Oct. 10, 1961 B. KARLOVITZ 3,004,137

METHOD AND APPARATUS FOR THE PRODUCTION OF HIGH GAS TEMPERATURES

Filed June 7, 1960 3 Sheets-Sheet 1

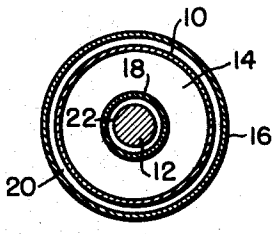


Fig. 2

Fig. 1

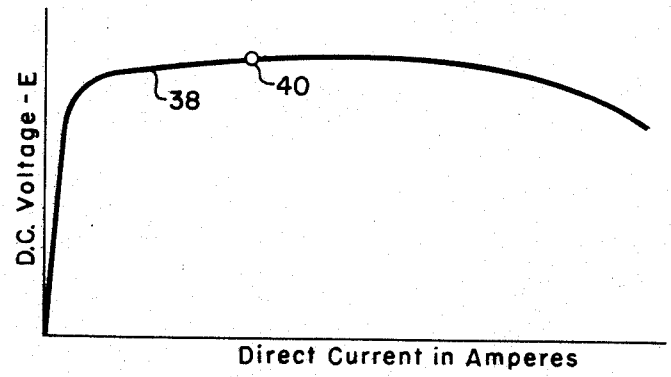


Fig. 3

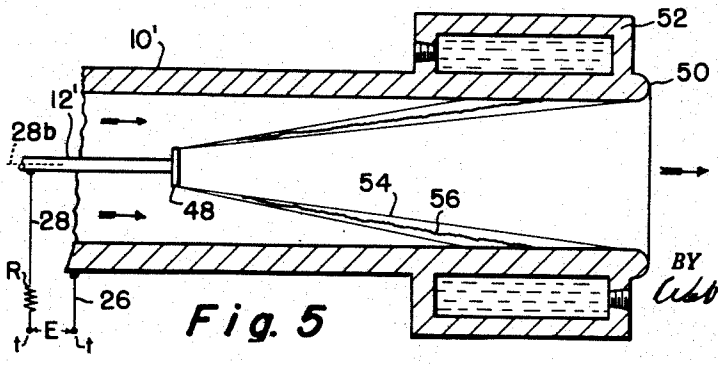


Fig. 5

INVENTOR.
Bela Karlovitz
BY
Abbott Mackey & Burden
HIS ATTORNEYS

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METHOD AND APPARATUS FOR THE PRODUCTION OF HIGH GAS TEMPERATURES

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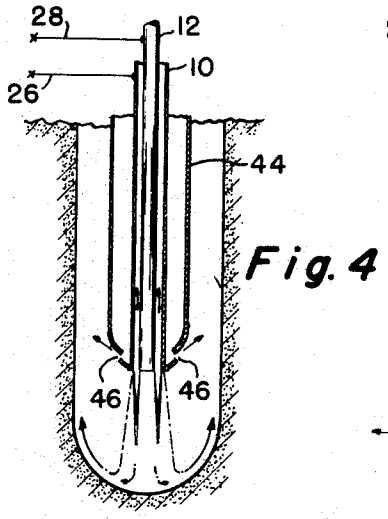


