Feb. 1, 1966 B. KARLOVITZ 3,232,746

METHOD FOR REDUCTION OF METAL OXIDE

Filed Oct. 4, 1961 3 Sheets-Sheet 1

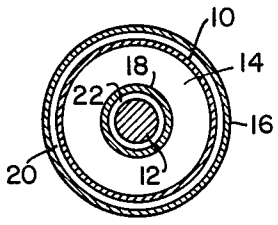


Fig. 2

Fig. 1

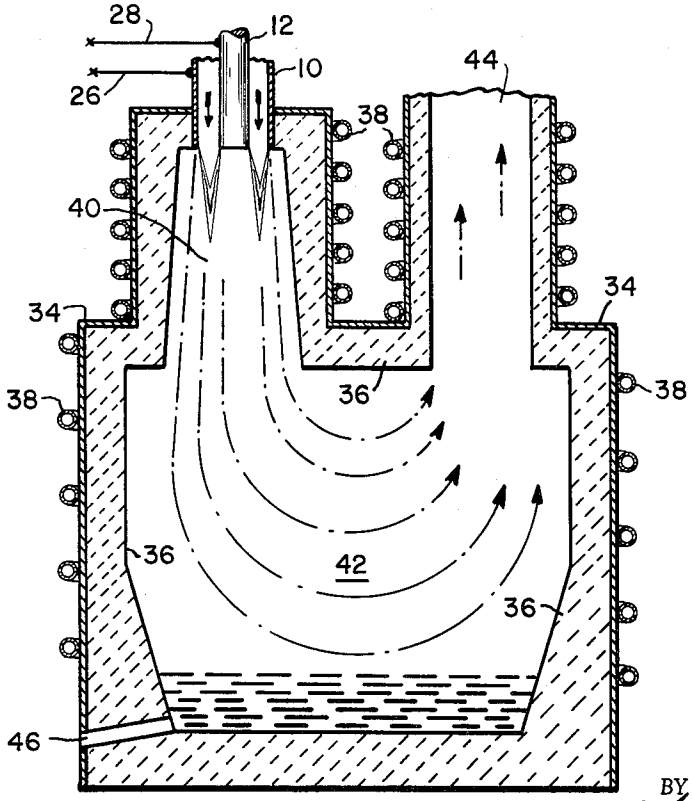


Fig. 3

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METHOD FOR REDUCTION OF METAL OXIDE

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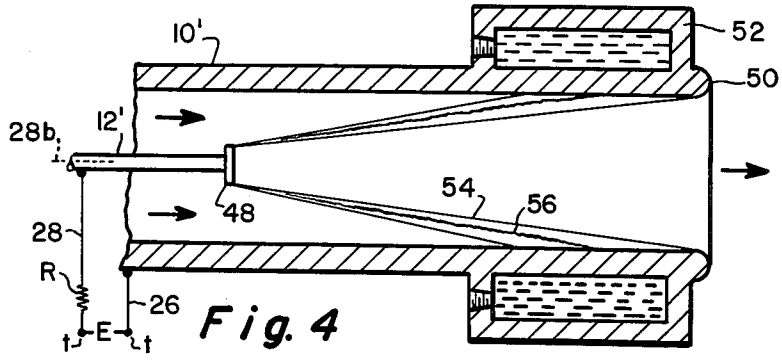


