length of arc elongation may vary, and it may be desirable to adjust the magnetic field strength and/or configuration.

As previously stated, the upstream electrode assembly is mounted on linear ball bearings so that when released from its clamped position, it may be moved away from the downstream electrode assembly to provide easy access to the arc chamber 20. Particular reference is made to FIG. 2A. Tie rods 267 and 268 extend in directions generally parallel to the longitudinal axis of the arc heater, the tie rods 267 and 268 also being shown in FIG. 1A. The bearing block assemblies are generally designated **269** and **270**. Each bearing block assembly includes a ball bearing block **271** and **272** respectively, these being secured to the outside of the arc heater by four bolts extending through each of the blocks, the bolts not being shown for convenience of illustration the bolts extending into threaded bores, not shown, in the outside wall of the arc heater and retaining the blocks in position thereon. Each block has therein a plastic bearing holder **277** and **278** respectively which generally speaking is made in square form and turned around on the ends, the bearings themselves being shown in FIG. 2A and designated **275** and **276** respectively.

As seen in FIG. **1**, there is a support bracket generally designated **280** for the remote ends of the tie rods, these being of reduced diameter and fitting snugly in bores **281** and **282** of the support bracket and having a pair of trunnions **283** and **284** on extensions thereof on the right-hand side of support bracket **280**, as seen in FIG. **1**, these trunnions **283** and **284** being provided for purposes to be made hereinafter more clearly apparent. On the right-hand end of the rods **267** and **268** as they emerge from the trunnions, which ends are threaded, there are washers **285** and **286** respectively and nuts **287** and **288** respectively.

Paying particular attention to FIG. 2A, as previously stated the upstream and downstream electrodes assemblies are easily separable, and there is a quick disconnect fluid manifold having one portion secured to the downstream electrode assembly and one portion secured to the upstream electrode assembly, and there is also a quick disconnect gas inlet structure with one portion secured to the downstream electrode assembly and the other portion secured to the upstream electrode assembly. In the portion **290** of the aforementioned quick disconnect manifold which is secured to the upstream portion of the arc heater, there is an annular opening **291** and a portion of this opening has an outside diameter of larger dimension forming the bore **292** upon which, when the entire disconnect manifold is assemblied and the two electrodes are as close together as the insulating plate **51** will permit, engages the tubular member **293** having an annular flange portion, the surface **295** of which firmly fits against the adjacent portion **297** of the quick disconnect manifold, which portion **297** is secured to the downstream electrode assembly. Whereas both portions **290** and **297** are shown as composed of electrically insulating material, one of these portions may be composed of conductive material, since the water, which serves as the cooling fluid, is fairly pure and has a low electrical conductivity. O-rings, not shown for convenience of illustration, seated in grooves, not shown for convenience of illustration, form fluid tight seals between member **293** and portion **290**, and between flange portion **294** and portion **297**.

Paying particular attention to the gas inlet arrangement shown in the lower portion of the drawing of FIG. 1, there is portion **299** secured to the upstream electrode assembly and a portion **298** secured to the downstream electrode assembly; whereas both of these portions are shown as composed of electrically insulating material, only one portion need be composed of electrically insulating material. The portion **299**, FIG. 2A, is seen to have a cylindrical opening therethrough designated **300** through which passes a tubular member **301**, FIG. 1, having a flange portion **302** which is forced into firm engagement with an adjacent portion of the general structure **298** which is secured to the downstream electrode assembly, and when the electrodes are joined to form the arc chamber, the tubular member **301** passes through the opening **300** forming a snug fit. O-rings seated in annular grooves are provided where needed to provide a fluid tight seal between the tubular member **301** and the adjacent wall portion of member **299**, and also to provide a fluid tight seal between the flange portion **302** and the adjacent wall portion of the gas inlet structure **298**.

Particular reference is made to FIG. 1. The feed tube generally designated **37** is seen to terminate at a selected axial position within the tubular portion which is integral with the admission tube assembly **42**. Threaded into the end of the feed tube **37** is a plastic feed stock tube **303**. The aforementioned trunnions **283** and **284** have secured thereto the removable links or arms **305**, with an admission tube trunnion **306** having a passageway therethrough for the sleeve portion **44** of the admission tube assembly **42**, having the flange **43** formed integral therewith, the flange being secured to the end plate **32**, the tube assembly having a threaded locking nut **308** which secures it in position in trunnion **306**. As seen in FIG. **1**, an insulating sleeve **304** separates the sleeve portion **44** of the feed tube assembly into two portions electrically insulated from each other.

