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Kofoid

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[54] **METHOD AND APPARATUS FOR HEATING SOLID AND LIQUID PARTICULATE MATERIAL TO VAPORIZE OR DISASSOCIATE THE MATERIAL**

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[52] U.S. Cl. .... **204/164;** 23/194; 75/.5 BB; 117/93.1 PF; 219/122; 250/542; 423/336; 423/608

[51] **Int. Cl.²**....................... **C01G 27/04;** C01F 7/30

[58] **Field of Search**.................... 204/164; 75/.5 BB; 423/33 L, 608; 250/542; 219/122, 76, 121 P; 117/93.1 PF; 23/294

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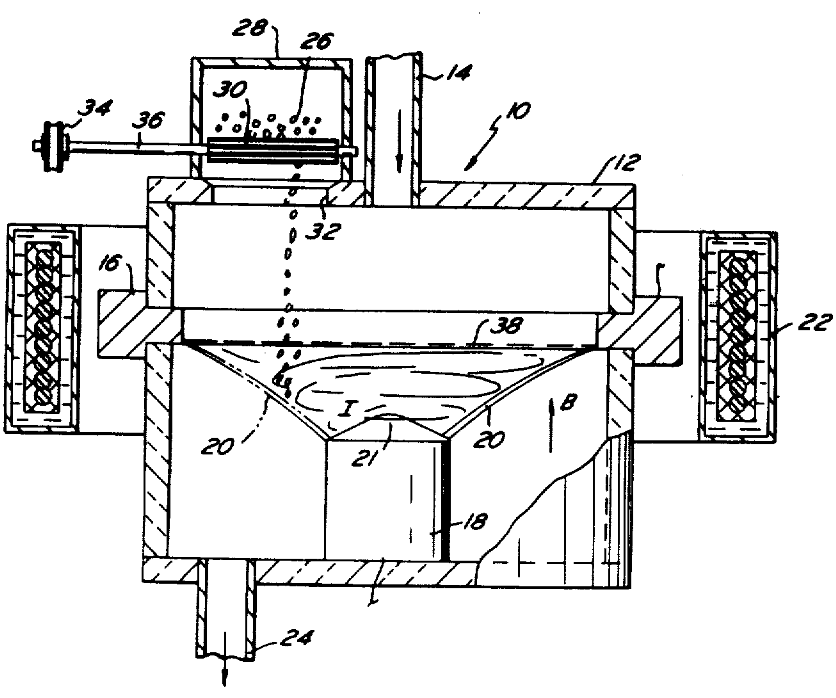
[57] **ABSTRACT**

A method and apparatus for heating solid and liquid particulate material to vaporize or dissociate the material uses an arc wall, generated by a revolving arc, to increase residence time of the material until it is at least vaporized. The arc wall passes gas or vapor but is impervious to the passage of solid or liquid particulate material that is incident upon the wall.

