PLASMA ENGINEERING

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Plasma engineering is defined as the use of partly ionized gases for industrial purposes. The partly ionized gases may be made by high temperature combustion with seeding, by means of detonation waves or by means of high intensity electric discharges (DC arc or radio frequency induction). Plasma engineering has three branches: (i) Plasma power engineering. This includes the diode generator, plasma electrolyte fuel cells and magnetohydrodynamics (MHD). In the case of MHD to generate electricity from combustion or nuclear fission the problem is to get sufficient ionization to give a reasonable electrical conductivity after expansion to give the necessary high velocity for the gases. (ii) Plasma chemical engineering. This contains some very interesting possibilities for the manufacture of important endothermic compounds or elements produced by endothermic reactions from compounds. (iii) Plasma process engineering. Here the plasma torch is used to replace a combustion torch in cases where a pure inert atmosphere is essential or temperatures above 2500°K are required.

APPLICATIONS OF PLASMA ENGINEERING

1. Introduction

A whole new branch of engineering is growing up concerned with the applications of plasma physics and chemistry for useful purposes[1–4]. It is sufficient for the present purpose to treat as a "low-temperature" plasma any gaseous system containing at least of the order of 1 per cent of its molecules in the ionized state. Thus ordinary fuels burnt with air preheated to the highest industrial temperatures of 1400°C as in the open hearth furnace which give temperatures not exceeding 2000°C do not count as plasma since ionization is well below 1 per cent and in any case it is only a disadvantage where the object is to obtain as high a gas temperature as possible as it causes a considerable increase in the apparent specific heat of the gases. However, by preheating the air to 2000°C as can be done in a hot-valve pebble bed regenerator or by burning a rich fuel (*e.g.* oil or natural gas) with pure oxygen and then by adding an alkali metal with an ionization potential of a few volts, a genuine plasma with an electrical conductivity of the order of 1 (mho/cm) can be produced by turbulent diffusion flames. Plasma can also be produced by having a heavy electric current flowing between electrodes after combustion in a flame so that the combustion produces a certain proportion of the required enthalpy rise and also enough ions to give electrical conductivity to the gases. Fuel/oxidant

combinations with still higher theoretical combustion temperatures are hydrogen/fluorine (64,000 cal/mole HF) and aluminium/oxygen (388,000 cal/mole Al_2O_3). In effect the use of these fuels, like the use of the recombination energy of an already ionized gas like H^+, is not a method of producing a plasma from natural fuels, but a method of storing electric energy which has an infinite equivalent temperature on the thermodynamic scale since it can theoretically be turned into heat without any flow of gas having a heat capacity.

There is one other method of obtaining a plasma for a few hundred micro-seconds without electric power; the shock-tube in which a high pressure gas or a combustible mixture usually of H_2 or O_2 is held in a small chamber at one end of a strong cylindrical tube; a disc is ruptured and the gas or combustion products expand into a low pressure gas accelerating the shock-wave up to a velocity of several hundred m/sec. Adiabatic but not isentropic compression of the low pressure gas in front of the shock-wave produces a brief pulse of temperature up to some thousands of °K. The temperature ratio across the shock front is given for a perfect gas by†

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1/\gamma)} \exp\left(\frac{\Delta S}{C_p}\right)$$

The entropy increase is due to the sudden pressure rise and may be calculated from the conservation of momentum and energy. Thus for a pressure ratio of 200:1 across the shock, $\gamma = 1{\cdot}4$, $T_1 = 293°K$, the shock Mach No. required is 13·1, and the maximum temperature T_2 is 11,700°K whereas with isentropic compression over the same pressure ratio, T_2 would be 1330°K. This calculation only applies to an ideal gas with γ constant at 1·4 right up to the top temperature; a real gas such as nitrogen only reaches 6000°K at Mach 13. The shock Mach No. is highest when the ratio of sound velocity in the driver/driven gases is greatest and γ is low in the driver gas. The purpose of combustion in the driver gas is to raise its temperature and hence the sound velocity in it. The shock tube has so far only been used for experimental purposes but it is possible that it can be used for industrial production, *e.g.* of radicals.

The other methods of producing plasma all require the release of electrical energy in the gas. These are the direct and transferred DC high intensity constricted arcs and the high frequency induced discharge while the use of electron beams for heating may also be included here as a potential engineering technique. The DC arcs usually have carbon or tungsten cathodes which are not cooled so that they become hot enough to emit electrons freely. In one common arrangement the cathode projects along the axis of a cylindrically symmetrical water cooled anode and the cooling gas is introduced at the cathode end, often with a high velocity tangential flow. The hole in the water cooled anode narrows to a tube at the end remote from the cathode through which the plasma flows after heated by arc discharge.