The feed tube **303** extends to a hose connection, not shown for convenience of illustration, which it is understood connects with a feeding device for feeding a secondary feedstock into the arc chamber when desired through the aforementioned opening **40**.

The aforementioned end plate **32** is fluid cooled, having a fluid inlet passageway **309** and having therein a plurality of radially spaced circumferential passageways **310** with holes communicating between these passageways and fluid inlet **309**, the holes being shown at **311**. It will be understood that there is also a fluid exit, not shown in the plane selected for illustration, communicating by way of other holes, not shown, with the cylindrical passageways **310** so that fluid passing through these cylindrical or circumferential passageways may be exhausted from the end plate after heat has been transferred to the fluid.

The end plate **32** also has a gas inlet **313** communicating with a gas header **314** whence gas passes through a plurality of radially extending peripherally spaced slots or grooves **315** in the ring **33**, and thence through the space **34** into the arc chamber **20**, this means of admitting an additional gas into the arc chamber being used or not used at the will of the operator.

Preferably, both of the members **112** and **137** have peripherally spaced pins in the flat portion of the wall thereof which is parallel to the plane of the gap through which gas enters the arc chamber **20**. These pins provide initial spacing between the portions of the electrode and keep the fluid passageway open during assembly; after fluid under pressure is passed through the passageways, the pins serve no further purpose, the pins not being shown for convenience of illustration.

With further reference to the operation of the apparatus of FIGS. 1A, and 1B, 2A and 2B, 3A through 3F, and FIG. 4 the arc **104a** shown in the very narrow gap **25** is the initial spark formed by electrical flashover between electrodes, it being recalled that a system voltage is always maintained between electrodes sufficient to cause flashover. The arc is extended rapidly by the high velocity gas. Furthermore, it will be understood that in any position, including an arc path shown at **104A** as well as an arc path shown at **104**, the arc is substantially continually rotated around and between the electrodes by forces exerted thereon by a magnetic field or fields set up by at least two of the four field coils generally designated **129**, **130**, **141** and **142**.

As previously stated, the size of the gas feed openings between passageways 73 and 74 and gas headers 71 and 72 may be varied at will by selecting components having the desired opening sizes, so that the mass flow rate of gas entering the arc chamber **20** may be varied. It will be understood that this mass flow rate is controllable in part by the size of the passageways and controllable in part by the pressure of the gas fed into gas inlet **75**.

At the point where the gas passes from manifolds **298** and **299** into electrode plate **83** and **89** there are orifices trapped therebetween for the dual purpose of regulating gas flow, and dividing the flow to each electrode plate equally. These orifices may be changed by removing manifolds **298** and **299**.

It will be further understood that means are provided where needed for securing the various parts of the arc heater apparatus to each other, these not being described in detail, but being in the main devices which one skilled in the art would recognize as necessary or desirable and would employ.

Particular attention should be paid to the method of holding the two electrodes tightly together during operation of the arc heater. This is accomplished by first tightening nut 308 so that it engages tube 44, then tightening nuts 287 and 288 to a predetermined torque sufficient to overcome, the internal pressure of the heater. The shafts 267 and 268 pull on the downstream electrode assembly and the tube assembly 42 pushes on the upstream electrode assembly. The trunnions insure that no loading occurs other than axial when tightening the nuts.

Particular reference is made to FIG. 4. Radially extending slots 55 in manifold ring 53 are shown. Annular gap 69 provides the gas header 76, FIG. 1B. Annular lip portion 58 corresponds to the annular lip portion of FIG. 1B. Circle 48*a* in dashed line indicates the relative position of the lower surface of radially extending electrode lip 48, and circle 126*a* in dashed line indicates the relative position of the upper or inner surface of axially extending flange portion 126, FIG. 1B.