27 Claims, 4 Drawing Figures



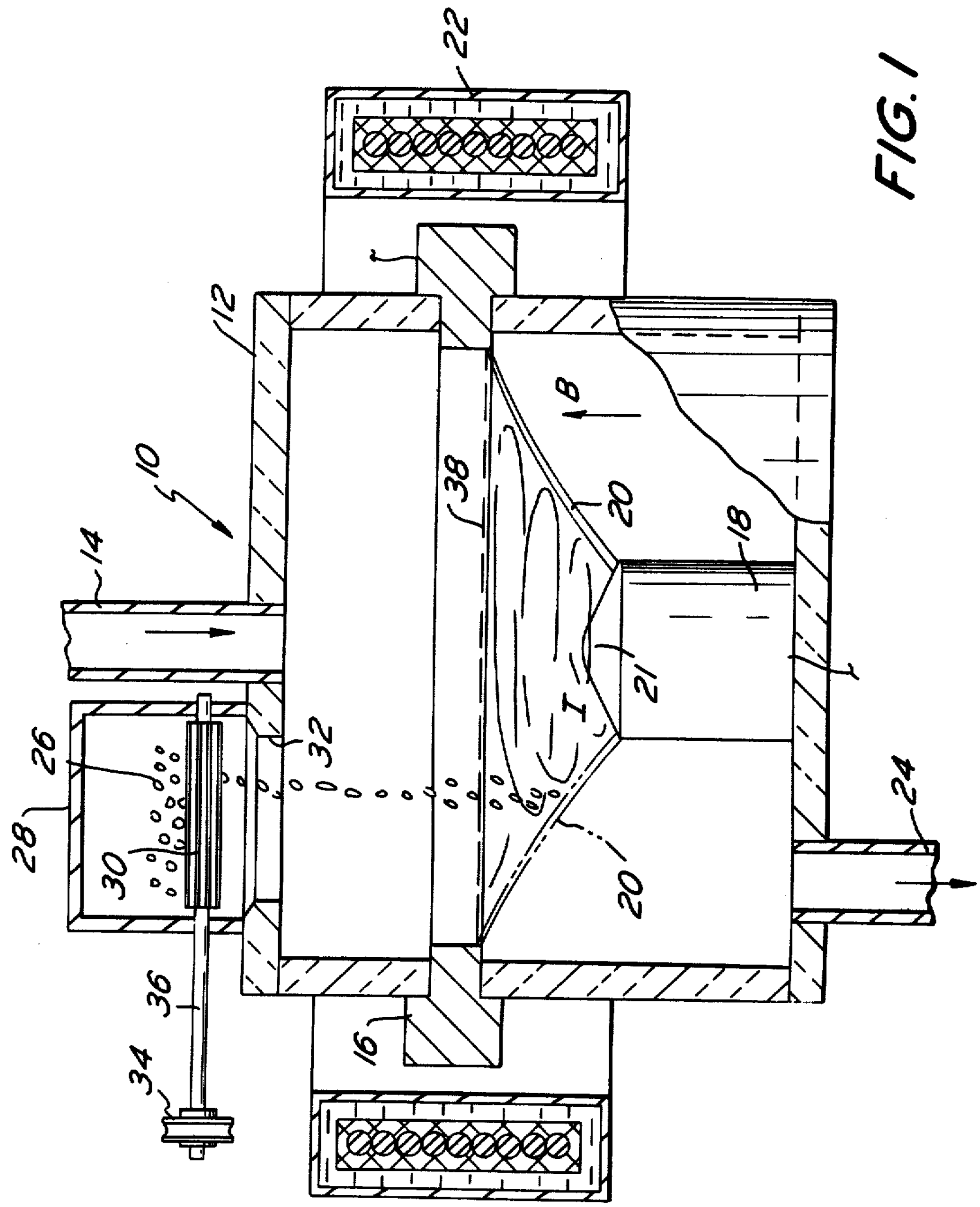


FIG. 1

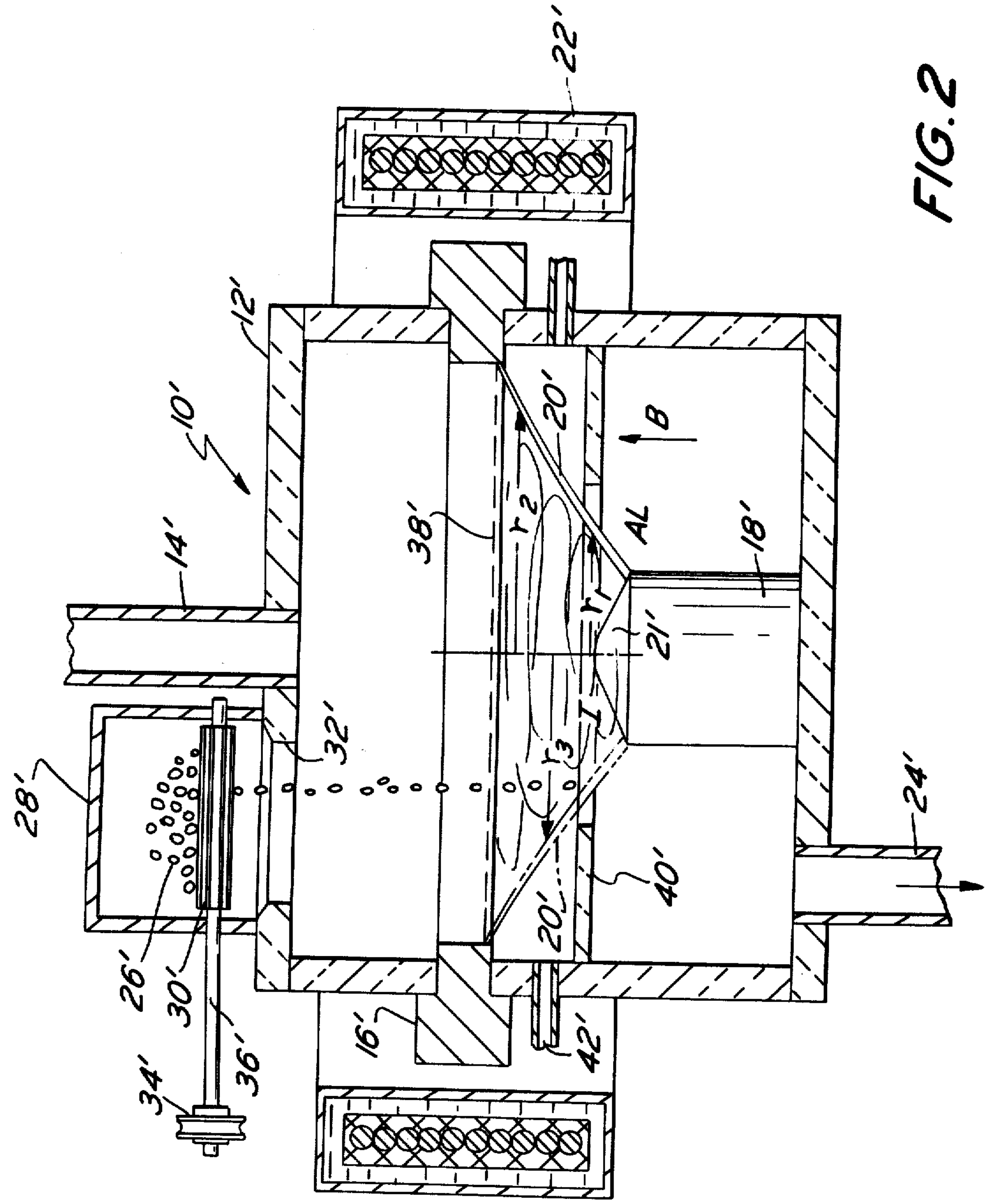


FIG. 2

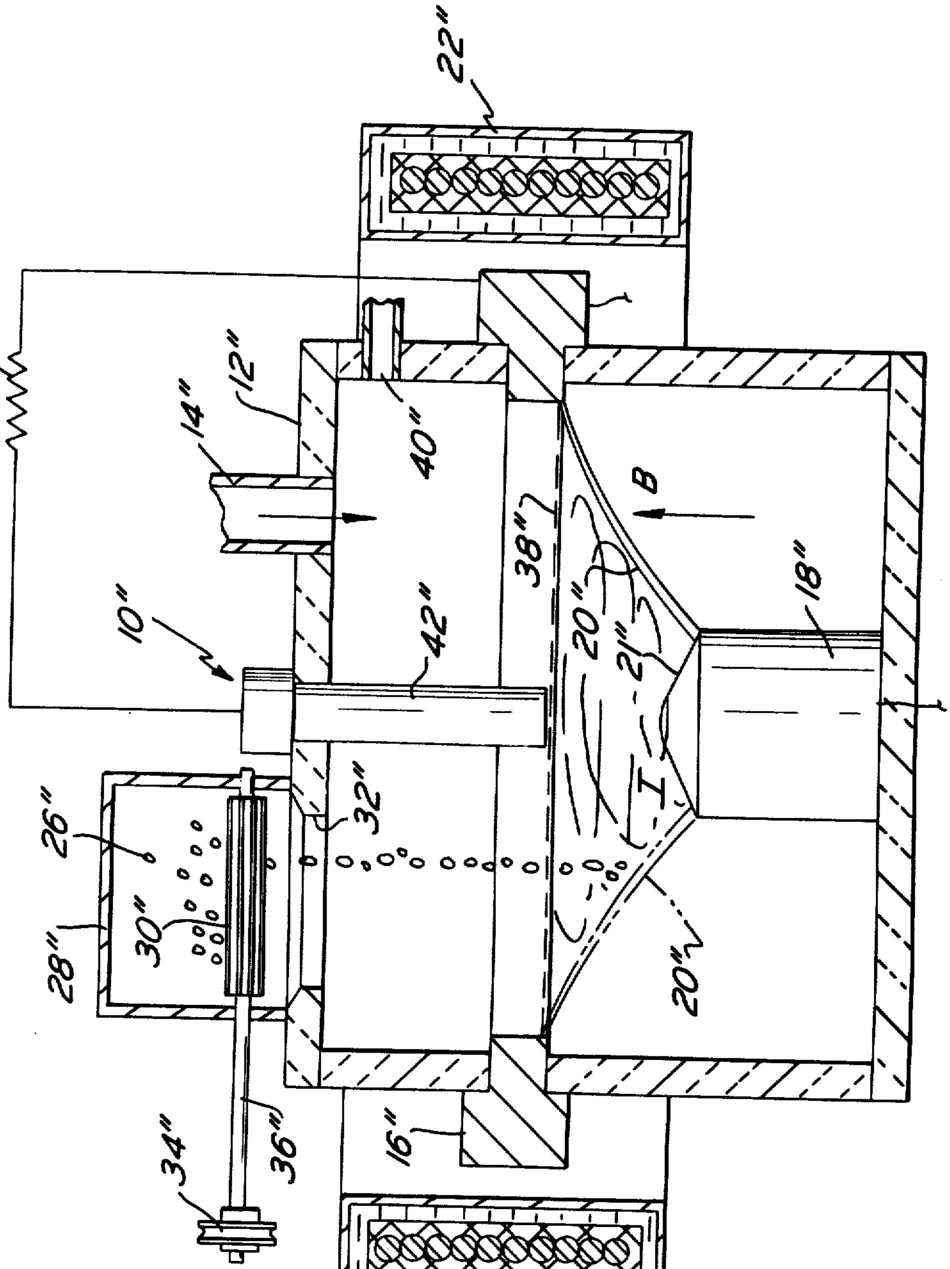


FIG. 3

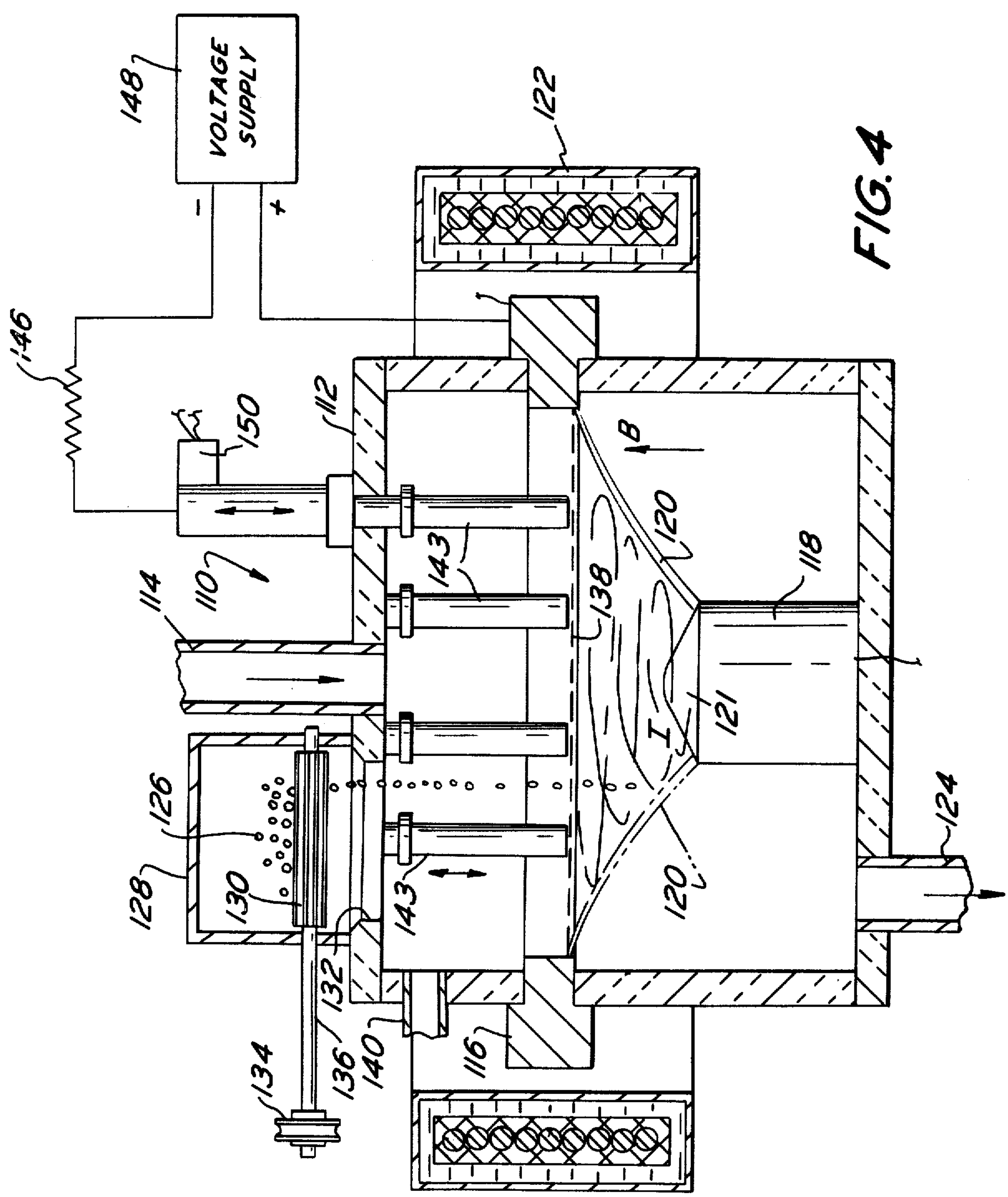

VOLTAGE SUPPLY
148
146
150
112
114
110
122
143
138
120
118
121
B
I
126
128
130
132
134
136
140
116
124
-
+

FIG. 4

METHOD AND APPARATUS FOR HEATING SOLID AND LIQUID PARTICULATE MATERIAL TO VAPORIZE OR DISASSOCIATE THE MATERIAL

This invention relates to a method and apparatus for heating solid and liquid particulate material to vaporize or dissociate the material. More particularly, this invention relates to the use of a revolving arc to heat and vaporize liquid or solid particulate material by increasing residence time of the material in a high temperature zone.

There are many circumstances in which it is desirable to vaporize materials which reach that condition only at very high temperatures, such as in excess of 2000°K. Refractory materials are among those that desirably must be heated to vaporization temperatures. An example of such a material is Al_2O_3 which vaporizes at above approximately 3900°K. An exemplary purpose for vaporizing al_{AlO3} is described in co-pending patent application Ser. No. 269,634 filed July 7, 1972 for Method and Apparatus for Reducing Matter to Constituent Elements and Separating One of the Elements from the Other Elements. Other uses for the invention should be obvious to those skilled in the art from what is described herein.

There are several known heat sources capable of heating materials of this type to varporization. Among these are radio frequency induction discharge devices, plasma jet devices, and electric arc devices. Radio frequency discharge devices have certain advantages not present in plasma jet and arc devices, such as long residence time in the high temperature region. However, they are not commercially economical, particularly where large amounts of power are to be used to heat relatively large amounts of material. Plasma jet heating devices and arc heating devices are different forms of high