Fig. 4

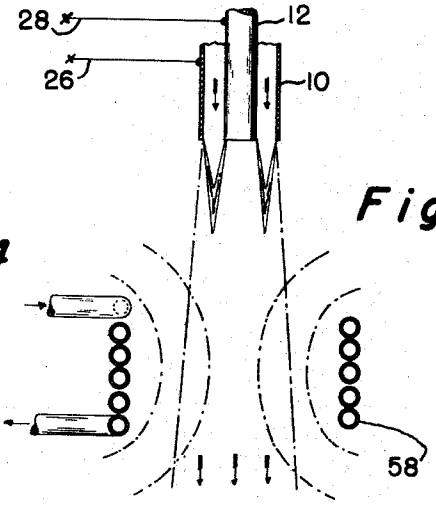


Fig. 6

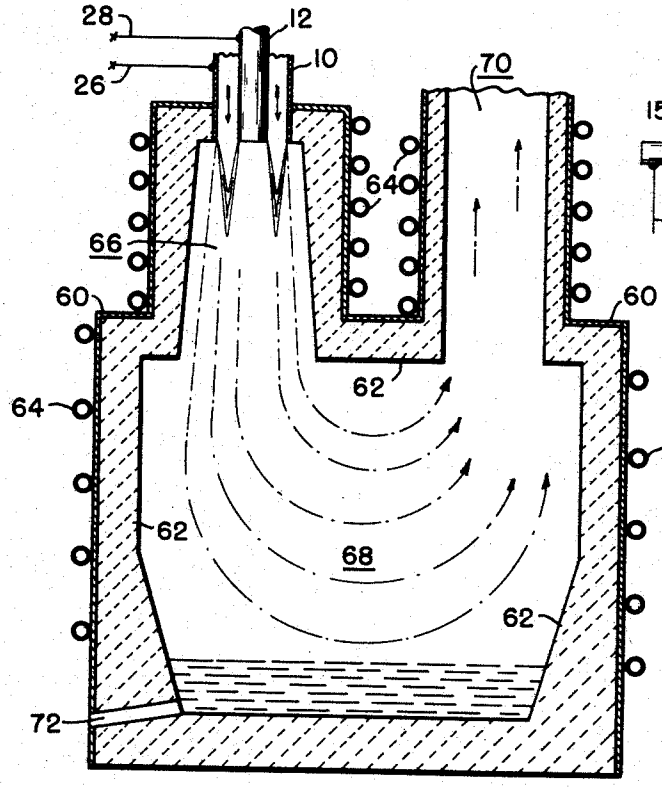


Fig. 7

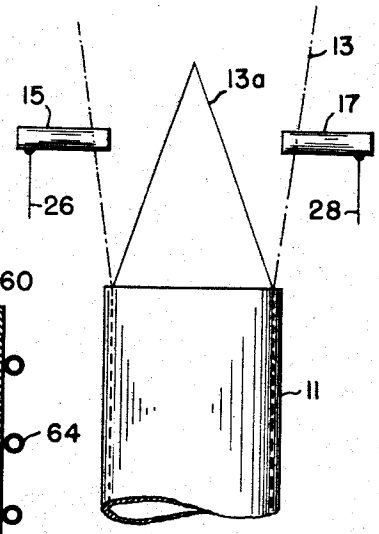


Fig. 2A

INVENTOR.
Bela Karlovitz

BY
Wilt Mackey & Burden
HIS ATTORNEYS

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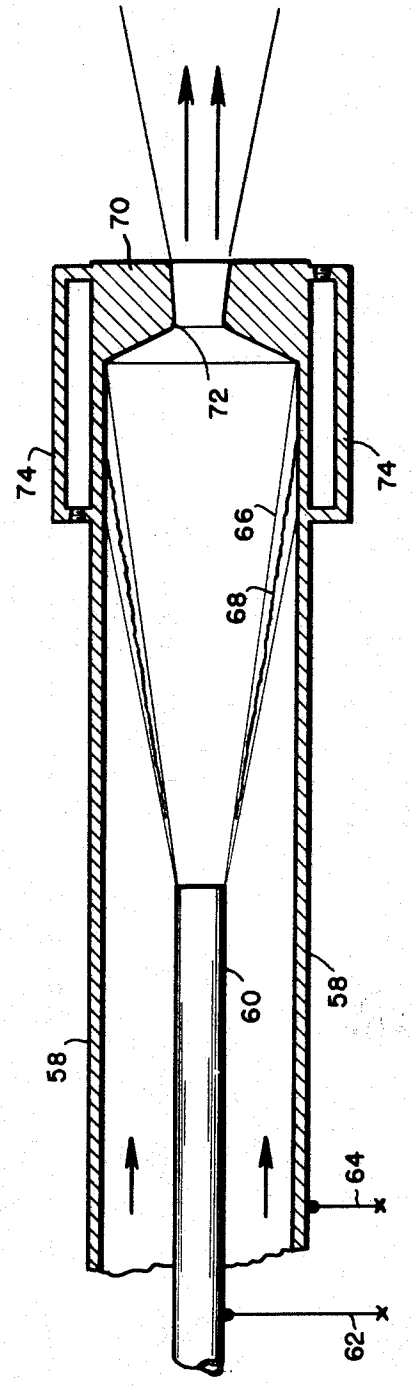


Fig. 8

INVENTOR.
Bela Karlovitz
BY
Wibb Mackay + Burden
HIS ATTORNEYS

United States Patent Office 3,004,137 Patented Oct. 10, 1961

3,004,137

METHOD AND APPARATUS FOR THE PRODUCTION OF HIGH GAS TEMPERATURES

Béla Karlovitz, Pittsburgh, Pa., assignor to Combustion and Explosives Research, Inc., Pittsburgh, Pa., a corporation of Pennsylvania

Filed June 7, 1960, Ser. No. 34,590
14 Claims. (Cl. 219—75)

The present inventions relate to method and apparatus for the production of high gas temperatures. More particularly, they relate to the burning of ordinary fuels, such as air-fuel mixtures, and superimposing on the flame a substantial electrical discharge to further heat the products of combustion. This addition of electrical heating energy to a hot flame readily elevates it to a working level ranging essentially between the exceedingly high operating temperature of an electric arc, on the one hand, and the ordinary air-fuel flame on the other, this temperature range being otherwise an expensive one to operate within by known methods, such as burning premium fuels like hydrogen or acetylene or by oxygen enrichment of the combustion air, or is not obtainable at all without the use of electric arcs.

This application is a continuation-in-part application of my copending application Serial No. 663,065, filed June 3, 1957.