Furthermore, the cyclic arc elongation and gap breakdown produces much greater turbulence in the gas in the arc chamber with increased heating efficiency, and where chemical conversion is one of the objectives of the use of the arc heater, chemical recombination is enhanced by the increased turbulence in the gas. Additionally, this arc heater is especially suitable for use where a particulate solid is at least one material introduced into the arc heater; the gas passes through the narrow gap at such a very high velocity that it is practically impossible for any of the particulate solid to pass through the gap and deposit on the electrical and gap insulating plate 51 or other insulating surface to the derogation of the insulating properties of the material. By utilizing two field coils in each electrode, increased flexibility in adjustment of the strength and/or configuration of the magnetic field is provided. By utilizing long substantially cylindrical electrodes with elongated arcing surfaces which provide substantially the entire wall enclosing the arc chamber, the volume into which the arc may be expanded is increased, the possibility of the arc striking to some surface other than the electrode is practically eliminated.

Further, the gas itself acts as an electrical insulator between the electrode potentials, and is subject to higher electrical stress than any other insulation in the arc heater; therefore, there is no tendency to spark-over at any other location than the electrode minimum gap. In other words, the active insulation between electrodes is a stream of high speed gas.

The electrode geometry is very simple, and electrode cost is greatly reduced. The electrodes are slidably removable from the electrode assemblies after the arc chamber has been opened; electrode change time is measured in minutes, not hours or days as is the case in prior art arc heaters.

The spark-over feature results in very high power factors, greatly increased over prior art alternating current arc heaters.

There is no upper limit on the gas flow rate; in practice, no maximum gas flow has been obtained. It has been found impossible to increase gas flow rate to the point of arc extinction.

The arc heater is not limited in length; the electrodes could be made longer and the number of field coils axially spaced along each electrode could be increased. In certain applications, it may be desirable to shorten the electrodes and reduce the L/D ratio, and use only one field coil around each electrode. The most desirable L/D ratio may change from gas to gas, and will be affected by the gas flow rate.

The downstream portion of the arc heater is operated or operable at ground potential, thus protecting attaching downstream equipment from ground arcing.

The arc heater includes the use of a water-cooled nozzle which can be attached to the downstream electrode for those applications requiring high pressure operation or supersonic expansion for quenching of the reactants.

Particular reference is made to FIG. 5 in which is shown a slotted manifold ring generally designated 511 having an annular manifold 512 and peripherally spaced tangentially extending slots 513, through which gas passes from one of the manifolds 71 or 72, FIG. 1 to the annular manifold 512 and thence through the gap. It will be understood that there are two manifold rings with tangential slots therein separated by a gap insulating plate 51, FIG. 1, the slotted manifold rings employed in the apparatus and process of my invention being disposed on both sides of the gap insulating plate 51 and corresponding to the slotted manifodl rings 53 and 54, FIG. 1, except that the slots in my rings extend in a tangential direction rather than a radial direction.

Particular reference is made to FIGS. 8A and 8B. FIG. 8A shows a sketch of the inside wall surface of the arc chamber in which there are two cylindrical portions 521 and 522 shown separated by a narrow gap 523 which it is understood extends around the entire arc chamber. Arrows A and B represent respectively components of the gas flow after passing through the gap. The arrow A indicates the swirl or tangential component, and it will be understood that the tangential component spreads the end or radial portions of the arc out until the arc assumes a path generally similar to that shown in FIG. 8A, the final arc path being shown at 530 and having three portions 531, 532 and 533, to be described in greater detail hereinafter.

The radial component defines the mass flow of the gas; the resultant of the radial and tangential components (or total velocity) is that required to displace the arc from the short gap 523. There is an extension of the arc downstream as a result of the net gas flow and there is a similar extension of the arc upstream from the gap. This axial extension is also induced by self-induced forces acting on the arc column as a result of current path to the electrode through the gas admission. Rings and manifold flanges at the gap (FIG. 1B). The high density gas or cold gas stays near the walls of the arc chamber, and is a good insulator compared to the hot gas area. The cold gas drives the arc upstream and downstream from the gap. Additional arc lengthening is accomplished as a result of the arc's following the axial lines of magnetic flux.

The tangential component represented by arrow A has an initial velocity imparted to it in the slots in the manifold rings outside of the gap. Wall friction reduces the momentum of the swirl or tangential flow (or strength of the swirl flow); the swirl or tangential component represented by arrow A gets weaker in both directions as the distance from the gap increases, and the arrow representing the component may change in direction. When the swirl flow becomes weak enough, the arc strikes through it to the wall of each cylindrical electrode; in other words, the swirl or tangential component spreads the ends or radial portion 351 and 352 of the arc generally designated 530 until the arc assumes an arc path similar to that generally designated 530.