The temperature of the heated gas will correspond to the equation which relates electric power input (expressed in cal) Z to the enthalpy of the plasma plus the heat radiated and conducted to the water cooled anode. In arcs at

†The list of symbols used herein is given on page 342.

atmospheric pressure radiation is the main mechanism of heat transfer and increases as T^4 for a "grey-body" arc.

$$Z = H(T) \cdot w + L$$

w = flow rate (g mol/sec);

$H(T)$ = enthalpy of plasma regarded as a function of its temperature (cal/g mol);

L = rate of heat flow to anode (cal/sec).

If w is made very small (zero gas flow) all of Z goes to the walls, in practical high intensity arcs L can be as low as 5 per cent of Z if T is at the lower end of the range, but will clearly rise and the highest temperature achievable is that when L is nearly equal to Z. The scale effect comes in here; for a constant length of arc and constant gas velocity the wall heat loss will increase as the diameter but with constant velocity the heat capacity of the gas will increase as d^2 so that the larger the arc the greater the temperature achievable. The electron temperature will be considerably higher than that of the heavy particles in the plasma since the applied electric field directly heats the electrons which heat the heavy particles by collision. The heavy ions will be at a slightly higher temperature than the heavy neutral particles, and any solid or liquid drops will be at a lower temperature again because of their thermal radiation to the walls. In the free burning arc the current lines are displaced by natural convection since the hottest regions have the highest gas conductivity, while temperatures are limited to about 7000°K max. In the constricted arc on the other hand temperatures exceeding 15,000°K have been obtained as the arc is mechanically held in place by the constricting walls.

The transferred arc has a second applied voltage which may be AC or DC between the cathode and an external conducting surface on to which the plasma jet is played. This is used when the surface is to be treated by the plasma, often containing a powder or liquid drops.

The velocity of the plasma jet leaving through the water-cooled anode is usually very high because of the great thermal expansion.

The "induction plasma torch" or radio frequency induction gas heater is used to produce temperatures up to 20,000°K in gases at relatively low velocities. The gas flows into one end of a quartz tube which is surrounded at the other end by a flat or cylindrical water-cooled copper coil. Ionization is initiated in the gas by various means such as a pilot arc discharge or an inductively heated graphite rod and 3–40 megacycle oscillation with a power of the order of 2 kw/ml of discharge volume, into the outer coil produces a single turn discharge in the gas. The upper limit of power input to the plasma is set by the overheating of the enclosing tube. The scale-up laws for such high intensity arcs have not yet been developed so the power input may depend on the volume or on the surface area. It is necessary to match the output impedance of r-f generator + work coil to a load impedance much less than that of the pilot plasma as the plasma impedance drops greatly as it enlarges. The plasma is hydrodynamically unstable unless one

uses vortex injection of the gas or better magnetic confinement by having a work coil with one reverse turn at the downstream end. The flux from this turn repels the plasma carrying the current induced from the other turns.

In applying the heat balance (equation 2) to this case ZE must be taken as the actual electric power input to the stabilised plasma which is equal to the HF generator power multiplied by an efficiency factor which may be much less than unity if the coupling is weak and is about a half under normal operating conditions.

Electron beams in high vacua are being used for melting refractory metals of high purity so that they should be included in an engineering review although there are no positive ions or neutral gas atoms in this case.

Thus for engineering purposes the production of a plasma is a matter of heating the gas to the required enthalpy shown in *Figure 1* so that the