Fig. 4

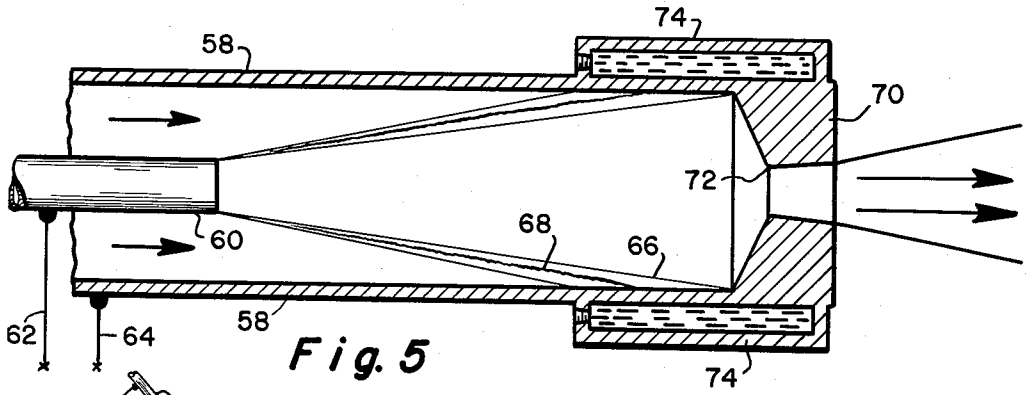


Fig. 5

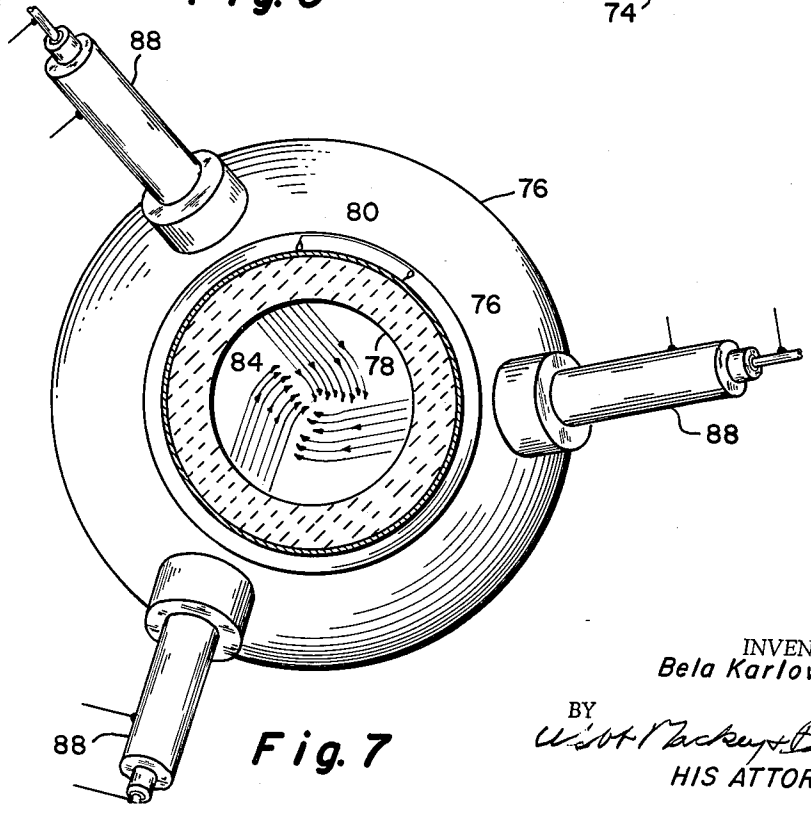


Fig. 7

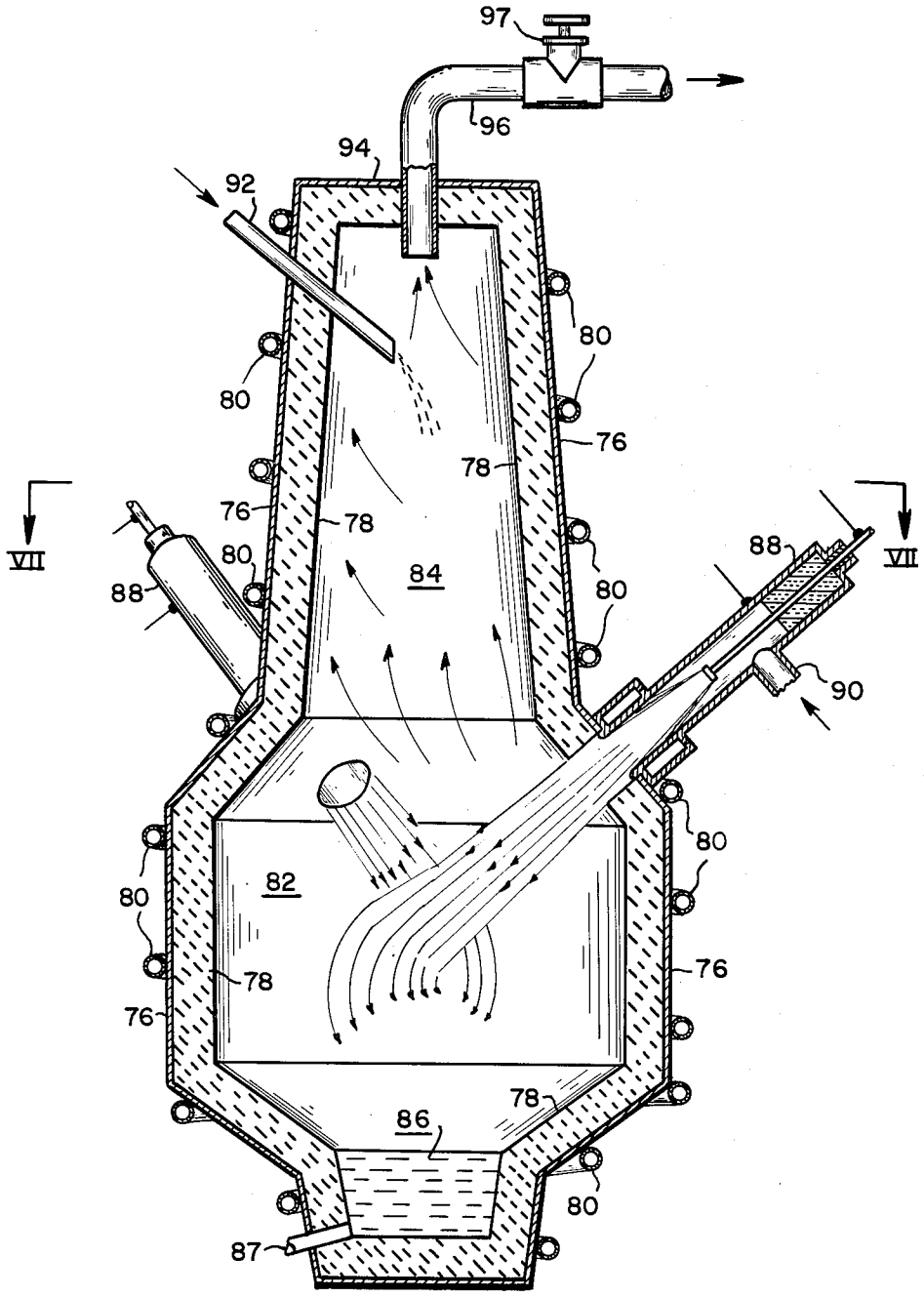
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METHOD FOR REDUCTION OF METAL OXIDE

Filed Oct. 4, 1961 3 Sheets-Sheet 3



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Fig. 6

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United States Patent Office 3,232,746 Patented Feb. 1, 1966

3,232,746

METHOD FOR REDUCTION OF METAL OXIDE

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Filed Oct. 4, 1961, Ser. No. 142,951
6 Claims. (Cl. 75—10)

This application is a continuation-in-part of my application Serial No. 34,590, filed June 7, 1960, now Patent No. 3,004,137, for "Method and Apparatus for the Production of High Gas Temperatures," which is a continuation-in-part of my application Serial No. 663,065, filed June 3, 1957, now abandoned.

My application Serial No. 34,590, now Patent No. 3,004,137, is directed primarily to inventions relating to method and apparatus for the production of high gas temperatures. The high gas temperatures produced by those inventions are useful in the reduction of metallic oxides and this application is directed to that subject-matter which is also disclosed in part in said application.