In general, my inventions use inexpensive fuels which, in the burning stage, produce temperatures reaching roughly 2000° K. or above, and then a relatively high voltage, low current distributed discharge is introduced utilizing electric power as the second stage to reach the high temperature desired. There are many important applications involving heat which cannot be carried out at the lower temperatures available from burning ordinary fuels. Desired metallurgical processes like the termal reduction of aluminum cannot be carried out at these low temperatures. High temperature welding and flame cutting work, melting metals, refractories, and materials present in the earth's crust are greatly improved by my method and apparatus. My inventions are also useful in chemical processes requiring high temperatures, for example, the manufacture of acetylene.

By "distributed discharge," I refer to an electrical discharge which is distributed more or less uniformly through the flame produced by burning gases. It is to be emphasized that the distributed discharge provided by my invention is a separate and distinct thing from arcs which are low voltage, high current discharges concentrated into narrow filaments between two electrodes. The distributed discharge applied by my inventions consists of a relatively high voltage, low current discharge which, in effect, supplies heating current flowing through the entire flame volume. The advantages of this type of discharge are, first, the electrode problem is simpler due to the smaller currents for the same power input, and, second, substantially the entire volume of gas flow passes through the discharge and, therefore, is heated directly by the discharge.

I have shown certain presently preferred embodiments of the invention in the accompanying drawings, in which:

FIGURE 1 is a fragmentary longitudinal sectional view which is partially schematic and illustrates apparatus embodying my inventions;

FIGURE 2 is a transverse section taken along the lines II—II of FIGURE 1;

FIGURE 2A is an elevation view of a different form of apparatus embodying my inventions;

FIGURE 3 is a graph showing an operating characteristic of the burner;

FIGURE 4 is a diagrammatic showing of the use of

apparatus embodying my inventions in the drilling of holes in the earth's surface;

FIGURE 5 corresponds to FIGURE 1 but shows a modified form of apparatus;

FIGURE 6 is a fragmentary vertical section showing a further modified form of apparatus;

FIGURE 7 is a vertical section of a furnace for reducing metallic oxides and embodying my inventions; and

FIGURE 8 corresponds to FIGURES 1 and 5 but shows a still further modified form of apparatus.

Referring to FIGURES 1 and 2, my burner has a casing or burner tube **10** forming an outer electrode and containing a concentric center electrode **12**. The electrodes **10** and **12** are spaced apart to define an annular gas flow channel **14** adapted to carry an explosive mixture composed, for example, of air and an ordinary hydrocarbon fuel.

An outside sleeve **16** and an inside sleeve **18** closely fit the respective electrode members to provide an annular gas passage **20** surrounding the main channel **14** and another annular gas passage **22**. The gas passages **20** and **22** terminate at the rim of the burner to supply a pair of annular pilot flames **20***a* and **22***a* which may be used to stabilize an annular wedge-shaped flame brush **24** when the velocity of the gases requires it.

An electrical power circuit comprises a lead **26** which may be grounded and is connected to the burner tube electrode **10** and a lead **28** connected to the center electrode **12**.

In operation, the mixture is burned in the flame brush **24**. Within the visible turbulent flame brush, a thin instantaneous combustion wave, indicated by the wavy lines **36**, separates the cold unburned mixture from the hot combustion gas. Within this thin combustion wave, the gas temperature increases severalfold and the density of the gas correspondingly decreases. In the absence of any externally applied electric field, ionization of considerable concentration appears in the combustion wave **36** and a lower level of ionization persists in the hot gas flow downstream of the flame brush.

The electrodes **10** and **12** are physically separated by a cold relatively dense mixture of electrically insulating gas inside the burner tube and by a generally wedge-shaped cold mass of combustible gas extending between the rim of the burner tube and the body of the flame brush. In the electrical sense, however, the electrodes **10** and **12** are connected by the ionized regions of the combustion wave and by the ionized region of the hot burned gas.

I impress either A.C. or D.C. voltage on the electrodes **10** and **12** to add electrical heating current to the flame and FIGURE 1 is illustrative of one way of using A.C. power. An input circuit **30** including the secondary winding of a step-up transformer **32** is connected to supply alternating current to the electrode lead wires **26** and **28**.

This impressed voltage moves the ions and the electrons present in the flame and produces a comparatively weak current flow between the electrodes, distributed throughout the volume of the flame. At first, the current density is highest in the immediate vicinity of the combustion wave, because here the ionization density is the highest and the path length of the discharge is shortest. As the voltage applied to the electrodes is increased ionization by collision sets in, the current and with it the power input into the flame increases. With increasing power input, the gas temperature increases. At high gas temperatures, significant amounts of temperature ionization may appear, depending on the ionization potential of the constituents of the burned gas. This ionization, due to the high temperature of the gas, increases the current density and reduces the voltage at which the desired power can be applied to the flame. Therefore, thermal ionization of the gas flow introduces an upper limit for the tempera-

ture up to which the gas flow can be heated by a distributed high voltage discharge. However, the gas temperature can be increased beyond this limit by low voltage, heavy current type distributed discharge, as will be discussed below.

