IONIZATION PROCESSES IN GASES AND THEIR APPLICATION TO ENERGY CONVERSION SYSTEMS

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INTRODUCTION

The fact that gases will conduct electricity has been known for many years. It would appear that the first experiments on gaseous conduction were carried out in England. Gilbert, Queen Elizabeth I's physician, found that a charged conductor lost its charge when brought near a flame and that an electroscope became charged when connected to a flame. He gave the results of his experiments in his book *De Magnete* which was published in London in 1600[1].

Many experiments on discharge physics were carried out in the 17th and 18th centuries, culminating in the discovery of the arc discharge in 1800 by Davy in England and Petroff in Russia. They were able to produce very high temperatures in the arc, high enough to fuse lime and magnesia and to vaporize graphite.

Faraday then came into the picture working at the Royal Institution in London. His published works contain a vast amount of data on gas discharges and form an important part of his classical studies on electricity. It seems that Faraday also carried out the first experiment on power generation by motion of a fluid conductor in a magnetic field[2] (the process we now call magnetohydrodynamics).

His experiment involved pumping mercury, the fluid conductor, through a magnetic field and using the system to produce current by the dynamo principle.

Although the phenomenon of ionization in flames was discovered in 1600 and Faraday was aware of the possibilities of power generation using a moving fluid conductor as early as 1832, we cannot say with certainty what are the primary processes leading to ionization in flames. We have also been unable to build a magnetohydrodynamic generator, driven by an ionized gas stream, which can be safely operated for more than about four minutes.

During the last two decades there has been a tremendous increase in interest in methods of power generation. The possibilities of controlled thermal fusion reactions have led to a much improved understanding of highly ionized systems or plasmas; at the same time, the idea of using a weakly ionized (0·1 per cent rather than the 20–30 per cent ionization found in plasmas) high velocity gas stream as the moving fluid conductor in a generator based on Faraday's dynamo principle, is more attractive now

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than it was in 1832 because we have materials that will stand up to the very high temperatures involved.

The most convenient source of a high velocity, ionized gas stream is the exhaust stream from a high intensity combustion system feeding into a convergent-divergent nozzle—a rocket motor in fact. Such a gas stream is only weakly ionized, usually a good deal less than 0·1 per cent, but still sufficiently ionized to be a serious embarrassment to rocket guidance systems. The problem confronting the scientist who wishes to use the gas stream to produce electricity is the opposite of the rocket guidance engineer's problem, who wishes to eliminate ionization altogether. For efficient power generation the percentage ionization in the system must be increased. Up to now, this has been done by adding substances with low ionization potentials, alkali metals usually; caesium would be the best with an ionization potential of 3·89 eV. However, caesium is too expensive to use in an open cycle system, so potassium has been used; this has an ionization potential of 4·33 eV. It is usually added to the fuel in the form of a potassium soap and this is, of course, fairly expensive *Figure 1* shows the effect on the conductivity of seeding air with 1 per cent potassium[3]. The highest value of conductivity obtainable by potassium seeding of a conventional combustion system is not likely to be more than about 10 mho/metre, assuming equilibrium conditions.

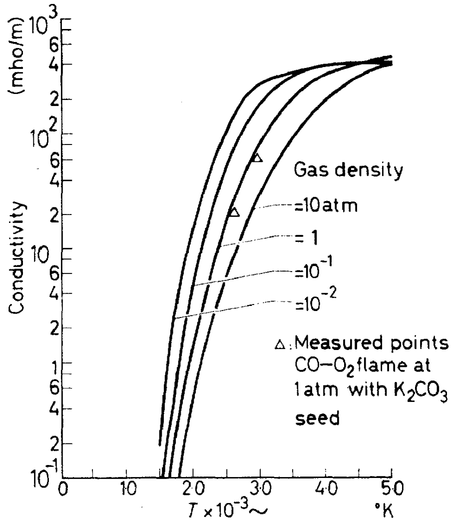

Figure 1. Electrical conductivity of air plus one per cent potassium

Even with this kind of system (hot gases seeded with low ionization potential metals), generators with reasonably high efficiencies can be designed—at least in theory. It is quite clear, however, that an increase in the percentage ionization of the combustion gas stream, without an attendant rise in temperature and preferably without potassium seeding, would be a distinct advantage, and some hope of achieving this may be inferred from our present knowledge of ionization processes in flames.