current arc devices. As such, they both have in common two basic enthalpy transfer problems. First, because a gas is heated as it approaches an arc, the density of the gas (and of the particles carried in it) is reduced. The result is that most of the mass (gas and solid) tends to avoid the high temperature zone or the discharge channel as in the case of a plasma jet. Indeed, rather little of the mass passes through it. The second enthalpy problem is one of residence time; that is, the time during which the material to be heated is in the vicinity of the arc. The residence time cannot be extremely short if the refractory or other material is to be vaporized, dissociated, or perhaps even ionized. A corollary to the foregoing is that heat transferred to a solid or liquid is governed by the enthalpy as well as the temperature of the surrounding gas. For high rates of heat transfer, the solid or liquid must be enveloped in a dissociated gas.

Electric arcs for heating can be divided into two groups for the purpose of evaluating the differences between arc heating devices. The most straighforward form of arc heating is to heat a volume of gas only in a highly thermally insulated chamber. In such a case, the total enthalpy is carried to gas in the chamber, the residence time of the material to be heated in the gas is long, and the gas is in intimate contact with the material. For this type of heating, constricted arc discharges in the form of plasma jets are entirely suitable. Such devices evidence a high efficiency and have been used effectively. For example, very high energy units have been constructed for high temperature wind tunnels. High efficiency can also be obtained for heating a volume of gas only by the use of long column a.c. polyphase arcs placed in the gas flow entering a chamber. But high efficiency heating using plasma jets or a.c. polyphase arcs is limited to gas only heaters. When attempting to heat liquid or solid material, the problem of mass avoidance and short residence time greatly reduces the efficiency of plasma jet and a.c. polyphase arc heaters.