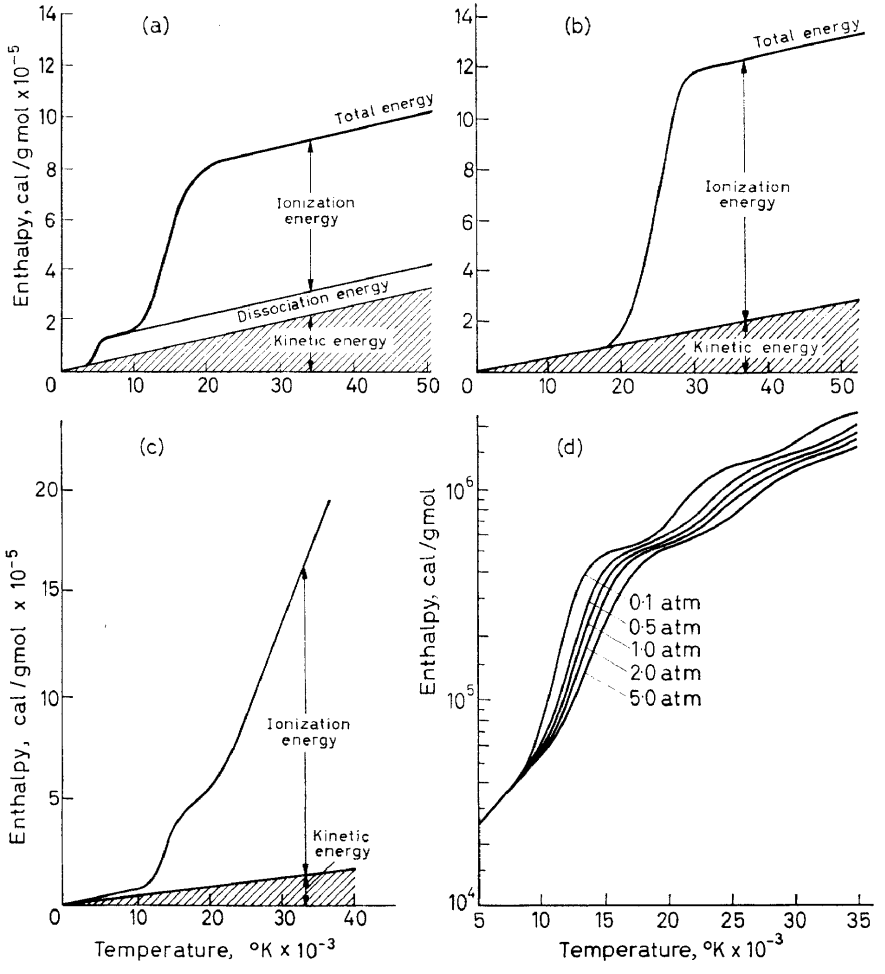

Figure 1. The enthalpy of pure gases at plasma temperatures. (*a*) Hydrogen (1 atm); (*b*) Helium (1 atm); (*c*) Argon (1 atm); and (*d*) Argon (various pressures—log scale).

required temperature and degree of ionization are produced. *Figure 2* shows the corresponding electrical conductivities.

Plasma engineering is the use of plasma for practical purposes and these are dealt with under the heading of electricity generation, chemical processes,

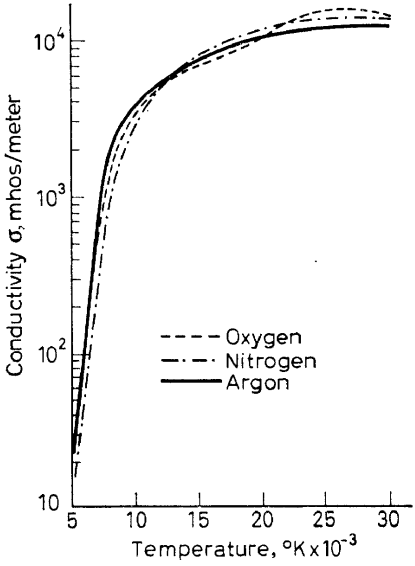

Figure 2. Variation of electrical conductivity with temperature for *pure* gases at 1 atm pressure.

and metallurgical and ceramic processes in the remaining sections of this paper. The use of plasma purely to provide high velocities or high temperatures for experimental purposes is not included.

2. The use of plasma for electricity generation

If plasma are to be used for electricity generation[5–9], the greater part of their enthalpy must come from the fuel which is the source of the energy, whether this is a chemical or nuclear fuel. This limits the equilibrium molecular temperature of the plasma very severely. On the other hand the plasma is required to conduct an electric current to an appreciable extent, so that a compromise with less than 1 free electron per 1000 molecules is usual in practice.

It is possible to use an electric arc, a high frequency discharge or other electrical method of increasing the electric conductivity of the working gas provided the electric power required for this is only a small fraction of the enthalpy released by the fuel reaction. There are two main methods at present whereby plasma are being used in the attempt to make an efficient conversion of thermal energy produced from chemical or nuclear fuels into electricity, the heated diode and magnetohydrodynamics. In the heated diode one plate is heated by the fuel reaction to a temperature at which it emits a substantial current of electrons, a cold anode nearby collects these

electrons so that for example, a current flows against a potential difference of the order of 2 volts with a temperature difference of 1500°K. By inserting low pressure cesium vapour which has an ionization potential of 3·88 eV the space between the electrodes can be essentially neutral so that space charge is eliminated and the current obtainable greatly increased. The system can be regarded in fact as a thermocouple with the cesium plasma as one of the metallic elements, the two electrodes being the hot and cold junctions. Obviously the inefficiency of this system is largely due to thermal radiation between the two electrodes which cannot be greatly reduced by reducing the emissivities of the surfaces. In practice 30 ampere can be obtained per square centimetre with a terminal voltage of 1 v.