IONIZATION IN FLAMES

Experimental observations on flames are difficult to make. The introduction of some kind of measuring device such as a probe into the system changes the system and a sort of macroscopic " Indeterminacy Principle " becomes apparent. The only way of dealing with such a situation is to use several different techniques, as the " Indeterminacy " here is not the result of any fundamental property of flames which makes precise measurement impossible. The techniques which have been developed for flame work are probes, first used by Langmuir[5–12], flame deflection methods[13,14], microwave attenuation[15–17] and mass spectroscopy[18,19]. The first three of these techniques usually give an integrated picture of what occurs in a particular flame, but mass spectroscopy using the flame itself as the ion source, gives the ion species present at particular points in the flame and their concentrations. The results obtained by these different methods have been gratifyingly consistent and the general picture of ionization in hydrocarbon flames can be summarized in the following terms:

(*i*) The ion concentration reaches a maximum in the combustion zone and decreases in the gases immediately after it.

(*ii*) The ion concentration in the combustion zone is about 10^{11} to 10^{12} ions/cm^3. This is a factor of 10^5 higher than equilibrium calculations based on the ionization potentials of flame species would suggest. The level of ionization in the combustion products following the reaction zone remains higher than the equilibrium value; *Figure 2* shows the variation of positive ion concentration through an ethylene–oxygen flame burning at low pressure[12].

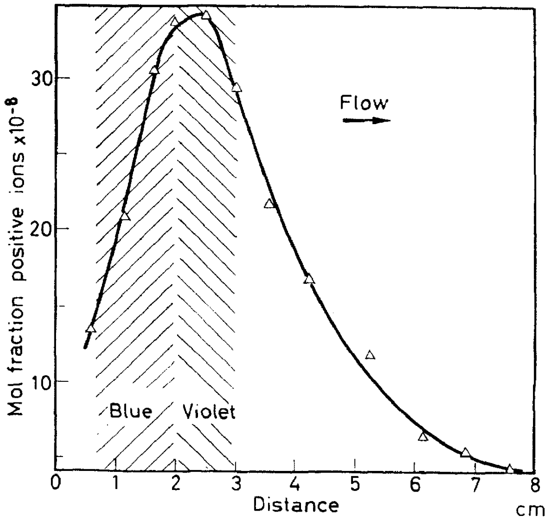

Figure 2. Variation of positive ion concentration through an ethylene–oxygen flame at 3mm Hg

(*iii*) The predominant ion present seems to be H_3O^+, at least in flames burning at less than one atmosphere pressure[18,19].

(*iv*) The ionized species in the system are positive ions, an almost equivalent number of electrons and a few negative ions. The ion velocities are about 1 cm/sec and the electron velocities about 1000 cm/sec; these very different velocities account for the charge separation observed in flames.

Any theory of ionization in flames must account satisfactorily for these experimental observations.

A wide variety of explanations to account for abnormal flame ionization, ranging from impurities present in the combustion air to friction of the gas flowing past the tube walls, have been suggested[10].

It is clear that in the reaction zone of a flame one cannot expect equipartition of the newly released energy in its various possible forms and that the distribution will not be of the Maxwell-Boltzmann type[20]. Flame spectroscopy indicates some very marked departures from equilibrium in reaction zones. The lack of equilibrium will tend to produce excess energy in some degrees of freedom and individual molecules will have excess energy above that for an equilibrium distribution. It is probably unrealistic, however, to suppose that such marked effects as ionization levels of 10^5 times the expected equilibrium values can be accounted for by general departure from equilibrium. Anomalously high ionization does not occur in hydrogen and carbon monoxide flames and seems to be restricted to hydrocarbon flames, so that any explanation must incorporate this interesting distinction.