The inventions described and claimed in my application Serial No. 34,590, now Patent No. 3,004,137 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 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.

In general, my inventions use ordinary 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 of heating to reach the high temperature desired, as is more fully explained in my application Serial No. 34,590, now Patent No. 3,004,137.

As stated, this application is directed to method and apparatus whereby the high temperatures produced in accordance with said inventions are used in the reduction of metallic oxides. Such reductions can be carried out directly by these flames because the flames can be raised to the required temperatures.

In the accompanying drawings, certain presently preferred embodiments of the inventions are shown, in which:

FIGURE 1 is a fragmentary longitudinal sectional view which is partially schematic and illustrates apparatus which may be utilized in accordance with my inventions;

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

FIGURE 3 is a diagrammatic showing of a furnace in which the apparatus shown in FIGURES 1 and 2 is used in the reduction of metallic oxides;

FIGURE 4 corresponds to FIGURE 1 and shows a modified form of apparatus;

FIGURE 5 corresponds to FIGURE 1 and shows a still further modified form of apparatus;

FIGURE 6 is a diagrammatic showing of a modified form of furnace for the reduction of metallic oxides; and

FIGURE 7 is a section along the lines VII—VII of FIGURE 6.

Referring generally to the drawings, FIGURES 1, 2, 4 and 5 show burners for producing high gas temperatures which are required for the direct flame reduction of metallic oxides, and FIGURES 3, 6 and 7 show furnaces for carrying out the reductions.

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 burper tube electrode 10 and a lead 28 connected to the center electrode 12.

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.

The process of reducing metallic oxides 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 metal oxide particles may melt and evaporate in the high temperature flame. Reduction is carried out on the surfaces of the particles or in the gas phase after evaporation. The metal, as reduced, appears in liquid droplets or in a vapor phase and is then condensed out from the gas stream as a liquid.

FIGURE 3 shows a furnace for carrying out this reduction practice. The furnace comprises a metal shell 34 lined throughout with refractory 36 and provided with cooling coils 38. The furnace is divided into a reduction chamber 40, a condensation chamber 42, and a gas outlet 44, the reduction chamber and outlet 44 being in the form of offsets from the condensation chamber 42 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 44. 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 reduces the metal oxide and the metal vapor or droplets along with the other products of combustion then enter 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 34 by the cooling coils 38 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 46.

The exhaust gases leave the condensation chamber through the gas outlet 44 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.

If a high gas flow rate is required in a particular operation, I prefer a modified burner, such as is shown in FIGURE 4, 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. The lead 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 disk-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 rim 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 4. 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 outside electrode 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 which may reach at least approximately the speed of sound.

In connection with the burners shown in FIGURES 1 and 4, I have described flames formed from premixed explosive mixtures. These burners may also be employed with diffusion flames, in which case fuel gas only, or very fuel-rich mixture, issues from the electrode. Air or oxygen is entrained by this fuel gas jet from the surrounding atmosphere and a diffusion flame is anchored on the electrode.

In certain cases when very high flow velocities and turbulence levels are desired, supersonic flame jets may be used. FIGURE 5 shows apparatus which can be incorporated in the furnace shown in FIGURE 3 to produce a concentrated stream of high temperature gases which flows at supersonic velocities.

The apparatus shown in FIGURE 5 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 5. 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 5 also includes conventional means (not shown in FIGURE 5) 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 5. 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.

My method and apparatus for producing high gas temperatures can also be used in a process of reducing metallic oxides in which the metal oxides and carbon are introduced in the form of fine dust in a reaction zone, provided that the temperature in the reaction zone is kept above a certain minimum value depending upon the metal being reduced. The approximate minimum temperatures for a few metals are:

Fe about 700° C.
Si about 1540° C.
Mg about 1350° C.
Al about 2000° C.
Ca about 2150° C.