It is at first sight theoretically possible to operate a plasma fuel cell, but no detailed theoretical or experimental work on this idea has been published. In this two exothermic reagents *e.g.* CH_4 and air, would be highly preheated in two separate heat exchangers, allowed to diffuse through two closely spaced permeable electrically conducting plates so that the exothermic reaction takes place partially at each electrode to give a DC power output with ionic diffusion across the plasma in the thin space between the electrodes. If the main ion is OH^- then the overall process is one of carrying oxygen from the air electrode (cathode for the cell reaction) to the fuel anode and the combustion products leave on the fuel side, passing to the two heat exchangers. Unless the enthalpy of the reaction products is able to supply almost all the preheat to the reactants in the heat exchanged the proportion of the reaction energy converted by reversible isothermal reaction to electricity will be small.

Interest in the use of plasma flowing at very high velocity through a magnetic field to generate a DC voltage and power output between electrodes at right angles to the flow and the magnetic field has been increasing very rapidly over the last 10 years. This is now usually called the magneto-hydrodynamic (MHD) or magnetoplasmadynamic (MPD) generation of electricity although I referred to it as the possibility of generating electricity by electro-magnetic gas braking in my Inaugural Lecture at Sheffield in 1954. In this case the induced voltage at right angles to the flow is given by the formula $E/d = 10^{-9}$ V.H. volts/cm.

There is also a Hall effect voltage along the direction of flow although the plans are usually made to keep this low ($w\tau \ll 1$). The external power W_0 obtained per unit volume of the magnetic field is given by the formula

$$W = \frac{r}{(1+r)^2} \cdot \sigma V^2 H^2 \cdot 10^{-6} \text{ watts/cm}^3$$

while the minimum length l required to slow the plasma down from velocity v_1 to a velocity v_2 which is a small fraction of v_1 is given by the formula

$$l = \int_0^1 \left[\left(\frac{P_2}{P_3} \right)^{3/2} \cdot d \left(\frac{v}{v_2} \right) \frac{\rho_2 v_2}{\sigma_2 H^2} \cdot \frac{(1+r)^2}{r} \right]$$

The minimum length occurs when the external load resistance is zero ($r = 0$); this is not a practical case since the useful power output per unit volume is then zero; however, the length for the maximum external power output case ($r = 1$) is less than 4 times this length, so this minimum length can be used for drawing conclusions. It is given by

$$l = \frac{\rho_1 v_1}{\sigma_1 H^2} \frac{2}{3\gamma M^2}$$

Thus if a given gas flow $\rho_2 v_2$ g/cm^2 of cross section of duct entry is to be slowed down in a reasonable distance σH^2 and $M_2{}^2$ must be as large as possible.

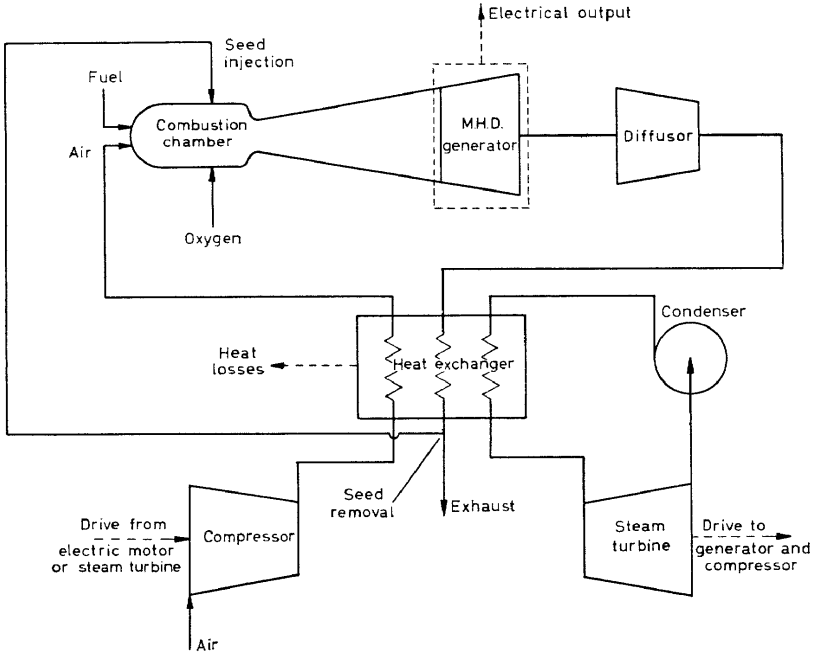

Figure 3. Simple thermodynamic diagram of a classical DC open cycle system

Figure 3 shows the simple thermodynamic diagram of a system of what may be called the classical DC open cycle. For a perfect gas going through a convergent/divergent nozzle of pressure ratio P_2/P_1 the temperature ratio due to the adiabatic expansion is given by the formula

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1/\gamma)}$$

while the velocity v_2 is given by the formula

$$\frac{1}{2} v_2^2 = \frac{C_p}{M} (T_1 - T_2)$$

Clearly, therefore, in order to give a high power output per unit volume of the magnetic field W there has to be a high velocity v_2 while in order to convert an appreciable fraction of the enthalpy after combustion into available kinetic energy one must have a big temperature drop $(T_1 - T_2)$ in the convergent/divergent nozzle.