Table 1 gives some indication of the ions present in acetylene and methane flames[18,19]. There are clearly important differences in the ion species found in flames burning at atmospheric pressure and flames burning at reduced pressure.

Table 1. Some ions found in flames

Acetylene or methane-oxygen flames burning at pressures of 10 *to* 40 *mm* Hg[19]

H_3O^+	90 per cent of the total ion concentration
$H_5O_2^+$	only in C_2H_2/O_2 flames above 25 mm Hg
CHO^+	weak peak
$C_3H_3^+$	only in rich mixtures
NO^+	with N_2 dilution

Weak peaks H_2O^+, $C_2HO_2^+$, $C_2H_3O^+$, CO^+, $C_2H_2^+$, C_2^+, CH^+, CH_2^+, CH_3^+ and OH^+

Acetylene-oxygen flames burning at 760 *mm* Hg *pressure*[18]

H_2O^+, H_3O^+, $H_5O_2^+$
NO^+ with N_2 dilution
$C_nH_m^+$ n varies from 3 to 10, the odd masses predominating
$C_2H_3O_2^+$—large peak
CH_3O^+, CH_4O^+, HO_2^+, O_2^+
C_nH_n (n odd) and $C_nH_{n\pm1}$ (n even) in oxygen-rich system
No CH^+, C_2^+ or CH_2^+

It has been suggested that thermal ionization of flame species such as C_2, CH and OH might account for the high ionization in hydrocarbon flames: it is now known that the ionization potentials of these and similar radicals are all higher than 11 eV which rules out high ionization values resulting from this mechanism.

Stern[21] has suggested that ionization is due to the presence of carbon particles or incipient carbon particles. The work function of solid carbon is 4·35 eV and the ionization potential of C_2 radicals is 11·1 eV so that incipient carbon may well have a value somewhere between the two. This hypothesis has been used by several workers to explain results in rich hydrocarbon flames and also to study the ionization of free carbon in acetylene flames[10]. The explanation, although satisfying in some respects, does not easily account for some of the experimental observations made on diffusion flames which show that maximum conductivity occurs in the lower part of the flame and not in the luminous part where carbon particles are more prevalent. One would also expect more ions in rich flames than in lean flames at the same temperature but this is not always found in practice. The same numbers of ions are observed in rich propane air flames and in lean flames at the same temperature; at reduced pressure the ion maximum is displaced towards the leaner mixture[22].

The presence of large polymers among the positive ions in both rich and lean mixtures may be the cause of high ionization. The ionization potentials of hydrocarbons decrease with increase in both molecular weight and unsaturation[20]. Calcote has shown[10], however, that even in the cases of radicals such as C_3H_3 (CH_2—C≡CH) and C_2H_3 (CH_2=CH) with low ionization potentials (around 8 eV), the required concentrations are much higher than one would expect to find in the flame front. (See *Table 2.*)

Table 2. Required species concentration (per cm^3) to produce thermally the experimental positive ion concentration in flames[10]

Species ionized	*Ionization potential*	*At the equivalence ratio* 0·70	1·0	1·5
	eV	*Lean*		*Rich*
CC	12	1×10^{32}	1×10^{29}	3×10^{31}
CH_2=CH	8·2	7×10^{21}	2×10^{20}	6×10^{21}
$C_6H_5CH_2$	7·73	4×10^{20}	2×10^{19}	4×10^{20}
CH_3—CH=CH—CH_2	7·71	3×10^{20}	2×10^{19}	3×10^{20}

The presence of abnormally excited OH radicals with high rotational energy may well lead to ion formation by a reaction such as[20,23]:

$$M + OH^* \longrightarrow M^+ + OH^-$$

Excited OH radicals might also lead to the formation of ions such as $C_3H_3^+$, which appears early in the reaction zone, by reaction with C_2[18]:

$$C_2 + OH^* \longrightarrow CO + CH^*$$

followed by

$$HC{\equiv}CH + CH^* \longrightarrow H_2^+{-}C{-}C{\equiv}CH + e$$

or CH^+ might be produced by:

$$C_2 + OH^* \longrightarrow CO + CH^+ + e$$

followed by direct attachment:

$$C_2H_2 + CH^+ \longrightarrow H_2^+C{-}C{\equiv}CH$$

Recent work by Calcote[13] using Langmuir probes has indicated that ion concentrations show little correlation with temperature but relatively good correlation with equivalence ratio (see *Figure 3*), the ion concentration is greatest near the stoicheiometric ratio (see *Figure 4*). Some possible ion-producing mechanisms, involving simple species dependent, therefore, upon both fuel and oxidizer, are listed in *Table 3*.