Right after the arc is blown out of the gap it assumes a somewhat narrow U-shaped path in which the arc spots are attached to the electrodes near the gap and the arc is blown a substantial distance toward the axial center of the arc heater by the tangential component which is very strong near the gap compared to its strength at positions remote from the gap. As aforementioned, the tangential component represented by arrow A tends to spread the ends or radial portions of the arc path farther apart, and further, the component represented by arrow B as aforementioned keeps the same momentum and this tends to spread the points of arc attachment farther apart.

As aforementioned, the relatively cold gas tends to stay close to the wall of the electrode whereas a core of hot gas extends axially of the arc chamber and surrounds the portion of the arc path designated 533. The total of a tortuous arc path produced in an arc heater configuration in which all of the gas is admitted radially through the gap.

In the arc path of FIG. 8A much of the arc voltage is expended in the portions of the path 531 and 532; the voltage gradient in the portion of the path 533 is relatively smaller, because it is enclosed by a slow flowing mass and is surrounded by hot gas. On the other hand, the portions of the arc path 531 and 532 are surrounded by gas of a relatively lower temperature and of a higher velocity, and the resultant increased heat transfer from the arc column effect an increased arc voltage gradient.

An additional increase in the arc voltage of portions **531** and **532** can be attributed to the magnetic field. Interaction between the radially directed arc current and the solenoid shaped field produces a spiral shaped arc of greatly extended length and resultant increased voltage.

It will be understood that the arc path illustrated in FIG. **8A** is exemplary then it may be modified by the strength of the magnetic fields which exert forces to rotate the points of arc attachment on the electrodes, and may be further modified by the relative strengths of the radial and tangential components of gas passing through the gap.

The arc is seen in FIG. **8B** as it would appear looking into the exhaust end of the arc chamber with the portion **531** of the arc for example attaching to the upstream electrode, the portion **532** of the arc attaching to the upstream electrode, and the portion **533** of the arc being shown as extending generally axially through the arc chamber.

Particular reference is made now to FIGS. **7A-7D**, in which FIGS. B and D are oscillograms illustrating arc voltages which occur in the processes of my invention in order to show the advantages of my invention over the aforementioned copending application entitled "A Recuring Arc Heating Process," comparable oscillograms obtained with purely radial flow through the narrow gap and shown in FIGS. 7A and 7C. FIG. 7A represents the arc voltage in a typical process employing radial gas admission where nitrogen is the gas to be heated, and FIG. **7B** shows the arc voltage pattern where there is swirl admission according to the process of my invention and the gas heated is again nitrogen. It will be understood that the oscillograms of FIG. 7A–7D are graphs of arc voltage plotted against time. Average arc voltage can be obtained from these oscillograms by integrating the area between the traces and the zero

random arc path experienced with prior art heaters employing radial flow through the gap.

As aforementioned, FIG. **7C** and **7D** represent arc voltage plotted against time where the gas to be heated is methane. Current zeros in the graph of FIG. 7C are illustrated at "*r*" and "*s*" one current zero is designated in FIG. **7D** at "*t*," whereas the other current zero substantially coincides with the vertical coordinate scale and is approximated by the point "*w*." The graphs of FIG. **7C** and **7D** have the same arc voltage scale, that is, 1,000 volts per centimeter, but have different time scales, that of FIG. **7C** being 2 milliseconds per centimeter, and that of FIG. **7D** being 1 millisecond per centimeter.

All of the graphs are reproductions of oscilloscope records actually made during testing of arc heater apparatus with radial or tangential gas admission in the various cases. It will be observed that in radial flow, FIGS. **7A** and **7C**, for both gases, there are many restrikes into the electrode gap occurring during each half cycle. On the other hand, the operating characteristic appears to be completely different for both gases where there is vortex flow or tangential admission FIGS. **7B** and **7D**, although the voltage stabilizing effect of the short electrode gap can be seen most clearly in the case of methane gas, FIG. **7D**, where several gap restrikes occur near current zero, the gap restrikes being designated "*x*" and "*y*." It can readily be seen from these arc voltage traces that the average arc voltage is substantially increased by employing swirl admission. This increase also results in a greatly improved power factor since the ratio of average arc voltage to system voltage is correspondingly increased. Power factors up to 58 percent have been experienced in practice with vortex flow, whereas operation with radial flow yields a maximum power factor of only about 40 percent.