The maximum gas temperature which limits the range of the high voltage discharge is determined by the ionization potential of the constituents of the combustion gas. For a gas mixture with about 1% NO content, the limiting temperature is around 4000° K. For gas mixtures consisting of CO, CO_2, N_2, and H_2O, the limiting temperature is around 6000° K.

It is well known that in a quiescent gas atmosphere a distributed "glow" type discharge can be maintained only at reduced gas pressure. With increasing pressure, the distributed discharge becomes unstable and ultimately the discharge current becomes concentrated into a narrow filament, and the discharge changes over into a low voltage arc. The reason for this instability and subsequent transition is that any small incidental increase in the current density in some portion of the discharge increases the gas temperature and ionization density in that region of the discharge and reduces the gas density. Thereby the conductivity of this region is increased above that of its surroundings which causes a further concentration of the current. At low gas pressures, diffusion equalizes differences in gas temperature and ionization density with sufficient rapidity so that a distributed discharge is possible. At higher gas pressure, molecular diffusion is not powerful enough to prevent instability and the discharge goes over into a concentrated, low voltage arc discharge.

As described above, it is highly desirable to maintain a distributed, high voltage discharge in the flame for my purposes. This is possible, and transition to a concentrated arc can be avoided, because in a flame there are several powerful factors acting which help to maintain the distributed discharge. First the flame temperature due to combustion is already high and, therefore, the density of the gas is small. For example, the density of a gas at 1 at. and at 2000° K. corresponds to the density of a gas at 0.15 at. at room temperature. Also, a small change in the already high gas temperature causes only a small change in the gas density. Furthermore, the flame gases are already ionized to a small degree due to the combustion process. Therefore, small fluctuations in the current density have much smaller concentrating effect on the discharge in a flame than on a discharge burning in atmospheric air.

Second, there is a strong turbulence present in a turbulent flame, which, enhanced by low density and high temperature, has a very strong dispersing effect as compared with molecular diffusion. Due to this turbulence, incidental fluctuations of temperature and ionization density are evened out before they could lead to a concentration of the discharge.

A third factor is the constant renewal of the gas mass which carries the electrical discharge. Thereby, any mass of gas is exposed to the discharge for a short time interval only during which large differences of temperature and density cannot develop.

With reference to the graph of FIGURE 3, I show an operating curve **38** illustrating my stabilized operation in which electric arcs are prevented from forming. The curve **38** represents current in amperes plotted against a D.C. voltage E. At first, the current increases slowly with increasing voltage. In this region, the current is carried by the ionization present in the flame. At higher voltage, the current increases more rapidly because of additional ionization produced by collisions. At somewhat higher voltages, the current increases rapidly due to thermal ionization of the gas. At some point (**40**), the voltage reaches a maximum and from there on the voltage decreases with increasing current. In this region of negative characteristic, the density of thermal ionization increases rapidly and the discharge eventually may break down into a low voltage arc.

As a safety measure to prevent arcing and runaway current in case the voltage becomes too high, I may provide a pair of series ballasts including a resistance R and an inductance L in the input circuit **30** of FIGURE 1. The voltage drops across R and L as the current and its rate of change increase, thereby absorbing more voltage and lowering the available potential drop between the electrodes **10** and **12**. The ballast thus produces a necessary stabilizing effect to the current curve over the area beyond the point **40** where it starts to display a decreasing or negative resistance characteristic.

In FIGURES 1 and 2, I have shown a burner in which the flame is completely bounded at its base by the electrodes. However, it is not necessary that the flame be so bounded. The electrical discharge can be distributed by two electrodes separated from the burner and projecting into the flames from opposite sides thereof. FIGURE 2A shows such an arrangement, in which there is a burner tube **11** through which a fuel-air mixture flows and is ignited at the mouth of the tube forming a flame **13** having a flame brush **13***a*. Two electrodes **15** and **17** connected to leads **26** and **28**, respectively, extend into the flame from opposite sides. A distributed electrical discharge is created across the flame and substantially all of the stream of combustion gas passes through the discharge.

In connection with FIGURES 1, 2 and 2A, I have described flames formed from premixed explosive mixtures. My inventions may also be employed with diffusion flames. In such case, the fuel gas only is supplied to the tubes **10** and **11**.

In the following, I estimate the discharge voltage, first, for the case when thermal ionization is negligible, and, second, for the case of appreciable thermal ionization of the gas. To begin with, the electric field strength of a glow discharge positioned in a column of air is in the order of

$$E/p = 20 \frac{\text{volt/cm.}}{\text{mm. Hg}}$$

where E is the electric field strength in volt/cm., and p the gas pressure reduced to 0° C. Under working conditions with a flame temperature of 2730° K. and atmospheric pressure, the corrected gas pressure is $p=76$ mm. With this value of p, the electric field strength of the discharge equals:

$$E=p=76\times 20=1520 \text{ volt/cm.}$$

Reasonably, under working conditions, a path length of discharge connecting the electrodes along the flame is 10 cm. and the voltage of the discharge under these conditions equals:

$$E=10\times 1520=15{,}200 \text{ volts}$$

to which the voltage drop at the electrodes, amounting to several hundred volts, has to be added in figuring the overall voltage required.