The plasma goes through the magnetic field under conditions of constant density and static pressure and temperature while the directed kinetic energy is being converted into the electric power output. Now the electrical conductivity of the plasma depends on the concentration n_e of free electrons and this in turn is given by the formula

$$n_e = \text{const. } T^{3/2} \exp\left(-\frac{eV_1}{RT}\right)$$

where V_1 is the ionization potential of the most easily ionized atomic species in the gas. In order to get a reasonable length to bring down the gas velocity and a reasonable power output per unit volume of the magnetic field one must have an electrical conductivity of the plasma greater than 10 mho/m. This requires a concentration of free electrons roughly one in a thousand of the neutral species; such a proportion can only be obtained by making the exponent in the above formula very small. To do this one has to add to the gas an alkali metal such as potassium with an ionization potential 4·33 and even then as shown by *Figure 4*. T_2 has to be of the order of 2500°K.

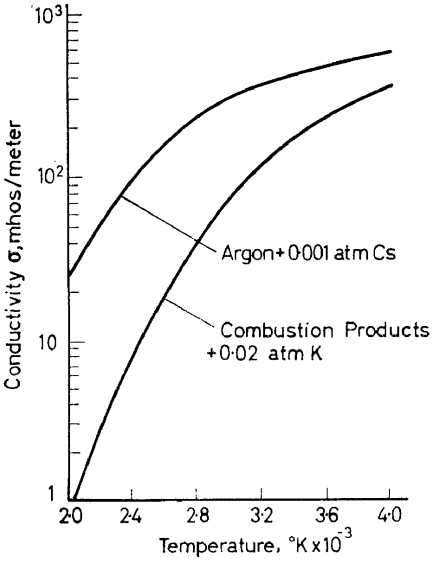

Figure 4. Variation of electrical conductivity with temperature for *seeded* gases

If we take the case of combustion of fuel oil with air preheated to 1000°C T_1 will not exceed 2500°K since the enthalpy of the combustion gases is of the order of 13,000 calories per gram mole. Thus T_1 is hardly any higher than T_2 so that one can only use a small temperature drop for accelerating the gas and can only convert a small fraction of the fuel into electricity. A considerably higher T_1 can be obtained by using pure oxygen for combustion or by using a regenerative hot valve reversing system to preheat the combustion air after compression to a temperature of 2000°C. Alternatively one can accept the low efficiency and regard the system as one which gives a small amount of additional energy before the combustion gases are passed at atmospheric pressure through a conventional boiler system. This is the basic problem of the classical DC generating system that one only obtains a high thermodynamic efficiency at the expense of a big temperature drop and this makes it very difficult to obtain sufficient conductivity in the plasma.

A rather similar difficulty arises in the case of the closed cycle system. Here one can choose a better carrier gas for the seeding material, for example argon or helium which are monatomic and therefore much less likely to absorb free electrons when the proportion of free electrons greatly exceeds that corresponding to thermal equilibrium. It is also possible to use cesium with an ionization potential of 3·8 eV as the seeding material. Here, however, one has to use a heat exchanger working up to T_1 as there is no reaction enthalpy to increase the working fluid temperature with the problem of sealing against leakage at very high temperatures; thus T_1 is much more limited in this case.

It is possible to accept these basic limitations caused by the thermal nature of the plasma in MHD generation and conclude that open cycle MHD generation from combustion will only be used either to give a few per cent topping up efficiency at the beginning of a normal 30–40 per cent efficient steam cycle or, using pure oxygen for combustion to produce a multi megawatt output for special experimental purposes with a low capital cost and very low efficiency for periods up to half an hour. This last alternative is already being developed in the United States but it does not of course make any significant contribution to the major problem of making electricity more efficiently for normal purposes out of fossil fuels. In my opinion there is an extremely fruitful field for the theoretical and experimental study of these very low-temperature plasma with the clear purpose of trying to find a more sophisticated way of obtaining directly a thermal efficiency of over 30 per cent from the MHD part of the cycle so that the waste heat system part only has to produce the smaller fraction of the efficiency of 10 or 15 per cent.