The following table of actual test data compares the performance of swirl and radial gas admissions for methane and nitrogen feedstocks:

Test number	Admission	Gas	Mass flow lbm./sec.	Arc current amps	Arc voltage volts	Enthalpy B.t.u./lbm.	Power factor, percent
31H025	Radical	CH_4	.259	2,300	1,015	5,287	34.0
31H050	Swirl	CH_4	.060	1,630	1,395	24,384	40
LH037	Radical	N_2	.075	435	301	1,468	16.3
LH055	Swirl	N_2	.068	740	595	4,540	37.2

line. The average voltage of 7B is seen to be higher than that of 7A, indicating that the combination of arc length and arc-to-gas heat transfer are higher with swirl gas admission than with radial gas admission.

FIG. 7C illustrating the prior art shows arc voltage plotted against time where the gas to be heated is methane (CH_4), and gas is admitted radially through the gap, FIG. 7D shows the arc voltage plotted against time where the gas to be heated is again methane and the gas is admitted tangentially according to the process and apparatus of my invention.

In FIGS. 7A and 7B the time scales are the same, that is, 2 milliseconds per centimeter. The voltage scales differ in that the voltage scale of FIG. 7A is 500 volts per centimeter, whereas the voltage scale of FIG. 7B is 1,000 volts per centimeter. Current zeros of the alternating current waveform are indicated at points "*m*" and "*n*" in FIG. 7A, and current zeros are indicated at points designated "*p*" and "*q*" in FIG. 7B. Generally speaking, the time scales of both graphs are sufficiently long to include two alternations of the alternating current supplying and sustaining the arc at a power frequency of 60 cycles per second.

Paying more particular attention to the graph of FIG. 7B, it will be observed that the vortex flow provides a very smooth, nearly square wave arc voltage waveform rather than the nearly sawtooth voltage waveform which has been experienced where flow through the gap was in a radial direction, this sawtooth waveform being illustrated in FIG. 7A. The square waveform of FIG. 7B may be associated with the establishment of the axially extending arc path at the center of the arc chamber, FIGS. 8A and 8B, rather than the

One of the most significant ways in which I obtain processes which represent substantial improvements over the prior art is by effective use of a magnetic field or fields, relying upon electromagnetic forces to rotate the arc rather than upon aerodynamic forces.

Arc motion is extremely important in "cold" electrode arc heaters if electrode evaporation is to be kept down to an acceptable level. In general, the geometry of the electrode surface is circular and electrode erosion is reduced by forcing the arc to rotate over the electrode surface. FIGS. 9A, 9B and 9C illustrate in part how I utilize a magnetic field to accomplish this. It has been found in practice that arc current and arc spot residence time have the strongest effects on electrode erosion, and it has been further found by experiment that electrode erosion varies about as the third power of the arc current over a current range from about 1,000 amperes to about 100,000 amperes. It has been stated in published studies that arc erosion of contact materials is proportional to about the third power of arc spot residence time.

Vortex flow, which appears in the prior art, provides several effects beneficial to arc heater performance: 1) a strong tangential component to induce arc root motion by transverse blowing; 2) vortex stabilization of the arc column wherein centrifugal forces tend to lengthen the arc and keep it along the centerline of the heater and 3) provide a cold boundary layer along the electrode surface thereby reducing convective heat loss.

Arc motion induced by electromagnetic interaction may be accomplished in arc heaters of the type previously mentioned (having coaxial, tubular shaped electrodes) by providing long solenoid magnetic field coils just outside the electrode surfaces, as shown in FIG. 1A. It will be noted that the field coils are long and have opposing polarities, providing a cusp-shaped resultant magnetic field at the electrode gap. The electrode surface and resultant field have been designed to coincide as closely as possible and the field coils extend over virtually the entire electrode surface, thus providing a very strong and well directed field for arc rotation over the entire electrode.

The force acting on the arc column to provide arc motion is (I×B) and is balanced by an aerodynamic drag force ($\frac{1}{2} \rho C_b V^2 D$) where ρ is the gas density through which the arc is moving, C_d is the drag coefficient, V is the arc velocity D is the equivalent diameter of the arc.