When using an arc heating device to heat liquid or solid materials to an evaporated, dissociated or even ionized condition, the problem changes from that of simply heating the gas to that of transferring sufficient enthalpy to the liquid or solid. High speed gas flow plasma heaters are disadvantageous because of the short residence time. Materials which require high temperatures to vaporize can be vaporized only if they pass through a part of the discharge volume where the gas is momentarily dissociated. This is necessary for large enthalpy transfer to the solid or liquid. Thus, as indicated above, plasma jets are not well suited for this heating task. Their difficulties are short resident time and getting an appreciable proportion of the liquid or solid material into intimate association with the arc and the dissociated gas.

The present invention seeks to overcome the problems of other types of heaters by using a revolving arc to keep the solid or liquid material to be heated in close proximity to the plasma for a residence time sufficiently long to effect the necessary transfer of energy. The revolving arc forces the material to be heated into the hottest plasma volume, where the gas is dissociated, in order to transfer the heat of reassociation to the solid or liquid material. In particular, the present invention overcomes the problems of the prior art by revolving an arc to generate an arc wall. The arc wall defines a volume filled with vaporized material. Still further, the arc wall has the characteristic of passing a gas or vapor but is impervious to the passage of solid particles or liquid droplets which are incident upon the wall, provided that they do not strike the wall with too high a force.

The arc wall is created by causing a high current d.c. electric arc to revolve about an axis thereby describing a surface of revolution which is the arc wall. The arc extends between appropriate electrodes and is revolved in a conventional manner such as by reason of the force ($I \times B$) developed when the arc current I interacts with a steady state magnetic field B. The arc revolves at a rate such that insofar as the liquid or solid material is concerned, it is omnipresent. On the other hand, gas or vapor, because of its relatively low viscosity, can flow through the arc wall; that is, it passes through points where the arc instanteously is not present. Thus, in contradistinction to the liquid or solid material, the gas or vapors see the arc wall as being porous.

Such an arc wall enables the heater to meet the objectives of keeping the solid or liquid material to be heated in close proximity to the plasma for sufficient residence time to effect the necessary transfer of energy and to force the material to be heated into the hottest plasma volume where the gas is dissociated in order to transfer the heat of reassociation to the material to vaporize it. This is accomplished because the arc wall is generally impervious to solid particles or liquid droplets impinging upon it. The revolving arc can be thought of as a solid rod rotating at a very high rate. Any particle of material incident upon the wall will have transferred to it a certain amount of momentum by reason of the impact from the revolving rod. The particle might be stopped or, more likely, it is deflected. However, before the carrier gas in which the particle is immersed, which gas is flowing through the wall, can give the particle appreciable acceleration in a direction which would force it through the wall, it will be again struck by the revolving arc making its next revolution. When the particle, upon its first impact with the arc wall is deflected, it travels until it hits the arc wall at another point. It may be deflected several times before it has sufficient residence time to vaporized. The vaporization can develop any needed pressure above the wall. Moreover, each time the particle is impacted by the revolving arc (i.e., is incident upon the arc wall), it is in the hottest plasma volume where the gas is dissociated and the heat of reassociation can be transferred to the particle. Thus, sufficient residence time is achieved.

It therefore is an object of the present invention to provide a method and apparatus for heating solid and liquid particulate material to vaporization or higher temperature using a revolving arc to generate an arc wall.

It is another object of the present invention to provide a method and apparatus for heating solid and liquid particulate material to vaporization or higher temperature using an arc wall to provide sufficient residence time.

Other objects will appear hereinafter.

For the purpose of illustrating the invention, there are shown in the drawings forms which are presently preferred; it being understood, however, that this invention is not limited to the precise arrangements and instrumentalities shown.

FIG. 1 is a sectional view of an apparatus for performing the invention.

FIG. 2 is a sectional view of another form of the invention wherein separation of constituent species takes place.

FIG. 3 is a sectional view of yet another form of the invention for separating constituent species of the material.

FIG. 4 is a sectional view of still another form of the invention for separating constituent species of the material.

Referring now to the drawings in detail, wherein like numerals indicate like elements, there is shown in FIG. 1 apparatus 10 for heating solid or liquid particulate material to vaporize the same. As shown, the heating apparatus 10 includes a chamber 12 into which is fed a carrier gas under pressure through inlet 14. The type and purpose of the carrier gas is described below.

Within the chamber 12 is an annular electrode 16 and an axial electrode 18. The annular outer electrode 16 may be connected to the positive terminal of a high current source of direct current and the inner cylindrical post electrode may be connected to the negative terminal of the same source. Both electrodes may be cooled by conventional means (not shown). The source of direct current is not shown since it is conventional. It should be noted, however, that the polarity of the electrodes can be reversed. The effect of such reversal will be to reverse the direction in which the arc 20 revolves, assuming the direction of the magnetic field B remains the same.

A solid cone 21 of a refractory material is fixed to the top of post electrode 18. The purpose of the cone 21 is to prevent material being heated from accumulating on the relatively cool post electrode 18. The cone 21 is either electrically insulating or semi-insulating and is cooled only by heat transmission to the water cooled post electrode 18. It is sufficiently hot to prevent the material from condensing upon it.

The magnetic field B is generated by the magnetic coil 22 connected to an appropriate source of direct current. If desired, the magnetic coil 22 can include a low temperature superconductor coil if a stronger field and hence higher angular velocities of the arc 20 are desired. Morevoer, the magnetic field B need not be linear across the length of the arc. Indeed, a non-linear magnetic field can be used to shape the arc to a straight line as it revolves about its electrodes. However, it should be pointed out that in general the magnetic field B is parallel to the axis about which the arc 20 is to revolve and exists throughout the entire interior of the chamber 12.

The structural walls of the chamber 12 are preferably electrically and thermally insulating. Appropriate cooling means (not shown) are provided. Since such cooling means do not form a part of the present invention, they need not be described. The chamber 12 also includes a gas outlet 24 through which the carrier gas and the vaporized material is to flow. The gas outlet 24 may be connected to an appropriate separator for separating the vaporized material from the carrier gas if such separation is required. Such separator may not be necessary if the carrier gas is also the vaporized material.

The material 26 is contained within a material chamber 28 having an appropriate feed apparatus 30 controlling the opening to a material inlet 32 in the chamber 12. The feed apparatus 30 may be any conventional means for injecting material in particulate form into the chamber 12 through the material inlet 32, such as a grooved roller as illustrated. Feed apparatus 30 is driven by a motor (not shown) connected to a pulley 34 fixed on shaft 36. The motor and pulley 34 are interconnected by an appropriate belt.

The interaction of the magnetic field B and the current I flowing through the arc 20 extending between the electrodes 16 and 18, generates a force (B × I) which causes the arc to revolve as indicated by showing the arc 20 in the phantom position. Thus, it may be said that the movement of the arc 20 causes it to describe a surface of revolution. This surface of revolution may be described as an arc wall and, in the example shown, is a generally conical surface. Stated otherwise, the arc wall is effectively a coneshaped wall of highly heated gas and vapor having a temperature in the range of 4000°K to 12,000°K. The arc normally passes through the carrier gas which enters through inlet 14 and exits through outlet 24. The carrier gas may, by way of example, be one of the noble gases such as argon. Of course, other gases may be used as desired. The carrier gas may be needed only for start-ups. Thereafter, only the vapors from the material 26 may be used.