If the metal oxide and carbon are kept in intimate contact at temperatures exceeding those given above, oxygen will leave the metal and join the carbon to form carbon monoxide. If the metal oxide and carbon are introduced in the form of particles, each of which contains both the oxide and the carbon in the right proportions, then the reduction is carried out as a homogeneous reaction. If the metal oxide and carbon particles are introduced separately, then the reaction is a heterogeneous reaction. In this case, oxygen is transferred from the metal oxide particles to the carbon particles by CO molecules which are oxidized by the metal oxide to form CO_2 which, in turn, is reduced to carbon monoxide by the carbon. If the temperature is maintained at least as high as the values stated above and if the carbon is well dispersed within the reaction zone, the transfer of carbon dioxide to carbon within the mixture is very rapid, provided there is also strong turbulent mixing of the components of the mixture.

In carrying out the reductions of metallic oxides in accordance with this process, the larger of the metal droplets formed in the reaction zone are thrown out of

the zone and they are allowed to flow into a pool. Smaller droplets float around in the reaction zone until they coagulate to form larger droplets or they may be carried out of the reaction zone by a stream of exhaust gases. These particles are entrained upon metallic oxide being introduced into the furnace if the oxide is introduced countercurrently to the exhaust gases.

However, it is not possible to carry out the reduction of all metal oxides at atmospheric pressure because of the vapor pressure of the metals at the temperatures at which the reduction takes place. For example, the reduction temperature of iron is 700° C. and its melting point is 1530° C., at which temperature the vapor pressure is 3×10^{-2} Hg and, therefore, evaporation losses of pure metal during the reduction process are negligible. However, aluminum melts at 658° C., but the reduction of Al_2O_3 must be carried on at least 2000° C., at which temperature the vapor pressure is 150 mm. Hg. Therefore, most of the aluminum metal would be produced in the vapor phase and would flow out of the reaction zone with the exhaust gases. During cooling of the exhaust gases, the reaction reverses and much of the metal vapor would reconvert into fine oxide dust. From the finely-divided fumes of metal and metal oxide, the metal could not be recovered.

To prevent the evaporation loss of metals having high vapor pressures at the temperatures at which the reductions must be carried on, the reaction is carried on at pressures higher than atmospheric so that the vapor pressure of the metal becomes small as compared to the total pressure. If pressures substantially higher than atmospheric pressure are maintained in the furnace, then the pure reduced metal can be collected in the form of droplets in the same manner as the metals having low vapor pressures at the temperature at which they are reduced. The required pressure for any given case can be determined as follows.

The products of the reduction reaction are the reduced metal and the exhaust gases which consist mainly of CO if oxygen is used to produce the flame, or CO and N_2 if air is used for this purpose. Some of the metal is carried off by the exhaust gases in vapor form. The fraction of metal carried off in vapor form is calculated from the following formula:

$$\frac{G_{vapor}}{G_{metal}}=\left(\frac{G_{CO}}{G_{metal}}\right)\left(\frac{P_{vapor}}{P-P_{vapor}}\right)\left(\frac{R_{CO}}{R_{metal}}\right)$$

where

G_{vapor} is the weight of metal carried off in vapor form;
G_{metal} is the weight of metal produced in the reduction process;
G_{CO} is the weight of CO produced in the reduction process;
P_{vapor} is the vapor pressure of the metal at the reduction temperature;
P is the total gas pressure in the furnace;
R_{CO} is the gas constant of CO; and
R_{metal} is the gas constant of the metal vapor.

In the example used for the reduction of aluminum, 2.34 kg. CO is produced for one kg. aluminum. The vapor pressure of aluminum is 150 mm. Hg at 2000° C.

$$\text{The gas constant for CO}=30.28\frac{\text{mkg.}}{\text{°C. kg.}}$$

$$\text{The gas constant for aluminum}=31.4\frac{\text{mkg.}}{\text{°C. kg.}}$$

Therefore, at one atmosphere absolute pressure

$$\frac{G_{vapor}}{G_{metal}}=\left(\frac{2.34}{1}\right)\left(\frac{150}{760-150}\right)\left(\frac{30.28}{31.4}\right)=55.5\%$$

At 5 atmosphere absolute pressure

$$\frac{G_{vapor}}{G_{metal}}=\left(\frac{2.34}{1}\right)\left(\frac{150}{5\times760-150}\right)\left(\frac{30.28}{31.4}\right)=9.25\%$$

The metal carried off in vapor form can therefore be reduced to any desired fraction by increasing the gas pressure in the reduction chamber.