By photographic techniques, arc velocities in air up to about 1,200 ft/sec. have been observed with the arc spot residence times between 10 and 100 microseconds for arc currents in the order of a few thousand amperes and magnetic flux densities of several hundred to a few thousand gauss. For this range of conditions arc spot motion is not continuous, but jumps from one point to another. Arc column motion is, however, continuous. An important benefit of electromagnetic arc motion results from the fact that there is a strong magnetic force acting on the radial and tangential components of the arc column which is always normal to it. Reference is made to FIGS. **9A** and **9B** which show the arc column in the region near the electrode surface. The electrode surface is shown flat and represents a very small portion of an electrode surface of large diameter. The magnetic field is normal to the surface of the paper. As the arc column moves away from the arc spot, the resultant Lorentz (I×B) force has an increasing component which is directed toward the electrode surface. The electrode field or voltage gradient between the arc column and the electrode surface rapidly increases as the column nears the surface until sparkover occurs and initiates a new arc spot. In this way, the arc spots appear to "walk" over the electrode surface with very short arc spot residence times. This phenomenon is not present for aerodynamically blown arc motion due to the lack of the magnetic field, and although the arc root jumps from point to point in the latter case, arc spot residence times are probably much higher than for magnetically rotated arcs.

In operation with a.c. arcs in a d.c. magnetic field, the arc changes direction each half cycle. Photographs have been taken using a high speed (6,000 frames/sec) movie camera which show the arc moving over the electrode surface with tangential gas admission. The electromagnetic force, being proportional to the arc current, is sinusoidal. The aerodynamic force, which would tend to rotate the arc column if the magnetic field were not present, is constant and unidirectional. Thus, in one polarity of the a.c., the Lorentz (I×B) force and aerodynamic forces oppose each other, while in the other polarity these forces are additive. It has been experienced that during the early part of the former half-cycles, the arc begins to rotate in the direction of the gas swirl, but very soon changes direction and rotates in the Lorentz (I×B) direction. The time at which this occurs is less than 10 percent of the half cycle or when the Lorentz force less than sin ($180° \times 0.1$) ≈ 0.30 of its full value. Thus it can be seen that for arc currents in the range of a few thousand amperes and magnetic flux densities of about a kilogauss, arc rotation which is induced by electromagnetic interaction would appear to be preferable.

A comparison may be made of electrode wear data for the two types of arc rotation described herein. Development work sponsored by the USAF under contract No. AF 33 (616)–8437 and described in aforementioned Technical Documentary Report RTD–TDR–63–4055 was performed in the early 1960's to develop a high enthalpy, high power arc air heater which employed aerodynamic arc rotation. Listed are the results of some electrode wear tests, hereinafter referred to as the first tests, for which the conditions were: arc current 400 amps d.c., polarity-anode, pressure-205 psia, material electrolytic tough pitch copper. The measured electrode wear rate was 2.74 grams/min. A somewhat comparable test, hereinafter referred to as the second tests, was run on 10–3–69 at the Westinghouse Arc Heater Laboratory for which the conditions were: arc current-1,800 amps a.c., pressure-**15** psia, material-oxygen free copper, magnetic flux - **1K** gauss. The measured wear rate was **0.05** grams/min. as for the several differences in operating conditions, i.e.,: d.c. (anode) vs. a.c. — the experience of applicant's assignee has been that anode wear is roughly 10 times lower than cathode wear. Since in a.c. a given electrode is anode and cathode on alternate half cycles, an equivalent wear rate for a.c. should be about **5** times higher than d.c. (anode). Arc current level: as previously mentioned, electrode wear is about proportional to the third power of the arc current, thus for conditions of the second tests we would expect a wear increase of about $(1,800/400)^3 \approx 90$ times higher for 1,800 amperes. Pressure: 205 psia vs. 15 psia. Our experience has generally indicated that in this range of pressure level, very little increased wear is experienced. An increase in wear may, however, be associated with decreased aerodynamic force ($\frac{1}{2} \rho V^2$) as pressure in increased for the same flow. This would tend to reduce the arc rotation speed even further and result in increased arc spot residence time. Thus for conditions of the second tests and assuming that adequate electrode cooling is provided in both cases, we would expect a wear rate of $2.74 \text{ gms/min} \times 5 \times 90 = 1,232$ gms/min if we had the same arc spot residence time as in the reported data. Since we experienced only 0.05 gm/min weight loss, the ratio of arc spot residence times is probably therefore of the order of $(1232)/0.05^{1/3} = 29.2$. Since there is only a factor of about 3.0 in Lorentz force over aerodynamic force, the remaining portion of this large difference in arc spot residence times can only be explained by the "walking" mode of arc spot motion which has been previously discussed. The study previously mentioned to the effect that erosion is proportional to about the third power of residence time indicates the importance of this feature of my invention.