The arc 20 is typically about 2 to 4 mm. in diameter and carries approximately 100 to 10,000 amperes. The arc would typically be approximately 3 mm. in diameter. Accordingly, the thickness of the arc wall is 2 to 4 mm. with a typical wall thickness of 3 mm.

In order for the apparatus and process to work effectively, the arc must revolve at a high number of revolutions per minute. Accordingly, the magnetic field B is adjusted in respect to the current flowing through the arc so that it revolves at a rate between 5000 to 100,000 revolutions per minute. An optimum range for vaporizing small size particles may be 12,000 revolutions per minute. At such a rate, the revolving arc **20** passes through each point in the arc wall 200 times per second. This makes it, for the purposes of this invention, onmipresent to the particulate material **26.** At rates below 5000 rpm, the effectiveness of the arc wall becomes lost. At rates above 100,000 revolutions per minute, the arc effectively may become a solid disc of plasma. Thus, for uniform heating of material, the time for one revolution of the arc **20** must be considerably less than the time required for the material to pass (in the axial direction) through the region being heated by the arc.

An electric arc may be looked upon as having a core that is impervious to the flow of gas or solid material through it. While this view may not be absolutely correct, it is generally believed to be more correct than assuming that the arc permits uniform flow through its thickness with only moderate opposition. The temperature through an arc is a gradient. The core has a temperature of between approximately 10,000° to 14,000°K surrounded by an enevelope at a lower temperature but greater than 5000°K. Beyond the envelope, the temperature drops off rapidly and is relatively cool. Just the same, an electric arc **20** can be viewed as a hot solid rod revolving at a fixed rate. The result is uniform and closely controlled heating of material which comes in contact with or flows through the arc wall.

Gas, or vapor, because of its relatively low viscosity can flow through the arc wall, passing through points where the arc instanteously is not present. To the gas or vapor, the arc wall is porous. However, the arc wall is impervious to solid particles or liquid droplets impinging upon it. Thus, the material **26** should be particulate material or, if initially in a liquid form, it may be droplets.

As the particulate material **26** enters the chamber **12,** it becomes immersed in the carrier gas or material moving at a sufficiently low velocity and pressure to have little effect upon the particulate material **26,** yet it should cause the material **26** once vaporized to flow through the arc wall and through outlet **24.** The particulate material falls, generally under the force of gravity, until it strikes the arc wall. If gravity is not used, then another means to force the particulate material **26** against the arc wall can be used. For example, a carrier gas or a material vapor at a somewhat higher pressure such that it would entrain the particulate material or some means of projecting the material into the chamber with an initial velocity can be used.

In any case, each particle, when incident upon the arc wall, whether it be a drop of liquid or a solid particle, receives a certain amount of momentum by reason of the impact from the rotating electric arc **20** which looks very much like a solid rod. The particle will be either stopped or deflected to another point of incidence upon the arc wall. But before the gas or material vapor in which it is immersed can give the particle appreciable acceleration in a direction that would send it through the wall, it will be again struck by the rotating arc making its next revolution. The particle is once again deflected until it is incident upon the arc wall at another point. It may be deflected many times before it has sufficient residence time to be vaporized. But, it continues to make contact with the arc wall until it is vaporized and thus the requisite sufficient residence time is achieved. The vaporization pressure is allowed to rise to an amount sufficient to force the vapor and gases through the arc wall.

The residence time of liquid droplets and/or solid particles in the vicinity of the rotating arc is much increased by the following factors: (1) transfer of momentum from the rotating arc **20;** (2) differential vaporization; (3) turbulence; and (4) entrainment in the circulating gases and vapors. Transfer of momentum from the rotating arc has already been described.

The concept of differential vaporization may be described as follows. At a certain elevation above the arc **20,** such as at the material inlet **32,** a solid particle is released. The particles move downward under the influence of gravity and drag exerted by the environmental gases including material vapor and/or carrier gas, if used. When the particle is in contact with the plasma arc **20,** heat is being transferred from the hot plasma to the particle through the front face of the particle. If the heat transfer rate is fast enough, and downward motion of the particle is slow enough, the particle is melted and partially vaporized. In this case, vapor would be released from the front face of the particle. This vapor ejection exerts a thrust on the particle, which has a component in the upward or reverse direction in which it initially moved into contact with the arc **20.** Thus, the motion of the particle is governed by the gravitational force, drag forces, the thrust due to vapor ejection, and also to the momentum imparted to it by the solid character of the rotating arc **20.**

If the heat transfer rate is so slow and the motion of the particle is so fast that there is no vapor released from the particle before it is fully immersed in the plasma arc **20,** the motion of the particle will again be governed by the gravitational force and the drag forces. These latter forces tend to again direct the particle into the plasma arc **20** until is melted and vaporized. The net result then is the conversion of the solid particles into a vapor.

The combined effect of the transfer of momentum from the rotating arc **20** and the reverse thrust created by vapor ejection is so great that the particle is trapped above the rotating plasma arc **20** until on repeated encounters it is completely vaporized.

It should be understood, however, that the use of vapor ejection to maintain the particle within zone I is not absolutely necessary to the operation of the heater **10.** The transfer of momentum from the rotating arc **20** should be sufficient to accomplish this purpose, but it may be aided by the use of vapor ejection as described immediately above.

Thus, the apparatus **10** provides a solution to the problem of vaporizing material by heat, that is, total enthalpy. As stated above, the problem of vaporizing material, particularly refractory material using the plasma of electrical discharges, is largely one of (1) keeping the material to be heated in close proximity to the plasma for a residence time sufficiently long to effect the necessary transfer of energy, and (2) to force material to be heated into the hottest plasma volume where the gas is dissociated in order to transfer the heat of reassociation to material to vaporize and dissociate it. The arc wall enables both objectives to be met. It functions to keep all solid and liquid materials in the zone which is generally defined by imaginary line **38** and the arc wall generated by the rotating arc **20.** Only when the material (such as Al_2O_3) is vaporized can it leave zone I.

The rotating arc also imparts high rotational velocities to the gases and/or vapors in the volume defined as zone I. Any mass rotating with the vapors will have a significant centrifugal force acting upon it. The force acting upon any mass within the zone I will be:

$$F = mv^2/r$$

where:

m is the mass

r is the radius measured from the central axis of the volume defined in zone I

v is the velocity normal to the radius.

The force acting upon the mass can also be written as follows:

$$F = (2\pi)^2 mr\phi^2$$

where:

ϕ is the rotation per second of the gas (and/or vapor) in the arc wall volume.

The gas and/or vapor within the zone I may consist of vaporized material and/or the carrier gas.

The particles of material **26** must necessarily become entrained in the whirling gases and/or vapors. Thus, a centrifugal force is also applied to them. Stated otherwise, the rotating arc acts like a solid stirring rod to cause the mass of gas and/or vapor to attain a high rotational velocity which tends to entrain material that enters arc wall volume defined as zone I.

The net force exterted on a mass of gas or vapor at a particular radius at the arc wall is the difference between the force of restraint imposed by the wall and the centrifugal force on the mass at that point, with proper attention being given to the vector directions of the forces. For a fixed magnetic field intensity B, current I, and rotational velocity ϕ, such difference force is clearly dependent upon the radius r. Therefore, the arc wall created by the rotating arc **20** is differentially permeable in that the net restraint imposed by the wall is a decreasing function of the radius. This fact permits the arc wall to selectively pass the vapor particles of different mass as described below.