One group of ways in which this solution may be found is in achieving an electric conductivity of the gas at temperatures around 1500°C considerably in excess of that predicted by thermodynamic equilibrium ionization according to the Saha equation with seeding. This line of approach includes the possibility of continuing the last few per cent of the combustion reaction to provide a substained generation of free electrons within the magnetic field. Secondly, there is the possibility that the presence of ash from pulverized coal can have a very low effective work function and so can provide

free electrons and thirdly the development of a radio frequency AC generator having a frequency such that the ionization corresponding to the high temperature part of the cycle continues significantly during the high velocity part of the cycle. The second main group of possibilities stems from the suggestion put forward by the present author in the Parson's Memorial Lecture of 1962, of the possibility of separating the electrically conducting fluid and the fluid. Operating through the ideal working cycle into separate layers or striations which spread right across the flow so that the working fluid is pushing against the electro-magnetic force retarding the conducting layer. The third main group of possibilities lies in the change of thermodynamic cycle from the simple classical DC cycle outlined above. This includes the use of pulsating combustion which can give the effect of combustion at constant volume with direct conversion of the resulting pressure rise into high velocity. Pulsating combustion can be very effectively combined with the production of alternating current and the introduction of striations at the front of each pulsation. The other main way of improving the thermodynamic cycle is the use of the shock wave with the resulting very high temperature wave discussed in Section I of this paper. Here the main problem is to find a way of providing the energy by combustion and precompression for a shock wave which either travels backwards and forwards down a long tube or rotates continuously in a cylindrical tube.

The most interesting possibility for the use of plasma for electricity generation from nuclear fission is probably the homogeneous gaseous reactor in which a fully stirred gaseous compound of the fissile element becomes critical and heats itself to a temperature of about 5000°K at a very high pressure in a spherical vessel surrounded by boiler tubes. The heated gas expands through a convergent/divergent nozzle to about half the reaction temperature at which temperature it is still a good electric conductor. It then passes through a magnetic field where its velocity is essentially destroyed. It is further cooled in a water tube boiler and recompressed to be returned to the reaction vessel. There is a bleed of reaction products out and a bleed of fresh fissile material into the gas to maintain the concentration of fissile material.

3. Plasma chemical engineering

The use of high intensity arcs, concentrated high frequency discharges and detonation waves to produce products by chemical reactions which require temperatures over 2500°K constitutes the chemical engineering application of plasma[10–14]. Reactions will obviously be extremely fast at these very high temperatures so that very rapidly a plasma equilibrium will be obtained which can be frozen out by very rapid cooling. These plasma equilibria will not necessarily be those obtained by extending the normal chemical reaction equations to the high temperatures because the temperature of the electrons will not equal that of the atoms and molecules owing to the presence of the electric discharge. The chemical reaction properties of the atoms will no longer be entirely dependent on the degree of completion of the outer electron shell so that, for example, the noble gases with completely filled outer shells can undergo reactions such as oxidation. It is also possible to quench out free radicals in significant concentrations

from such high temperature plasma and if these can be stored they would provide a very high reaction energy fuel. Broadly speaking, however, one can apply the law of mass action to say that because of the high temperatures in the plasma all equilibria are pushed in the direction of endothermic reactions, *i.e.* either to the formation of endothermic compounds or the more or less complete decomposition of exothermic compounds fed in. The pressure in these plasma can be varied from very small fractions of an atmosphere up to many atmospheres and this fact can also be made use of since low pressures will favour lack of equilibrium between temperatures of the different particles and in particular will lead to an increased electron temperature and electron concentration. On the other hand by increasing the pressure the equilibrium can be moved in the direction of the formation of more complex molecules.

The most important reactions which have been studied with the possibility of using the electrical discharge plasma, or the shock tube plasma as a commercial reaction system are the following.

(i) Nitric oxide formation from nitrogen and oxygen. Here the main problem is to provide the energy of 7·4 eV to split up the nitrogen molecules and in fact an electron energy of about 17 ev is required to produce the reaction at a reasonable rate so that the process probably requires the ionization of the nitrogen molecule. A discharge with frequency of the order of 10^6 c/s gives a considerably higher yield than with DC. The arc temperature should be in the neighbourhood of 3000°K and the pressure about 100 mm mercury. The electron temperature must of course be very much higher than this gas temperature to give the energy of 17 eV. This reaction is not in fact competitive commercially with the Ostwald process (oxidation of ammonia).

(ii) Nitrogen/hydrogen reactions. By operating at low or medium temperatures a reasonable yield of ammonia can be obtained but at higher temperatures the main yield is hydrazine. The use of solid catalysts are a great help in the production of ammonia and the optimum pressure is around 100 mm mercury.