FIG. **9C** shows the I×B force which results from self-induced magnetic field and moves the arc away from the gap. While this concept is not unique, I employ it to assist in accomplishing the desired result.

Whereas I have invented apparatus especially suitable for practicing the processes of my invention, arc heaters having other electrode configurations, other than the axially spaced annular electrodes shown, may be employed in practicing the processes of my invention. For example, the processes of my invention may be practiced with a pair of radially spaced electrodes having the same axial extension with a narrow annular gap between the electrodes through which gas is admitted, the electrodes tapering from each other at an angle as required to permit both radial and tangential components of gas admission through the gap between electrodes, and in which the arc while elongated extends radially between electrodes a distance from the gap. Additionally, the processes of my invention may be practiced employing a three phase alternating current source in which four coaxially aligned electrodes are provided with a short gap between each adjacent pair of electrodes, one phase of the three phase source producing each of the three arcs respectively between the four electrodes.

By way of further summary, my process includes the steps of forcing a gas to be heated through a relatively short gap between a pair of electrodes while maintaining across the electrodes a system or backup voltage at all times sufficient to cause breakdown of the gap between electrodes, the gas which passes through the gap and leaves the gap inside the arc chamber having a radial component which defines the mass flow rate and a tangential component, the resultant of radial and tangential component, the resultant of radial and tangential components being effective in displacing the arc from the short gap. My process produces an arc which extends substantially axially in the arc chamber and is surrounded by a core of hot gases with the ends of the arc attaching to the surfaces of the electrodes providing more efficient heating of the gas, substantially increasing the power factor of the arc heater apparatus, and permitting an enthalpy to be imparted to the gas several times that previously obtainable because the processes of my invention permit the mass flow rate to be substantially reduced to a small percentage of that required to elongate the arc where purely radial flow is utilized, with the result that the energy in the arc can be imparted to a smaller volume flow of gas and the enthalpy imparted to the gas may be at least several times that obtainable where gas is admitted through a narrow gap in a radial direction.

Additionally, since the arc roots are periodically moved by a magnetic field around the inner surface of the cylindrical electrodes shown, the arc because of its dynamic, fluctuating nature may vary somewhat in length as illustrated by the graphs in FIGS. 7B and 7D, this variation occurring many times during each alternation of the alternating current, the effect being more marked in the case of methane, the surface area of the electrode contacted by the arc roots is greatly increased, with a corresponding reduction in erosion and in increase in total electrode life.

Furthermore, since average arc voltage is greatly increased over that possible with radial flow for a given power input, the arc current can be reduced, the reduction in arc current decreasing the electrode erosion rate which varies exponentially with variations in arc current.

As long as the system or backup voltage exceeds the gap breakdown voltage or sparkover voltage, the arc is never extinguished, and in the process the arc is thus stabilized.

My processes employ either alternating current or direct current to produce the arc.

Furthermore, in my process the periodic reversal of the direction of rotation of the points of arc attachment to both electrodes when the polarity of the alternating current reverses after each alternation results in increased turbulence in the gas in the arc chamber, better mixing, and more efficient heating.

Whereas the operation of the arc heater and my processes have been illustrated in FIGS. 7A–7D with respect to the heating of nitrogen and methane, and will be understood that in my processes any gas can be heated, or any gas mixture such as air.

By way of further summary, the lower gas flow limit can be reduced substantially by tangential admission of the incoming feedstock below the lower limit required in prior art arc heaters using radial flow. The vortex flow of my invention performs several beneficial functions, one of which is that the high tangential flow component provides sufficiently large gas velocity to blow the arc from the electrode gap at greatly reduced gas mass flow rates. It will be understood that in the prior art, the lower limit was set by the minimum gas velocity which will blow the arc from the minimum gap after a restrike had occurred. If the gas flow was reduced below this lower limit the arc would remain in the minimum gap resulting in greatly reduced arc voltage. The centrifugal effects in the arc chamber establish vortex stabilization of the arc column wherein the column virtually follows the centerline of the heater. A further effect of the vortex flow is the establishment of the cold gas boundary at the electrodes. After sparkover in the gap, the arc roots quickly traverse to that pseudoequilibrium axial position where the swirl induced boundary layer is weak enough to allow arc attachment at the electrodes. The establishment of the cold vortex flow of gas through the electrode gap decreases the recirculation of arc heated gas into that region, thereby increasing the sparkover voltage of the gap and the resultant average arc voltage. Vortex flow provides a very smooth, nearly square wave arc voltage waveform rather than the nearly "sawtooth" waveform which has been experienced with short gap heaters and processes employing radial flow. As aforementioned the increased average arc voltage results in a greatly improved power factor where the swirl or tangential gas injection of my process is employed, and the increased arc voltage permits a reduction in the arc current level for a given predetermined power level resulting in a substantially reduced electrode erosion rate.