As will be explained later, such a relatively small amount of metal escaping in vapor form can be returned to the furnace with the incoming metal oxide and carbon particles. Thus, the pressure to be used in any particular case is determined by the amount of metal in vapor form which practically can be returned by the incoming feed materials.

FIGURE 6 shows an improved furnace which I have invented for the reduction of metallic oxides. The furnace comprises a metal shell **76** lined with suitable refractory material **78** and cooled with external cooling coils **80**.

The furnace is divided into a reaction zone **82** and a feed shaft **84** which rises from the top of the reaction zone. As shown in FIGURE 6, the cross-sectional area of the feed shaft **84** at its portion adjacent the reaction zone **82** is smaller than the cross-sectional area of the reaction zone **82**. The furnace has a collecting zone **86** beneath the reaction zone and formed in the bottom of the furnace, from which molten metal can be withdrawn through a tap hole **87**.

Heat for carrying on the reaction of reducing a metallic oxide is supplied to the reaction zone preferably by a plurality of burners **88** which extend through the walls of the furnace at a point above the reaction zone **82** and which are positioned so as to direct a flame into the reaction zone.

As shown in FIGURE 7, the burners **88** are equally spaced around the furnace and they direct flames into the reaction zone in a direction slightly inclined away from the radial direction so that they impart a rotational motion to the gases in the furnace.

In FIGURE 6 burners such as the one shown in FIGURE 4 of the drawings are used. However, burners such as are shown in FIGURES 1 and 5 could also be used. An explosive mixture of fuel and air is supplied to each burner through an inlet pipe **90**. The fuel may be a hydrocarbon fuel, such as methane, powdered coal or coke, which is mixed with air, oxygen, or oxygen enriched air. Carbon monoxide generated in the reduction process can also be recycled to the burners. Instead of feeding an explosive mixture to the burners, fuel only can be supplied and the burners can be operated to produce diffusion flames.

If a concentrated stream of gases at high temperatures and flowing at supersonic velocities is desired to produce very high flame jet velocities and very high turbulence levels, a burner such as is shown in FIGURE 5 of the drawings may be used.

Inasmuch as a plurality of burners is used, the source of electrical power can be a balanced polyphase alternating current system in which the instantaneous sum of all currents is zero. In the furnace shown in FIGURES 6 and 7, three burners are used and, therefore, a three-phase system is used. Use of a polyphase system as the source of electrical current simplifies the connections because only one electrode is required for each flame. If only the electrodes of the burners are connected to the source of power, then an electrical discharge is distributed through the flames by voltage created between the electrodes.

A tube **92** (or several tubes) extends through the side wall of the feed shaft **84** near the top of the shaft and slopes inwardly to a point adjacent the center of the shaft. This tube is used to supply the metallic oxide to be reduced and the carbon both in the form of fine particles.

The feed shaft also has a top cover **94** through which an exhaust stack **96** extends. As shown in FIGURE 6 this exhaust stack extends through the top of the shaft and down into the shaft for a short distance and forms a cyclone separator which functions as hereafter described.

In operation, the powdered metallic oxide and carbon are introduced through the tube **92** and they move coun-

tercurrently through the outward flow of exhaust gases. The oxides will not be carried out through the exhaust stack because of their weight. If any particles are so small as to be carried upwardly by the exhaust gases, they will be separated by the cyclone separator just described.

Flames from the burners create a vortex due to their positioning and also create a high degree of turbulence. The high degree of turbulence increases the rate of reaction, i.e., the rate at which metal is reduced, and also makes possible the use of high voltages. The flames entrain the descending metallic oxide and carbon, carry them into the hottest portion of the reaction zone, and continuously agitate the particles until the oxide particles are reduced to metal droplets.