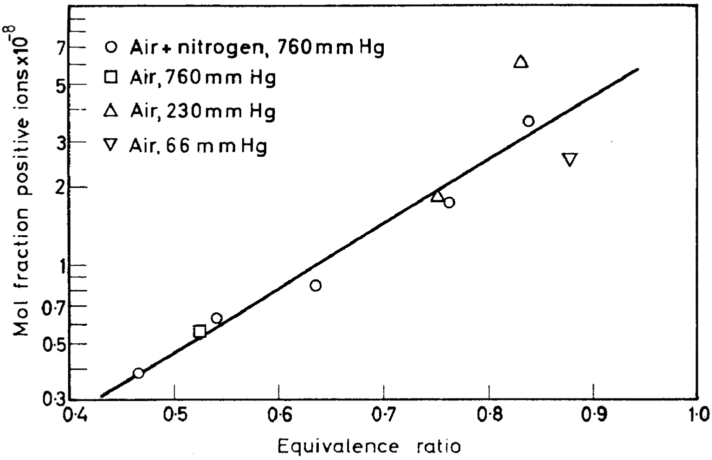

Figure 3. Correlation of maximum positive ion concentration with equivalence ratio

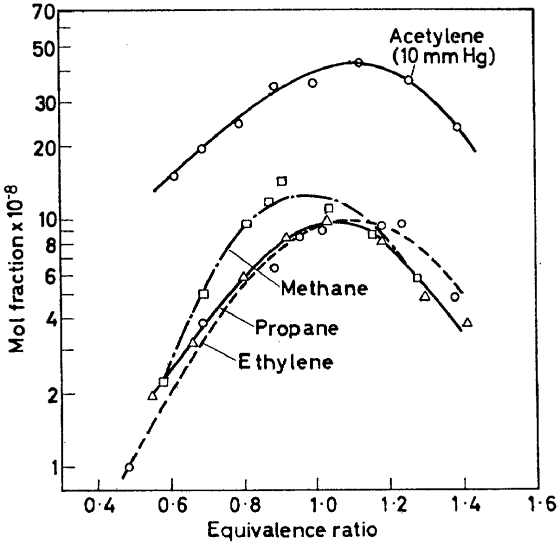

Figure 4. Maximum positive ion concentration with air at 33 mm Hg

The high concentration of H_3O^+ and different hydrocarbon ions found by mass spectrometric identification through the flame zone can be accounted for by charge exchange with the initial ion species formed as indicated in

Table 4. A similar reaction system has been set up by Eyring[24] and his co-workers (see *Table 5*) in order to calculate the quasi-equilibrium concentration of H_3O^+ which they use to predict approximate ion populations in hydrocarbon flames.