It is obvious that the angle of the arc **20** with respect to the axis of rotation has a direct effect upon the process. Such angle affects the centrifugal forces of the rotating mass of gas and/or vapors and also the angle has an effect in creating an elevated temperature in zone I which contributes to the heating of the solid and liquid material. The angle of the rotating arc **20** must be chosen so as to avoid throwing the material **26** out of the zone I. The angle measured from the horizontal of the arc **20** should be between 15° and 60° with preferred range being between 15° and 45°. If the angle becomes too great, then the arc follows the magnetic field too well and is therefore difficult to control.

Another factor which works together with the entrainment effect to keep the particles in the arc volume (zone I) is the higher viscosities of the gas within the arc volume. Viscosity of the gas and/or vapor is proportional to the square root of temperature. Because of its extremely high temperature, the viscosity of the gas and/or vapor within the arc wall volume is much higher than the adjacent cooler gases and/or vapors below and above the arc wall volume.

The present invention is intended to be particularly useful in vaporizing materials which have very high vaporization temperatures, such as Al_2O_3. Within the arc volume defined by zone I, the temperature is well in excess of the 3253°K boiling point of Al_2O_3. Importantly, these vaporization temperatures exist only in the relatively small arc wall volume defined as zone I. The temperatures above zone I and below the arc **20** can be and are substantially less than 3000°K. The walls of the housing **12** therefore have still lower temperatures. Thus, difficult problems of wall structure and cooling at temperatures in excess of 3000°K are avoided. Relatively simple solid walls made of common materials can be used.

The present invention has been used to vaporize Al_2O_3 in the following manner. An apparatus similar to what is shown in FIG. **1** was constructed except no outlet **24** was provided. Thus, the vaporized material was retained within the chamber **12.** The water cooled copper electrodes **16 and 18** were connected to a source of electrical power which developed **36** kva. Argon was used as a carrier gas and injected through an inlet 14 at 12 cubic feet per minute. The distance between the electrodes **16** and **18** was **4** centimeters and an arc of that length was struck between the electrodes with a resulting arc current of 400 amperes producing an arc voltage of 90 volts. The electrodes **16** and **18** are positioned such that the arc **20** and hence the arc wall measured at an angle of 30° from the horizontal. The magnetic coil **22** was energized by an appropriate source of electrical power so as to generate an axial magnetic field B equal to 4000 gauss. As stated above, the material **26** was Al_2O_3. The charge was 100 particles of chemically pure number **8** to number **14** mesh (0.060 – 0.080 inch) particles which were fed downwardly onto the arc wall over a period of about 3 seconds. The arc duration after start of the particle insertion was approximately 8 seconds. Following shut-down, examination revealed more than 80% of the particles of Al_2O_3 were vaporized. Still further, a deposit of aluminum was found on the initially bright copper annular electrode **16.** The reasons for this is discussed in respect to the embodiments illustrated in FIGS. **3–4.**

It has heretofore been explained that the arc wall developed by revolving arc **20** is differentially permeable and that the net restraint is a decreasing function of radius (r) as measured from the central axis of the apparatus **10.** This fact permits the arc wall to be used to pass, selectively, vapors of different mass. In other words, the arc wall can be used as a separator.

Referring now to FIG. **2,** there is shown an apparatus **10′** similar to the apparatus **10** of FIG. **1** except that it has been modified to function as a separator as well as a heater and vaporizer. Because of the similarity between the apparatus **10** and the apparatus **10′**, like elements illustrated in FIG. **2** have been identified by primed numbers. Accordingly, a complete description of the apparatus illustrated in FIG. **2** is not necessary. Rather, reference to the description of the apparatus in FIG. **1** can provide sufficient details as to the function of various elements of the apparatus **10′**. Instead, what follows is a description of those elements which differentiate the apparatus of FIG. **2** from that of FIG. **1.**

It may be that the material to be vaporized in the apparatus **10′** consists of a molecule made up of two atoms. For example, such material may be Al_2O_3. Assume further that the magnetic field, current and rotational speed of the arc **20′** have been optimized for the vaporization of Al_2O_3. If vaporization takes place at a sufficiently high temperature, it will be accompanied by dissociation into the components Al and O, with different atomic masses of **27** and **16,** respectively. Other materials may similarly dissociate into their atomic constituents or a mixture of two or more gases of any kind.

As previously stated, the arc wall generated by revolving arc **20'** presents a uniform restraint to the gases and vapors whirling within the arc volume of zone I. However, a differential force due to the varying centrifugal forces is acting upon the arc wall. Since aluminum and oxygen have different atomic masses, the aluminum will pass through the wall at some radius r_1 and the oxygen will pass through the wall at some radius r_2. The radius r_1 must be smaller than the radius r_2 where the oxygen O will feel sufficient centrifugal force to escape through the arc wall. The volume into which the oxygen escapes can be divided from the volume into which the aluminum escapes by a dividing wall **40'**. Wall **40'** can be made of any material that is capable of withstanding high temperatures, such as carbon. The aluminum can be condensed and collected as a liquid on a cool wall surface of the chamber **12'**. The oxygen can be allowed to escape through the outlet **42'** or in any other conventional manner.

Thus, the apparatus **10'** acts to separate constituent elements by heating them beyond vaporization to the point where they are dissociated.

As an alternative, the rotational speed ϕ of the arc **20'** can be reduced to where the oxygen is not forced through the arc wall. Instead, the aluminum passes through the arc wall at some radius r_3 which is greater than r_1. The oxygen can then be taken off from the arc volume (zone I) in any convenient manner such as through an opening provided in the electrode **18'**.

Regardless of whether the apparatus illustrated in FIGS. **1** and **2** is used as a separator or not, it is apparent that the aluminum or heavier molecules and of course the heavy particles prior to vaporization tend toward the apex of the conical arc volume. This is advantageous since this is the hottest part of the arc volume. For this reason, it is advantageous to arrange the feed apparatus **30** so that the particles of material **26** enter the arc volume defined by zone I relatively close to the central axis.

Although the present invention has been illustrated as including only one revolving arc **20** or **20'**, it should be understood that two or more revolving arcs could be used. Thus, revolving arcs below the arc **20** could be provided so that additional heating of the vaporized material takes place. In this way, it may be possible to heat the vapor beyond dissociation even into partial or complete ionization.

Still further, it may be desirable to assist the heating effect of the revolving arc by providing a plasma torch or other heating devices. Such plasma torch may be located on the central axis of the device such as in the position of the electrode **18'**. Of course, electrode **18'** would have to be modified so as to be annular and surround the torch.