At such high voltages, moderate glow discharge currents are sufficient to carry large amounts of power to the flame. For example, with 16,000 volt discharge voltage, a current of 2 amperes releases

$$\frac{16{,}000\times 2}{1000}=32 \text{ kw.}$$

power in the flame, amounting to a substantial heat release rate of 110,000 B.t.u./hr.

In a situation where there is an appreciable thermal ionization of the gas, the calculations are as follows. A combustion gas at atmospheric pressure, consisting of N_2, CO_2, CO, and water vapor at a partial pressure of 140 mm. Hg but no NO or metal vapor, contains at 4000° K. approximately 2×10^{11} ions and electrons per cubic centimeter. At a voltage gradient of 500 volt/cm., the current density is 0.137 amp./cm.^{2}, the heat input is 68.5 watt/cm.^{3}, and the temperature increase of the gas flow,

685° C./cm. measured in the direction of the gas flow, at a gas flow velocity of 1000 cm./sec.

In contrast to the above example, the ion-electron concentration, and with it the current density, become much higher if only small amounts of NO or metal vapors are present in the combustion products. For example, at 4000° K., Na at a partial pressure of .01 mm. Hg provides an ion-electron concentration of 2.28×10^{13} ions and electrons per cubic centimeter. At a voltage gradient of 100 volt/cm., the current density is 5.1 amp./cm.^{2}, the heat input is 510 watt/cm.^{3}, and the temperature increase of the gas flow is 5100° C./cm. assuming a gas flow velocity of 1000 cm./sec.

The ion-electron concentration increases very rapidly with increasing gas temperatures. Therefore, the volt-ampere characteristic of the discharge can be very sensitive to changes in the gas temperature. This sensitivity may be reduced by the addition of very small amounts of metal atoms with low ionization potential to the gas mixture. These additives approach complete ionization at comparatively low gas temperatures and provide in the temperature range of interest a nearly constant background ionization. For example, at 3000° K., Na at a partial pressure of 0.001 reaches a degree of ionization of 0.48 and provides an ion-electron concentration of 1.5×10^{12}/cm.^{3}. At 4000° K., the degree of ionization is 0.995, and the ion-electron concentration is

$$2.4\times10^{12}/\text{cm.}^3$$

The important consideration in the carrying out of my inventions is the production in a flame of a distributed electrical discharge, i.e., a discharge which is spread out more or less uniformly throughout the volume of the flame. As much electrical power can be supplied through the flame as is required to achieve the desired temperature. The chief limitations are practical considerations. Thus, if the temperatures are high and if the constituents in the gases have low ionization potentials, heavy currents may result. The strength of these currents will be limited by the availability of suitable electrodes.

Because of the high temperatures developed in flames in accordance with my inventions and because of the excellent heat transfer properties of the products of combustion of these flames due to the recombination of disassociated molecules at lower temperatures, the flames can rapidly melt any material present in the earth's crust. Therefore, these flames are well suited for the production of deep wells. In FIGURE 4, I have illustrated diagrammatically apparatus whereby my inventions can be used for such a purpose. One or more burners, such as the one shown in FIGURE 1, is mounted in a drill tube **44**, one only being shown in FIGURE 4 for simplicity of illustration. In the burner, a combustible mixture is fed through a tube **10** which surrounds an electrode **12**, as explained in connection with the description of the structure shown in FIGURE 1. A high voltage is applied between the electrode **12** and the tube **10** by the leads **26** and **28**. The flame is stabilized by annular pilot flames (not shown in FIGURE 4) which are the same as the pilot flames **20***a* and **22***a* in FIGURE 1. Since the flame is stabilized by the annular pilot flames, the flow velocity of the gases may be very high, in the order of several hundred feet per second.

A high velocity, high temperature flame impinges on the bottom of the well where it is deflected and forms a thin sheet of hot blast which sweeps across the rock surface to be melted away. Because of the high flow velocity and resulting high turbulence, the relatively short distance between the stream of hot gases and the rock, and the high degree of disassociation of the products of combustion, the rate of transfer of heat to the rock is very high and heat loss from conduction in the rock constitutes only a small fraction of the heat supplied. The molten material is swept out from the bottom of the hole by the high velocity blast and may be broken up into small droplets

and carried to the surface by auxiliary air streams supplied through ports **46** adjacent the bottom of the drill pipe and opening upwardly.