Table 3. Possible chemi-ionization reactions

	Reaction	*Heat of reaction* (kcal/mol)
1	$C_2\ (^1\pi_g) + OH \longrightarrow CO + CH^+ + e$	−24
2	$C_2\ (^3\pi_g) + O_2 \longrightarrow CO + CO^+ + e$	−18
3	$C_2 + HO_2 \longrightarrow C_2O_2H^+ + e$	~ −80
4	$CH + O \longrightarrow CHO^+ + e$	41
5	$CH\ (^2\Sigma^+) + O \longrightarrow CHO^+ + e$	−50
6	$CH\ (^2\Sigma^+) + O_2 \longrightarrow CHO_2^+ + e$	~ −30
7	$CH\ (^2\Sigma^+) + HO_2 \longrightarrow CHO^+ + OH^-$	−37
8	$CH\ (^2\Sigma^+) + HO_2 \longrightarrow H + CHO_2^+ + e$	12
9	$CH + O_2\ (^3\Sigma_u^-) \longrightarrow CHO_2^+ + e$	~ −80
10	$C_2H + O_2\ (^3\Sigma_u^-) \longrightarrow CO_2 + CH^+ + e$	−13
11	$C_2H + O_2\ (^3\Sigma_u^-) \longrightarrow C_2O_2H^+ + e$	~ −120
12	$C_2H + O_2\ (^1\Sigma_g^+) \longrightarrow C_2O_2H^+ + e$	~ −15
13	$CO\ (^1\pi) + O \longrightarrow CO_2^+ + e$	5

Table 4. Suggested mechanism to account for H_3O^+ concentration in hydrocarbon flames

Charge exchange
$CHO^+ + H_2O \longrightarrow CO + H_3O^+$ $\Delta H = 24$ kcal
$CH^+ + H_2O \longrightarrow H_3O^+ + C$ $\Delta H = 63$ kcal
$CHO_2{}^+ + H_2O \longrightarrow H_3O^+ + CO_2$ $\Delta H = 0$
$C_2O_2H^+ + H_2O \longrightarrow H_3O^+ + 2\ CO$ $\Delta H = 40$ kcal

Formation of $NH_4{}^+ + H_2CN^+$ in hydrocarbon flames containing NH_3 or HCN
$CHO^+ + NH_3 \longrightarrow NH_4{}^+ + CO$
$CHO^+ + HCN \longrightarrow H_2CN^+ + CO$

Production of hydrocarbon ions
$C_nH_{m-1} + H_3O^+ \longrightarrow C_nH_m{}^+ + H_2O$

Decay of ion concentration behind flame front
$H_3O^+ + e \longrightarrow H_2O + H$

Table 5. Suggested mechanisms for H_2O^+ formation in hydrocarbon flames[24]

1. $Q + O_2 \longrightarrow \beta C_2H_2$ + other oxidation products
2. $C_2H_2 + O_2 \longrightarrow C_2H + HO_2$
3. $C_2H + O_2 \longrightarrow C_2O_2H^+ + e$
4. $C_2O_2H^+ \longrightarrow CHO^+ + CO$
5. $CHO^+ + H_2O \longrightarrow H_3O^+ + CO$
6. $H_3O^+ + e + M \longrightarrow H_2O + H + M$

The next stage in elucidating ion formation mechanisms is clearly the isolation of the primary ion-producing mechanism. It seems probable that further progress can best be continued by identification of the species present and we, together with workers at other Universities and Institutions, are carrying out a mass spectrometer programme designed to detect and measure radicals and positive and negative ions occurring in the reaction zones of flames.

The elucidation of the primary ion-forming mechanism may well give some clue to the reasons for the anomalously high level of ionization peculiar to hydrocarbon flames. If it is the result of a genuine departure from equilibrium the reaction and conditions leading to, and accounting for, this departure may well be artificially intensified and so lead to higher gas conductivities than have been possible up to now. The achievement of a high level of ionization is, however, only part of the solution to the problem of building a magnetohydrodynamic (M.H.D.) generator; the level of ionization must remain high right through the generator section and to this end, ion decay mechanisms must be retarded.

The solution to some of the problems of designing an M.H.D. generator clearly lie in a better understanding of the fundamental ionization processes which occur in a partially ionized gas stream.

MAGNETOHYDRODYNAMIC GENERATORS

Having said something about the fundamental processes leading to ion formation in flames I want to look at some of the problems associated with the use of a hot combustion gas stream as the moving fluid conductor in a magnetohydrodynamic generator.

Figure 5 shows a schematic diagram of a simple M.H.D. generator[3]. It consists of a duct through which the gaseous working fluid flows, coils which produce a magnetic field across the duct, and electrodes at the top and bottom of the duct. The ionized gas, by virtue of its motion through the magnetic field, has an e.m.f. generated in it which drives a current through it, through the electrodes and through the external load. The electrical efficiency of such a generator depends on how much of the generated power is actually delivered to the load and how much is dissipated in the internal resistance. There are various ways in which further losses occur: electrode losses, Joule losses in maintaining the applied field and heat losses through the walls of the generator.