(iii) Acetylene is normally made by using a normal low intensity arc to produce calcium carbide from lime and coke according to the reaction:

$$CaO + C \longrightarrow CaC_2 + CO - 111{,}000 \text{ cal}$$

The calcium carbide then reacts with water at room temperature according to the reaction:

$$CaC_2 + H_2O \longrightarrow C_2H_2 + CaO$$

At Sheffield high intensity radiation in an arc image furnace was used to produce very rapid heating of a thin layer of coal in an inert atmosphere giving yields of up to 14 per cent acetylene in the distillation products. In another series of experiments in America the plasma jet has been used to study the reaction between powdered carbon and hydrogen:

$$2\,C + H_2 \longrightarrow C_2H_2 - 54{,}300 \text{ cal}$$

and the formation of acetylene from methane according to the reaction:

$$2\ CH_4 \longrightarrow C_2H_2 + 3\ H_2 - 86{,}300\ \text{cal}$$

In both cases the best yield of acetylene was obtained by using the high intensity arc to heat the gases, argon or helium, into which the reactants were fed. With a plasma jet temperature of 12,000 °K 80 per cent of methane could be converted to acetylene in this way.

(iv) Cyanogen has been made from the carbon of the graphite cathode reacting with a nitrogen jet according to the reaction:

$$2\ C + N_2 \longrightarrow (C_2N_2) - 71{,}000\ \text{cal}$$

and 15 per cent of the carbon input has been converted into cyanogen.

(v) Hydrogen cyanide has been produced using a consumable graphite cathode with hydrogen and nitrogen according to the reaction:

$$2\ C + H_2 + N_2 \longrightarrow 2\ HCN - 60{,}200\ \text{cal}$$

over 50 per cent of the carbon input was converted to HCN with acetylene as the significant by-product.

(vi) Uranium carbide has been prepared from uranium oxide and carbon according to the reaction:

$$UO_2 + 3\ C \longrightarrow UC + 2\ CO - 179{,}000\ \text{cal}$$

In this case the two solid reactants are formed into a solid rod which is used as the anode. This anode is fed in horizontally into a reaction chamber; if the cathode is placed above it this produced a horizontal plasma arc with a temperature in the range 4000 to 5000°K in a water-cooled cylinder evacuated down to a pressure in the range 100 to 5000 μ. The uranium carbide is formed as a liquid sphere on the electrode face. Its m.p. is 2773°K but it is rapidly superheated to the boiling point so that it is purified of lower boiling point impurities.

Experiments have also been carried out on the direct reduction of aluminium oxide introduced as a powder into high intensity arc.

When it is required to heat chemical reactants to a reaction temperature by means of a conventional combustion flame the cost of the heating process rises steeply as the temperature at which the heat of the endothermic reaction must be supplied rises because the combustion products must leave the reaction chamber at a temperature somewhat above that of the reaction and it is then necessary to have very expensive preheat arrangements to recover some of their heat below this temperature by preheating the combustion air. Such preheat involves a high capital cost and at present there is no commercial way of producing continuous preheat over about 800°C with a metallic recuperator and reversing regenerative preheat over about 1400°C as in the open hearth furnace. This is why the highest temperature processes which are operated industrially on large scale are the melting of steel and very high silica glasses which require the heat at 1600°C. One

special furnace has been developed using pure oxygen for combustion and another with pure alumina tube recuperators to give working temperatures up to 1800°C and even 2000°C but the fuel economy is very poor in these furnaces, the efficiency being below 5 per cent. This is why electric arcs have been used for such processes as graphitization for carbon and formation of calcium carbide and even for the manufacture of more expensive steels. Combustion flames with pure oxygen may be extended to industrial temperatures of 2500°C but in all the systems above that temperature the high intensity plasma arc or the other methods of using electricity will be the methods which receive commercial development to a greater extent. The detonation wave may be used for certain cases especially if the rotating detonation wave in a cylindrical combustion chamber with tangential entry and axial exit which is being worked on at Sheffield can be made a practical proposition. In general, however, there is no doubt that there is a great field for development of the high intensity arc for all types of endothermic reactions producing products of sufficient value to pay for the electric power consumed. The efficiency of these processes will depend on what fraction of the electricity can be made to go into the endothermic reaction energy compared with that left as sensible heat of the reaction products.

4. The use of plasma for thermal processing

Both the high intensity arc of plasma jet and the electrically superheated conventional flame are being increasingly used as heating torches with inert gas atmospheres, capable of considerably higher temperatures and rates of heat transfer than conventional torches[15–19]. They can be used for fusion welding and for melting of very high temperature melting point metals and refractory oxides, carbides and nitrides. The materials can be fed in as a powder with the gas and be melted or even vapourized as they pass through the plasma. The very high temperature inert gas jets from the plasma arc can be played on to a surface for cutting or drilling or if a powder is fed through the arc it can be used for fusing this powder material on to the surface and producing a very firm bond of protective layer for high temperature uses. The transferred arc with a voltage difference between the water cooled anode and the work piece is particularly valuable for this type of purpose since the power to the outer second arc can be separately controlled to control the extent to which the surface itself is heated and melted. The high frequency induction plasma is also used for zone melting and floating zone refining to produce very pure high melting point metals and to produce single crystals of refractories. In this case the seed crystal is steadily withdrawn downward from the plasma zone. The powder material is fed into the centre of the arc surrounded by the carrier gas, argon, and melts as it goes through the high temperature zone. Very high purity tubes and rods of high melting point oxides, nitrides and carbides and a pyrolytic graphite can be made by precipitation from the gaseous phase.