The larger metal droplets are thrown out by centrifugal force to the walls of the furnace which form the reaction zone. From the walls, the molten metal flows down into the collecting zone 86. The smaller metal droplets may remain suspended in the reaction zone until they coagulate to form larger droplets or they may be carried upstream by the exhaust gases. These droplets which are carried up into the feed shaft solidify on the incoming raw material and are carried back into the reaction zone. Likewise, any metal which is vaporized and passes in this form from the reaction zone condenses on the incoming raw material and is carried back into the reaction zone. There is further cooperation between the incoming raw material and the exhaust gases in that the exhaust gases preheat the incoming raw material and, therefore, the exhaust gases leave the furnace at relatively low temperatures.

The pressures required within the furnace are obtained by feeding the gases to the burners 88 at suitable pressure levels and by controlling the outflow of exhaust gases through the exhaust stack 96 by the pressure regulating valve 97.

Vaporized metal within the furnace will provide an ionizing additive to the flames and produce the required ion electron concentration. At 2500° K., the partial pressure of aluminum vapor is 150 mm. Hg and produces an equilibrium ion electron concentration of approximately 1×10^{13} per cubic centimeter. As noted above, for the reduction of metals with such a vapor pressure, it is necessary to raise the pressure within the furnace to a pressure above atmosphere to prevent evaporation loss of the metal. For example, for the reduction of aluminum, a pressure of five atmospheres is required. At that pressure, the critical voltage gradient can be calculated to be 300 volts per centimeter. At a practical operating level, i.e., a voltage gradient of 100 volts per centimeter, calculations show that the power input density may reach the value of 350 watts per cubic centimeter.

In the hot reduction zone, metal oxide particles and carbon dust particles are floating in a gas mixture consisting mainly of CO, metal vapors, small amounts of CO_2 and H_2O, and of N_2 if air was used for the combustion. The temperature of the gas is kept well above the temperature required for the reduction process by the electrical power input notwithstanding the heat absorbed by the reduction process. The rate of the reduction process is probably limited by the transport of the CO_2 molecules, which are formed on the surface of the metal oxide particles, to the carbon particles where the CO_2 is reduced back to CO. This transport is accomplished by turbulent diffusion, just like the transport of oxygen to the carbon particles in a highly turbulent combustion system. It may be expected, therefore, that the reaction rate will be comparable to the combustion rate in a highly turbulent furnace, for example, in a cyclone furnace. The heat release rate of a cyclone furnace is in the order of 5,000 to 10,000 kw. per cubic meter at atmospheric pressure. Therefore, it is to be expected that, at a pressure of five atmospheres, the pressure used in the example above, the power input into the reactor could reach 25,000 to 50,000 kw. per cubic meter magnitude. This permits a very high metal production rate in a compartively small furnace. The permissible electrical power input rate far exceeds the reaction rate estimated from the turbulent transport process; therefore, it would not limit the production rate of the furnace.

Calculations show that the method and apparatus described with reference to FIGURES 6 and 7 would allow a very appreciable reduction in the electrical power required to carry on a reduction operation. Thus, using the reduction of aluminum oxide as an example, the reaction is described by the following overall equation:

$$\frac{2}{3}Al_2O_3+2C=\frac{4}{3}Al+2CO$$

This reaction proceeds at temperatures above 2000° C. and consumes 5920 k. calories or 6.88 kwh. of energy per kilogram of aluminum, the required theoretical quantities per kilogram of aluminum being as follows:

1.89 kg. Al_2O_3
0.666 kg. C
5920 kcal. or 6.88 kwh.
By-product: 1.56 kg. CO

Applying the above reaction equation to a reduction carried out in accordance with my method, the requirements of feed materials and power consumption for the production of one kilogram of aluminum are (assuming that one kilogram of carbon is used instead of the theoretically required .66 kilogram of carbon and utilizing the combustion heat of the extra .34 kilogram of carbon to supply some of the heat required):