However, in rock drilling, a high gas flow rate is important and, therefore, I prefer a modified burner, such as is shown in FIGURE 5, which produces a particularly high, burned-gas velocity. In this high velocity burner, two circuit leads **28** and **26** are fed from an electrical source in the preceding manner and these leads are respectively connected to a center electrode **12'** within the burner and to an outside electrode **10'** forming the burner tube. In the specific application to well drilling purposes, the lead **12'** to the center electrode is preferably arranged as an insulated coaxial conductor indicated by the dotted lines **28***b*, and the outer electrode **10'** constitutes the ground electrode. This conductor **28***b* will be attached to the inner end of the center electrode **12'** which has an enlargement at the opposite end forming a disc-shaped flame holder **48** which is both radially offset within the outer electrode **10'** and axially inwardly offset from the rim **50** thereof. A liquid filled cooling jacket **52** surrounds the burner tube in the vicinity of the burner tip **50** and suitable means is provided for circulating liquid coolant through that jacket while the burner is in operation. The flame holder **48** stabilizes the flame brush shown at **54** which is fed by an explosive air-fuel mixture flowing in the direction of the arrows to the right as viewed in FIGURE 5. The potential difference existing between the electrodes **10'** and **12'** causes a distributed discharge to form in the cone-shaped volume bounded by the combustion wave indicated by the wavy line **56**.

The tube **10'** has a uniform inside diameter and, therefore, the hot combustion products are confined in the same cross-sectional area as the unburned gases. The volume of the gases increases manyfold as they burn and the amount of their expansion forces them to accelerate and flow at a high rate. Consequently, feeding the unburned gas to the burner at an initially high flow rate will produce very high burned-gas velocities to reach at least approximately the speed of sound.

When a high velocity, high temperature jet of burned gases formed in this manner is used, the rate of progress is faster than when an arrangement such as is shown in FIGURE 4 is used.

As noted, heavy currents may be required to raise flame temperatures to the desired value. This is particularly true if the constituents of the gas forming the flame are such as to contain metal atoms in the flame because the ionization potential of metal atoms is low, for example, the ionization potential of aluminum is 5.90 volts and, of titanium, 6.83 volts. At temperatures exceeding 3000° K., the conductivity of the gas containing vapors of such metal will be high. For example, at 3000° K., a gas containing titanium vapor at a pressure of 1 mm. Hg will produce an ion-electron concentration of 2.56×10^{12} per cubic centimeter. At a voltage gradient of 1 volt per centimeter, the gas will carry a current density of .12 ampere per square centimeter. At 3500° K., the ion-electron concentration is 1.4×10^{13} per cubic centimeter and the current density is .38 ampere per square centimeter. At 4000° K., the ion-electron concentration becomes 1×10^{15} per cubic centimeter and the current density is 30 amperes per cubic centimeter.

Such high ionization densities require heavy currents in order to supply large amounts of electric power in any given volume of gas. It may be difficult or prohibitively expensive to use electrodes capable of carrying such heavy currents. In that case, it may be advantageous to introduce electric power to the high temperature gas by electromagnetic induction. Such an arrangement is shown in FIGURE 6. As there shown, a burner, such as is shown in FIGURE 1, is used to produce a flame, and a distributed discharge is created through the flame. Spaced axially from the front of the burner there is an electrical induction coil **58** which is energized by a source of

high frequency electric currents, the frequency being, for example, in the order of magnitude of 10,000 cycles a second. As shown in FIGURE 6, the products of combustion of the flame pass through the coil 58. The high frequency coil induces heavy current in the highly conducting gas stream in accordance with known principles of induction heating.

This electromagnetic induction heating method of increasing the temperature of the flame could be applied directly to the flame without creating a dtstributed electrical discharge through the flame as has heretofore been described, particularly if the ionization density of the gases has been increased by the addition of materials having a low ionization potential. However, it is particularly useful for increasing the temperature of flames which are already high due to the use of distributed electrical discharges, as it is at such temperatures that the design and construction of suitable electrodes becomes difficult.

My inventions are particularly well suited for certain metallurgical processes in which high temperature flames are required, for example, the reduction of aluminum or titanium oxide to the pure metal. I can carry out such reductions directly by flame because the flames can be raised to the required temperatures.

The reduction process is carried out in the flame by providing a reducing atmosphere in the combustion gas and introducing into the high temperature flame the metal oxide to be reduced in the form of a fine dust. The metallic particles melt and evaporate in the high temperature flame. Reduction is carried out on the surface of the particles or in the gas phase after evaporation. The metal as reduced appears in a vapor phase and is then condensed out from the gas stream as a liquid.

FIGURE 7 shows a furnace for carrying out this reduction practice. The furnace comprises a metal shell 60 lined throughout with refractory 62 and provided with cooling coils 64. The furnace is divided into a reduction chamber 66, a condensing chamber 68, and a gas outlet 70, the reduction chamber and outlet 70 being in the form of offsets from the condensation chamber 68 and being placed at the top of the chamber so that gas will flow from the reduction chamber into the condensation chamber and circulate in the condensation chamber before it passes out through the outlet 70. At the end of the reduction chamber which is away from the condensation chamber, I provide a burner similar to that shown in FIGURE 1. A combustible mixture is supplied to the burner of such nature that a reducing flame results with a high carbon monoxide or hydrogen content in the products of combustion. A distributed electrical discharge is established through the flame in the manner previously described, and the gas temperature is raised to the desired level. A metal oxide to be reduced in the flame is supplied to the flame by the gas stream in the form of fine powder. If carbon is necessary for the reduction process, this can be carried also by the gas stream, or it may be carried by a separate gas stream which envelops the flame.