There is no doubt that this is a greatly expanding field of use of plasma wherever conventional flames such as oxyacetylene or fuel/preheated air have been limited either with regard to the maximum temperature they can produce or by the fact that the products of the oxidation reaction are chemically unsuitable for the process.

5. Conclusions

1. The successful use of plasma for electricity generation from chemical fuels depends essentially on finding a sophisticated solution to the problem of combining an efficient thermodynamic cycle with an adequate plasma electrical conductivity.

2. The high intensity arc and the high frequency induction system are already useful methods of providing gas plasma with a gas temperature in the range 2500°K–20,000°K for endothermic reactions and ceramic and metallurgical purposes.

3. The main outstanding problems in the use of electrically produced plasma are firstly the attainment of a reasonable thermal efficiency, which is the ratio of electric power absorbed in work to the electric power input; and secondly the problems of feeding megawatts of electricity continuously into a small industrial appliance with control of container wall temperature, degree of ionization and supply and removal of reacting gases and solids. The scale effects may well make these problems easier on a large scale provided the gas flow pattern can be controlled.

6. List of symbols

E = Total voltage produced across electrodes
v = Gas velocity, cm/sec
H = Magnetic field strength, Gauss
d = Electrode spacing at right angles to flow, cm
x = Electrode spacing along flow, cm
ρ = Gas density, g/cm^3
σ = Gas specific electric conductivity, mho/cm
r = Ratio of external load resistance/internal plasma resistance

$\tau = \dfrac{\gamma_{\text{ext}}}{\gamma_{\text{int}}} = \dfrac{\gamma_{\text{ext}}}{d/6A}$, where A = Electrode area

SUFFIXES

1. At entrance to expansion nozzle or shock front
2. At exit from expansion nozzle or shock front.
3. At exit from MHD duct.

$$M = \text{Flow Mach No.} = \frac{v}{\gamma \frac{R}{M} T} = \frac{v}{\sqrt{\left((\gamma - 1)\frac{C_p}{M} T\right)}}$$

for perfect gas

M = Molecular wt of gas.
R = Gas constant, cal/mole—°K.
C_p, C_v = Specific heats of gas, cal/mole—°K.

References

[1] E. J. Hellund. *The Plasma State*, Chapter 3 (Reinhold Publishing Corp., New York), 1961.
[2] A. G. Gaydon. *The Shock Tube in High-temperature Chemical Physics*, Chapter 2 (Chapman and Hall Ltd, London), 1963.
[3] *J. Appl. Phys.* **22**, 821 (1961).

[4] *Industr. Eng. Chem. Process Design and Development* **1**, 161 (1963).
[5] M. W. Thring. Parsons Memorial Lecture (1962).
[6] M. W. Thring. *Revolution in Fuel Technology* (Institute of Fuel, London), 1954.
[7] R. A. Coombe. *Magnetohydrodynamic Generation of Electric Power* (Chapman and Hall Ltd, London), 1964.
[8] McGrath, Siddall, and M. W. Thring. *Advances in Magnetohydrodynamics* (Pergamon Press, Oxford), 1963.
[9] *Proceedings of the International Symposium on M.H.D. Electrical Power Generation*, Paris, 1964, Vols. 1–4 (O.E.C.D. European Nuclear Energy Agency, Paris).
[10] E. J. Hellund. *The Plasma State*, Chapter 4 (Reinhold Publishing Corp., New York), 1961.
[11] *Industr. Eng. Chem. Process Design and Development* **1**, 166 (1962).
[12] *Chem. Eng. Prog.* **59**, 53 (1963).
[13] *Industr. Eng. Chem. Fundamentals* **1**, 52 (1962).
[14] *Industr. Eng. Chem.* **55**, 19 (1963).
[15] E. J. Hellund. *The Plasma State*, Chapter 7 (Reinhold Publishing Corp., New York), 1961.
[16] *Iron and Steel*. 160 (April 1965).
[17] *J. Appl. Phys.* **32**, 2534 (1961).
[18] *New Scientist*. 552 (1963).
[19] *Battelle Tech. Rev.* **13**, 2 (No. 9) (1964).