	Kcal.
1.89 kg. Al_2O_3+1.00 kg. C+0.445 kg. O_2=2.34 kg. CO+1 kg. Al	5095
Heat of fusion for 1 kg. Al	96
	5191
Heat carried by the exhaust gases at 2000° C	1685
Heat recovered by preheating 1.89 kg. Al_2O_3	945
Heat lost with the exhaust	740

Power requirement for the production of 1 kg. Al:	Kcal./1 kg. Al
Reaction heat	5191
Exhaust losses	740
Heat loss from furnace	1000
Total	6931

Since 1 kwh. equals 860 kcal., then

$\frac{6931}{860}$=8 kwh/kg. Al or 3.66 kwh/1 lb. Al

Oxygen requirement—0.5 kg. O_2/1 kg. Al
Carbon requirement—1.0 kg. C/1 kg. Al

It appears, therefore, that the electrical power requirement is reduced to less than one-half of the power requirement of the presently used electrolytic process. The cost of the additional carbon and of the oxygen required in my process is offset by the fact that the carbon is in the form of dust rather than in the form of electrodes and by the fact that an electrolyte (cryolite) is not required. It should also be noted that electrical power in the form of alternating current can be used directly and that it is not necessary to convert the alternating current into direct current as is required in the electrolytic reduction of aluminum.

With the foregoing calculations, reduction of aluminum oxide has been used. Equal savings in electrical power can be obtained by the use of my inventions in the reduction of other metallic oxides.

My process of reducing metal oxides in a high temper-

ature reducing flame may be applied for the production of pure carbon from carbon-bearing materials such as coal or coke. For this purpose, an electrically augmented high temperature flame is formed by burning any fuel, preferably coal or coke dust, in air and superimposing a distributed electrical discharge over the flame. Additional coal or coke dust is introduced into this flame and the temperature maintained at the level where the metal oxides forming the ash content of the coal or coke are reduced to metal and carbon monoxide. Metals such as aluminum and silicon are carried off in vapor form with the exhaust gases, while iron is mostly retained in the form of droplets. The exhaust gases are separated from the solid carbon particles in a cyclone separator and, after cooling the products, the remaining iron particles may be removed by magnetic separators.

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

I claim:

1. A method of reducing metal oxides which comprises forming a flame by chemical combustion, creating a substantial electrical discharge distributed across the flame, passing substantially all of the flame through the discharge to increase the temperature of the flame, introducing the oxides in powdered form in the flame, creating a reducing atmosphere within the flame, collecting drops of molten metal from said flame, and withdrawing the exhaust gases from said flame.

2. A method of reducing metal oxides as described in claim 1 in which a reducing atmosphere is created within the flame by adjustment of the chemical composition of the flame.

3. A method of reducing metal oxides as described in claim 1 in which a reducing atmosphere is maintained within the flame by adding powdered carbon to the flame.

4. A method of reducing metal oxides as described in claim 1 in which the reduction reaction is carried on under a pressure sufficiently above atmospheric to reduce to a predetermined level the amount of metal in vapor form which escapes with the exhaust gases.

5. A method of reducing metal oxides which comprises forming a flame by chemical combustion, creating a substantial electrical discharge distributed across the flame, passing substantially all of the flame through the discharge to increase the temperature of the flame, introducing the oxides to be reduced in powdered form into the flame, introducing carbon particles into the flame, flowing exhaust gases from the flame countercurrently to the oxides and carbon, and collecting molten metal droplets from said flame.

6. A method of reducing metal oxides which comprises forming a plurality of flames by chemical combustion, creating a substantial electrical discharge distributed through each flame, passing substantially all of each flame through the discharge to increase the temperature of each flame, flowing the flames in directions slightly inclined away from the radial direction so that they impart a rotational motion to the gases in the furnace and create a vortex having a high degree of turbulence, introducing the metal oxide and carbon particles into said vortex, and collecting molten metal droplets from said flame.

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