In the embodiment illustrated in FIG. **1**, it was assumed that the apparatus would take advantage of the semi-permeable nature of the arc wall and that the vaporized material would be exhausted through the outlet **24**. In the embodiment illustrated in FIG. **2** wherein the apparatus **10'** is used as a separator, the aluminum vapors are passed through the arc wall but the oxygen vapors, as pointed out, can be otherwise exhausted, such as through an opening provided in the electrode **18'**. It should therefore be pointed out that it is not necessary to cause vaporized material to pass through the arc wall even where the process is used merely to vaporize, but not separate material. The rotating arc **20** provides an arc wall which in turn defines a volume (zone I) the interior of which is filled with vaporized material. This is what provides the sufficiently long residence time to vaporize a solid or liquid particulate material. However, the vapor, once generated, can be caused to pass through the arc wall, or to rise upwards and away from the arc volume (zone I).

The vapor generated within the arc volume is caused to pass through the arc wall if the volume above the imaginary line **38** is a closed volume so that the vaporization of the material causes a pressure build-up, or the pressure due to the carrier gas is sufficient, or the combination of these pressures is sufficient to force the vapors through the arc wall.

However, it is equally possible to vent the volume above the imaginary line **38** through an opening provided in the walls of chamber **12.** By appropriate venting, there will be either no appreciable pressure build-up or a small pressure build-up that is not sufficient to force the vapors through the arc wall. A small pressure build-up is preferred since the back pressure can be used to force vapors through the vent.

Referring now to FIG. **3**, there is shown a modification to the embodiment illustrated in FIG. **1** wherein an appropriate venting means **40''** has been provided in the wall of chamber **12** above zone I. The apparatus illustrated in FIG. **3** is the same as the apparatus **10** in FIG. **1** except that it has been modified as just described and in addition, the outlet **24** has been eliminated. The apparatus illustrated in FIG. **3** is designated as apparatus **10''** and like elements have been identified by double-primed numbers. Accordingly, a complete description of the apparatus illustrated in FIG. **3** need not be repeated herein.

A further modification of the embodiment illustrated in FIG. **3** is the displacement of inlet **14''** to a position remote from the axis of the apparatus **10''** so that the electrode **42''** can be suspended co-axial with and above the post electrode **18''**. As shown, the electrode **42''** is connected to the electrode **16''** by the resistor **46''**. This resistor prevents the arc **20''** from being transferred to the electrode **42''** by maintaining an appropriate potential difference.

The purpose of the apparatus **10''** illustrated in FIG **3** can now be explained. As indicated when describing an example of how Al_2O_3 can be vaporized, a coating of aluminum was found on the initially bright copper electrode **16.** Such a deposit of aluminum indicates that separation of constituent parts of the material being vaporized can be achieved. In the example given, aluminum was obviously separated from oxygen which is the only other constituent part of Al_2O_3. The mechanism by which the aluminum was separated from the oxygen is not completely understood, but there are two mechanisms by which such separation may occur. They are explained hereinafter. An important point, however, is that aluminum separation was accomplished without passing the vapor through the arc wall. The apparatus illustrated in FIG. **3** may be used to accomplish such separation.

As stated, there are two possible processes or mechanisms by which the apparatus illustrated in FIG. **3** may be used to separate one constituent species of material from the remaining constituent species. One process is by rapid quenching. Thus, in the example given, aluminum may have been quenched on the electrode **16**. Rapid quenching is a recognized mechanism and is described by Rains and Kadlec in Metallurgical Transactions, Volume **1**, pp. 1501–1506, published June, 1970

Rapid quenching can occur if the work material is only dissociated.

The second process or mechanism by which separation can occur (e.g., aluminum from oxygen) is when the material is both dissociated and partly ionized. Where Al_2O_3 is vaporized, the aluminum, having a lower ionization potential, is partly ionized. As such, it will be electrically attracted to the electrode **16.** It should also be noted that both the quenching and the ionization process may occur simultaneously.

From the foregoing, it can be seen that the apparatus illustrated in FIG. **1** can also be used to effect a separation process. Thus, if the electrode **16** be a cathode and the vapors within zone I be heated until at least partial ionization of the constituent species, such as aluminum, takes place, then the electric field will attract the partly ionized species to the cathode electrode and the pressure developed within and above zone I will force the other constituent species, such as oxygen, to flow through the arc wall.

The apparatus illustrated in FIG. **3** can be used to separate a constituent species from the remaining species with or without ionization. In this instance, one of the species can be quenched or, if ionized, attracted to the cathode electrode and hence deposited out. The remaining species, such as oxygen, can be freely vented through the vent **40''**.

The embodiment of the apparatus illustrated in FIG. **3** includes the third electrode **42''** which may be referred to as a cold finger collector. The electrode **42''** is preferably made of aluminum and is water cooled. The value of the resistor **46''** is preferably quite high, (e.g., two megohms) and serves to maintain the electrode **42''** at a potential difference with respect to the electrode **16''** so that the arc **20''** will not jump to electrode **42''**. Being cooled, the purpose of the electrode **42''** is to quench one of the constituent species (e.g., aluminum) after vaporization in a process wherein there is no ionization, only dissociation. Thus, the cold finger collector **42''** serves merely to supplement the electrode **16''** by causing one constituent of a dissociated material, such as aluminum, to condense upon its surface thus being collected apart from the remaining constituent species.

Referring now to FIG. **4**, there is shown yet another embodiment of the invention wherein the apparatus **110** can be used to separate an ionized vapor species from un-ionized vapor species and also to separate and collect that species by quenching on a cooled electrode. The apparatus **110** illustrated in FIG. **4** is similar to the apparatus **10** in FIG. **1** except that it has been modified as hereinafter described. Because of the similarity, like elements illustrated in FIG. **4** have been designated with similar numbers except that they are listed in hundreds rather than tens to distinguish the two devices. Accordingly, a complete description of the apparatus **110** is not necessary. Rather, reference to the description of the apparatus in FIG. **1** can provide sufficient detail as to the function of various structural elements.

The apparatus **110** includes several additional cold finger collector electrodes **143**. Only one of the electrodes **143** is fully shown. A description of one electrode **143** is sufficient since all of the electrodes are of the same construction.

As shown, electrode **143** is suspended from the top wall of the chamber **112** by the mechanism **150** which includes conventional means such as a hydraulic ram for adjusting the height of the electrode **143** is relation to the electrodes **116** and **118.** Electrode **143** is preferably made of aluminum and is water cooled by conventional means so that it is normally at a substantially lower temperature than the electorde **116.** Electrode **143** is connected through resistor **146** to voltage supply **148.** Voltage supply **148** is also connected to electrode **116.** The purpose of voltage supply **148** is to maintain electrode **143** at a higher negative potential than the electrode **116.** Preferably, the electrode **143** is at a higher negative potential of between 20 to 100 volts with respect to electrode **116.** Resistor **146** is a limiting resistor having a value of between 2 to 10 ohms. All of the electrodes **143** are spaced apart equally and located at the same radial distance measured from the central axis of the apparatus **110.**

The purpose of providing electrodes **143** is to collect ionized vapors from within the zone I. Because of their higher negative potential, ionized vapors will now be drawn to the electrodes **143** rather than to the cathodic electrode **116.** The advantage of such electrodes is that they provide a separate collector location that is neither disturbed nor strongly heated by the rotating arc **120.**

The apparatus **150** raises each of the electrodes **143** so as to maintain the position of their distal end approximately at the boundary of zone I (imaginary line **138**). This provides for the formation of aluminum rods on a continuous basis.