The hot flame melts and evaporates the powdered metal oxide and the oxide is reduced to metal when in the gas phase. The metal vapor, along with the other products of combustion, then enters the condensation chamber where the temperature of the gas is reduced to such a degree that the metal vapor condenses. The condensation chamber is maintained at the proper temperature for carrying out this condensation of the metal by adjusting the rate of cooling of the shell 60 by the cooling coils 64 and by choosing a refractory lining of suitable thickness so that the cooling coils will be effective. The condensed metal droplets settle out from the gas stream and are collected in a pool of liquid in the bottom of the condensation chamber. The molten metal is removed from the bottom of the condensation chamber through a tap hole 72.

The exhaust gases leave the condensation chamber through a duct 70 and their heat may be recovered and utilized for other purposes by well-known apparatus or techniques. Fine metal dust and ore dust can be removed from the gas stream and returned to the process for recycling.

In certain applications of my inventions, it is desirable to have a flowing stream of high temperature gases, which stream is concentrated in a relatively small cross-sectional area and which stream flows at very high, even supersonic velocities. For example, such a stream of hot gases is useful in cutting rock wherein the cut which is produced is relatively narrow but many times deeper than its width. A concentration of the flow of hot gases results in a narrow cut and the high velocity of the hot gases sweeps away the loosened particles of rock as cutting progresses. FIGURE 8 shows apparatus for producing a concentrated stream of high temperature gases which flow at supersonic velocities.

The apparatus shown in FIGURE 8 includes a tube 58 which serves as the outer electrode and through which an explosive air fuel mixture flows from the left towards the right as indicated by the arrows in FIGURE 8. The apparatus also includes a flame holder 60 which also acts as an electrode. The electrode 60 is spaced centrally in the tube 58 and is spaced axially within the tube a considerable distance upstream from the end of the tube from which the hot gases flow. The space within the tube 58 between the end of the flame holder 60 and the jet nozzle 70 forms a combustion chamber in which substantially all of the explosive air-fuel mixture is burned. The size of this chamber varies in accordance with a number of factors, all of which are known to those skilled in the art, such as the rate of flow of the gases, the pressure under which they are flowing, the nature of the mixture and the pressure at which combustion is accomplished. In general, the distance between the flame holder 60 and the jet nozzle 70 will be at least twice the internal diameter of the tube 58.

The apparatus of FIGURE 8 also includes conventional means (not shown in FIGURE 8) for supplying the explosive air-fuel mixture into the tube 58 at elevated pressure. The actual pressure in the combustion chamber is determined by the desired velocity of the stream of hot gas as it leaves the burner. The relationship between pressure in the combustion chamber and exit velocity is well known.

Two leads 62 and 64 connected to an electrical source in the same manner as the embodiments previously described create a potential difference between the electrodes 58 and 60.

A flame is formed at the end of the flame holder 60 which creates a flame brush indicated by the line 66 in FIGURE 8. The potential difference existing between the electrodes 58 and 60 causes a distributed discharge to form in the cone-shaped volume bounded by the combustion wave indicated by the wavy line 68. A jet nozzle 70 is placed in the end of the tube 58 from which the hot gases flow. The nozzle 70 restricts the end of the tube 58 so that all of the products of combustion of the air-fuel mixture flow through the throat 72 of the nozzle at increased velocities.

A liquid filled cooling jacket 74 surrounds the tube 58 in the vicinity of the jet nozzle 70 and suitable means is provided for circulating liquid coolant through that jacket while the burner is in operation.

The details of a typical burner as shown in FIGURE 8 and burning an explosive mixture of kerosene and oil will now be given. The tube and outer electrode have an internal diameter of 1½". The central electrode is ⅜" in diameter and the end of this electrode is spaced four inches from the entry of the nozzle throat. The diameter of the nozzle throat is 0.35" and the diameter of the nozzle exit is 0.38".

An explosive mixture of air and kerosene is supplied to the tube under a pressure of approximately 58 pounds

per square inch and the mixture is regulated so that the air flows at the rate of 127 pounds per hour and the kerosene flows at the rate of 8.7 pounds per hour.

The voltage required to supply the required electrical power will vary from 1,000 to 2,000 volts, depending upon the amount of preionization of the flame. Preionization of the flame is accomplished by the addition of salts to the explosive mixture as has been explained above. The higher the degree of preionization, the lower is the required voltage. The current through the flame will then vary from 50 to 25 amperes.

Such a burner, operated as described above, will release by combustion 172,000 B.t.u. per hour. The heat equivalent of the 50 kw. of electrical energy supplied is 172,000 B.t.u. per hour. Thus, the burner produces a total of 344,000 B.t.u. per hour. The velocity of the flame jet is 4,750 feet per second and its temperature is approximately 3300° K.