I claim as my invention:

1. An improved process for heating a gas as a process material which comprises the steps of forming in an arc chamber of generally uniform cross section an annular electrical breakdown path between two spaced elements having a generally common axis and at opposite polarity with respect to each other, maintaining across said elements a system voltage sufficient to cause path breakdown initially between said elements generally parallel to said axis, the electrical breakdown between elements causing an arc to form, passing the gas to be heated at high velocity through said path at a plurality of peripherally spaced positions, said gas having a component of direction after it passes through said gap which is generally tangential to the electrical breakdown path and a component of direction which is radial to said electrical breakdown path, both said components of direction being additionally generally transverse to said axis, the tangential component reducing the mass flow rate of gas required to periodically move the arc out of the breakdown path to cause elongation of the arc primarily in a direction transverse to said axis so that the radial and tangential components produce an arc path having a major portion extending axially to the annular electrical breakdown path, with other portions of the arc path extending from the major axially extending portion and attaching to the inside surfaces of the electrodes, the cross-dimension of the arc chamber in a plane passing through the arc gap relative to the arc gap being such that the length of the arc is periodically significantly longer than the distance between the portions of the arc attached to said electrodes, whereby the electrical power required for a predetermined total volume of gas to be heated to a predetermined temperature is reduced, the arc being elongated primarily transverse to said axis until said system voltage can no longer support it whereupon a new breakdown may occur.

2. A process according to claim 1 in which the current producing the arc is alternating current and the arc may return to the breakdown path once peralternation at or near each current zero.

3. The process according to claim 1 including the additional step of introducing another process material to be heated into the arc zone at one end of the arc chamber by a path other than through the gap.

4. A process according to claim 1 in which the points of arc attachment are rotated around the electrodes by forces resulting from a magnetic field.

5. A process for heating gas which comprises producing an electric arc in a gap of substantially uniform width between a pair of spaced coaxially mounted annular cylindrical electrodes wherein said width is substantially smaller than the largest distance across a transverse section of said electrode which is also perpendicular to said axis of said electrodes forming a chamber of generally uniform size within said electrodes, in which said arc may be elongated, maintaining a system voltage between said pair of electrodes sufficient to cause electrical breakdown in the gap at any portion thereof, and passing gas through said gap from the outside thereof, toward the inside thereof and thence into the arc chamber continuously at a high velocity, the gas leaving the gap and entering the arc chamber having a tangential component and a radial component, both of said components being generally additionally transverse to said axis, the tangential component resulting in an arc path increasing in length until said system voltage may no longer support it whereupon a new breakdown may occur, the major portion of said arc path extending into said arc chamber with end portions attaching to an upstream electrode and a downstream electrode respectively, the total mass flow rate of gas required to move the arc out of the gap between electrodes being substantially reduced, the power in the electric arc being transferred to a smaller volume of gas per unit time so that a greater enthalpy may be imparted to the last named gas, the cross dimension of the arc chamber in a plane passing through the arc gap relative to the arc gap being such that the length of said arc is periodically significantly larger than the distance between the portions of the arc attached to said electrodes.

6. A process according to claim **5** in which the average arc voltage is substantially increased and the average arc current is substantially decreased while maintaining a predetermined arc power thereby improving the power factor.

7. A process according to claim **5** wherein alternating current supplies the arc, wherein the arc spot moves on the electrodes and the direction of arc spot movement on the electrodes reverses periodically as the instant polarity of the alternating current changes, and wherein the reversal of the direction of arc spot movement as the instant polarity reverses between alternations produces increased turbulence in the gas in the chamber thereby providing better mixing and improved heating efficiency.

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