There are three electric fields which exist simultaneously within the apparatus **110** to affect the ions within the zone I. There is the electric field extending between the electrodes **143** and the anode post electrode **118.** There is also an electric field between the electrodes **143** and the cathodic annular electrode **116.** Still further, there is the electric field between the electrodes **143** and the rotating arc **120.** This latter field is strongest when the arc **120** is immediately below any particular electrode **143.** In the absence of positive ion flow to the electrode **143,** such electrodes are negative by the full voltage of the voltage supply **148.** Once ion flow commences, the negative potential of any one of the collectors **143** falls due to the ion current flow through resistor **146** until it approaches the voltage potential of electrode **116.** However, it cannot fall as low as the potential of electrode **116** because under such circumstances current could not be attracted to the electrodes **143.** Resistor **146** prevents transferring the arc from electrode **116** to one of the electrodes **143** as does the resistor **46''** in the apparatus in FIG. **3.**

In the embodiment shown in FIG. **4,** the uncollected gases, such as oxygen when Al_2O_3 is vaporized, are exhausted through vent **140.** In the alternative, vent **140** may be closed and pressure allowed to build until the uncollected gases are driven through the arc wall and exhuasted through outlet **124.** Outlet **124** would normally be closed when vent **140** is being used.

If desired, either or both electrodes **118** and **116** can be made of carbon rather than copper. This may be advantageous when separating aluminum out of dissociated Al_2O_3. Thus, evaporated carbon atoms or ions can combine with the O to form CO. In this way, contamination of the collected aluminum by evaporated can be avoided.

The present invention may be embodied in other specific forms without departing from the spirit or essential attributes thereof and, accordingly, reference should be made to the appended claims, rather than to the foregoing specification as indicating the scope of the invention.

I claim:

1. A process for separating the constituent species of solid or liquid particulate material by increasing the residence time of the material in a high temperature zone, comprising the steps of:

revolving an electric arc extending between two electrodes to define a surface of revolution, said surface of revolution including within its boundaries an arc volume;

directing said particulate material so as to be incident upon said surface of revolution;

revolving said arc at a rate sufficient to make the surface of revolution impervious to particulate material in solid or liquid form and to heat the particulate material within the arc volume so that at least a portion of the particulate material is vaporized and dissociated into constituent species; and

removing at least one of the dissociated constituent species from the arc volume.

2. A process in accordance with claim 1 wherein the step of removing at least one of the dissociated constituent species includes passing the dissociated constituent species through the surface of revolution.

3. A process in accordance with claim 1 wherein the step of removing at least one of the dissociated constituent species includes venting that species away from said arc volume through a surface remote from said surface of revolution.

4. A process in accordance with claim 1 wherein the step of removing at least one constituent species includes condensing the one constituent species upon a surface that is below the vaporization temperature of that species and at a lower temperature than the temperature within the arc volume.

5. A process in accordance with claim 4 wherein the step of condensing at least one constituent species includes condensing said species upon an electrode.

6. A process in accordance with claim 4 wherein the step of condensing the one constituent species includes condensing said species upon a third electrode to which the arc current does not flow.

7. A process in accordance with claim 1 including revolving said arc by interacting it with a magnetic field.

8. A process in accordance with claim 1

wherein said constituent species have significantly different masses and said step of removing at least one of the dissociated constituent species from the arc volume includes:

passing more than one dissociated constituent species through the surface of revolution while maintaining the particulate material within said are volume; and

separating at least one species from the other species passed through said surface of revolution by passing said at least one species through an area of the surface of revolution that is different from the area where said other species passed through said surface of revolution as determined by the different centrifugal forces applied to each constituent species depending upon its mass and rotational velocity; and

guiding that separated constituent species away from said arc volume.

9. A process in accordance with claim 1 including entraining said particulate material within a mass of gas revolving within said arc volume.

10. A process in accordance with claim 9 wherein said mass of gas includes said material in a gaseous form.

11. A process in accordance with claim 1 wherein said surface of revolution is generally conical.

12. A process in accordance with claim 11 including positioning said conical surface of revolution at an angle to define an arc volume that maximizes the residence time for said particulate material.

13. A process in accordance with claim 11 wherein the angle of said conical surface of revolution measured from a surface normal to the axis of said conical surface is 15° to 60°.

14. A process in accordance with claim 1 including revolving said arc at a rate between 5000 to 100,000 revolutions per minute.

15. A process in accordance with claim 1 the steps of causing a mass of gas to revolve within the arc volume and entraining said particulate material within said revolving mass of gas within said arc volume.

16. A process in accordance with claim 15 wherein said revolving mass of gas includes the dissociated constituent species of the vaporized particulate material.

17. A process for separating the constituent species of solid or liquid particulate material by increasing the residence time of the material in a high temperature zone, comprising the steps of:

moving an electric arc extending between electrodes to define an arc wall including within its boundaries an arc volume;

directing said particulate material into said arc volume so as to be incident upon said arc wall;

increasing the residence time of the particulate material inside said arc volume sufficiently to permit the transfer of heat energy to said particulate material so that at least a portion of the particulate material is vaporized and dissociated into constituent species; and

removing at least one of the dissociated constituent species from the arc volume.

18. A process for vaporizing solid or liquid particulate material by increasing the residence time of the material in a high temperature zone, comprising the steps of:

revolving an electric arc extending between two electrodes to define a surface of revolution, said surface of revolution including within its boundaries an arc volume;

directing said particulate material so as to be incident upon said surface of revolution;

revolving said arc at a rate sufficient to make the surface of revolution impervious to particulate material in solid or liquid form and to heat the particulate material within the arc volume so that at least a portion of the particulate material is vaporized; and

removing said vaporized material from said arc volume.

19. A process in accordance with claim 18 including removing said material in its gaseous form by passing the gaseous material through said surface of revolution while maintaining said particulate material within said arc volume by means of said revolving arc.

20. A process in accordance with claim 18 including removing said material in its gaseous form by venting it away from said arc volume through a surface remote from said surface of revolution.

21. A process in accordance with claim 18 wherein said surface of revolution is generally conical.

22. A process in accordance with claim 21 including positioning said conical surface of revolution at an angle to define an arc volume that maximizes the residence time for said particulate material.

23. A process in accordance with claim 21 wherein the angle of said conical surface of revolution measured from a surface normal to the axis of said conical surface is 15° to 60°.

24. A process in accordance with claim 18 including revolving said arc at a rate between 5,000 to 100,000 revolutions per minute.

25. A process in accordance with claim 18 including revolving said arc by interacting it with a magnetic field.

26. A process for separating the constituent species of solid or liquid particulate material by increasing the residence time of the material in a high temperature zone, comprising the steps of:

revolving an electric arc extending between two electrodes to define a surface of revolution, said surface of revolution including within its boundaries an arc volume;

directing said particulate material so as to be incident upon said surface of revolution;

revolving said arc at a rate sufficient to make the surface of revolution impervious to particulate material in solid or liquid form and to heat the particulate material within the arc volume so that at least a portion of the particulate material is vaporized and dissociated into constituent species and at least one of those species is at least partly ionized; and

removing the partly ionized species from the arc volume by electrically attracting that species to an electrode of opposite polarity.

27. A process in accordance with claim 26 wherein the step of electrically attracting the species partly ionized includes attracting that species to a third electrode to which the arc current does not flow.

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