From the foregoing description, it is apparent that the burner shown in FIGURE 8 will produce a concentrated stream of gases at high temperatures and flowing at supersonic velocities. Such a high temperature flame jet is useful in cutting or drilling extremely hard or refractory materials or for cutting metals by burning.

While I have described certain presently preferred embodiments of my invention, it is to be understood that they may be otherwise embodied within the scope of the appended claims.

I claim:

1. A method of producing a stream of high temperature gas which comprises creating a strongly turbulent stream of a combustible mixture forming a flame by chemical combustion in the stream, establishing a substantial electrical discharge distributed across the flame, and passing substantially all of the stream of combustion gas through the discharge to increase the temperature of said stream.

2. A method of producing a stream of high temperature gas which comprises forming a flame by chemical combustion in the stream, increasing the ionization density of the combustion gas, creating by electromagnetic induction a substantial electrical discharge distributed across the stream, and passing substantially all of the stream through the discharge to increase the temperature of said stream.

3. A method of producing a stream of high temperature gas which comprises forming an explosive mixture of gases flowing in a stream, creating a strong turbulence in that stream, forming a flame in the turbulent stream, establishing a substantial electrical discharge distributed across the flame, and passing substantially all of the stream of combustion gas through the discharge to increase the temperature of said stream.

4. A method of producing a stream of high temperature gas which comprises forming a diffusion flame in the stream, establishing a substantial electrical discharge distributed across the flame, and passing substantially all of the stream of combustion gas through the discharge to increase the temperature of said stream.

5. A method of producing a stream of high temperature gas as described in claim 1, in which metal compounds having low ionization potentials are added to the stream of gases in advance of the flame to increase the ion-electron concentration in the flame.

6. A method of producing a high velocity stream of high temperature gas which comprises creating a stream of a combustible mixture under elevated pressure, forming a flame by chemical combustion in the stream, establishing a substantial electrical discharge distributed across the flame, passing substantially all of the stream of combustion gas through the discharge to increase the temperature of the stream, and passing the heated stream through a jet nozzle thereby increasing the velocity of said stream.

7. A method of producing a high velocity stream of high temperature gas which comprises forming an explosive mixture of gases flowing in a stream at elevated pressure, creating a strong turbulence in that stream, forming a flame in the turbulent stream by chemical combustion, establishing a substantial electrical discharge distributed across the flame, passing substantially all of the stream of combustion gas through the discharge to increase the temperature of said stream, and increasing the velocity of said heated stream of combustion gas by passing it through a jet nozzle.

8. Apparatus for producing a stream of high temperature gas comprising a burner tube for creating a flame by chemical combustion in a gas stream, and means for establishing a substantial electrical discharge distributed across the flame, said means being positioned relative to the flame whereby substantially all of the combustion gas passes through said discharge and is heated by said discharge.

9. Apparatus for producing a stream of high temperature gas comprising a burner tube, an electrode centrally positioned within the tube and having one end terminating substantially at the center of the open end of the tube, means for supplying a flow of an explosive mixture in the annular space between the tube and the electrode, and means for creating an electrical discharge between the tube and the electrode.

10. Apparatus for producing a stream of high temperature gas as described in claim 9, in which a tube concentric with the electrode and a tube concentric with said burner tube form narrow annular channels through which an explosive mixture may flow to support pilot flames at the open end of the burner tube.

11. Apparatus for producing a stream of high temperature gas comprising a burner tube for creating by chemical combustion a flame in a gas stream, electrodes positioned adjacent the tube so as to have ends projecting into the flame, and means for establishing an electrical discharge between said electrodes and distributed through substantially all of the ionized portions of the flame.

12. Apparatus for producing a stream of high temperature gas comprising a burner tube for creating by chemical combustion a flame in a gas stream, a high frequency coil positioned axially of the burner through which the combustion gas may flow, and means for supplying a high frequency electrical current to said coil.

13. Apparatus for producing a stream of high temperature gas comprising a burner tube, a flame holder positioned centrally within the tube and defining with the tube an annular chamber for the flow of gas to support a flame within the tube, means for supplying a flow of combustible gas mixture through said annular chamber, said flame holder being axially spaced inwardly from an open end of the tube, the open end of said tube having a cross-sectional area at least equal to the cross-sectional area of the portion of the tube opposite to the flame holder, and means for creating an electrical discharge between the tube and the flame holder.

14. Apparatus for producing a stream of high temperature gas comprising a burner tube, a flame holder positioned centrally within the tube and defining with the tube an annular chamber for the flow of an explosive gas mixture to support a flame within the tube, means for supplying a flow of combustible gas mixture through said annular chamber at elevated pressures, a jet nozzle at the end of the tube from which the high temperature gas stream flows, said jet nozzle restricting the cross section of the end of the tube and having a jet throat therein through which the high temperature gas flows out of the tube, said flame holder being axially spaced upstream from said throat to form a combustion chamber of sufficient volume to burn substantially all of the explosive mixture within the chamber, and means for creating a substantial electrical discharge between the tube and the flame holder.

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