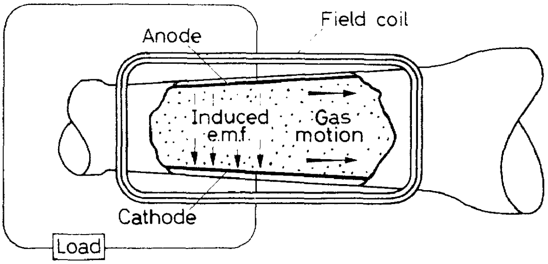

Figure 5. D.C. Magnetohydrodynamic generator

Probably the most important factor in determining the design and practicability of an M.H.D. generator is the gas conductivity. Roza and Kantrowitz[3] have shown that for a 100 MW generator with a working length of 30 ft. and a field strength of 10,000 gauss the minimum useful conductivity is about 1 mho/metre, which indicates a minimum temperature of about 2000°K using potassium seeding and thermal ionization. This temperature is high, particularly if expansion through a supersonic nozzle is used to increase the kinetic energy of the gas stream as it enters the working section of the generator, thus cooling the gas before it enters the generator. It would appear to involve the use of gas preheaters operating continuously at 2000°C or so. The best preheater available at present falls short of this figure by several hundred degrees. Clearly some method of achieving at least 1 mho/metre conductivity in the gas stream other than by purely thermal means is to be preferred. I shall discuss some proposals for getting over this problem shortly.

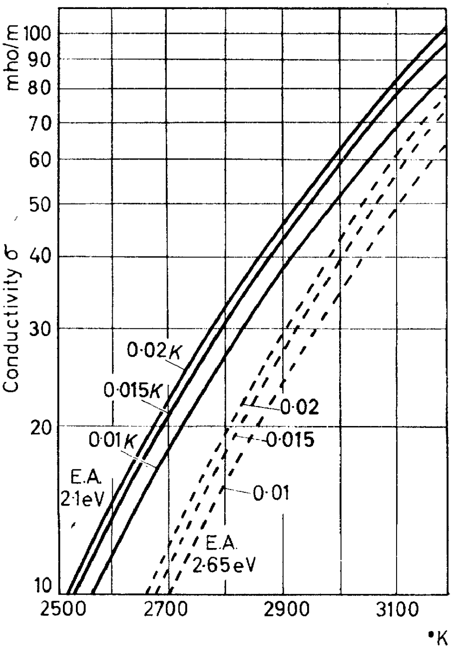

Figure 6. Conductivity of gaseous reaction products from $CH_2 + 3/2\ O_2 + n_k k$ at equilibrium at 1 atm; effects of ion scattering, electron attachment to OH, and KOH association considered

An M.H.D. generator operating on the principles already described has been built by Way and Hundstad[25]. A combustion arrangement was used in which fuel consisting of 43 per cent diesel oil, 45 per cent 2-ethyl potassium hexoate and 12 per cent butyl cellosolve was burned with an oxygen–nitrogen mixture at about 95 per cent oxygen equivalence ratio. The potassium in the fuel constitutes 10 per cent of its weight. Product gas at about 2800°K, 1·2 atm abs. and approximate equilibrium composition enters the generator with an electrical conductivity of between 20 and 50 mho/metre. *Figure 6* shows the gas conductivities expected. Using field strengths of up to 14,000 gauss open circuit voltages of about 100 volts have been observed, and 9·4 kW have been generated (see *Figure 7*). The observed open circuit voltage was usually somewhat less than the theoretical generated voltage, but this could be explained on the basis of leakage currents flowing in the ceramic side walls and the presence of electrode potential drops. The chief problems as far as this type of generator is concerned, apart from the cost of the heavily seeded fuel, are those associated with material durability combined with the requisite properties of low or high electrical conductivity.

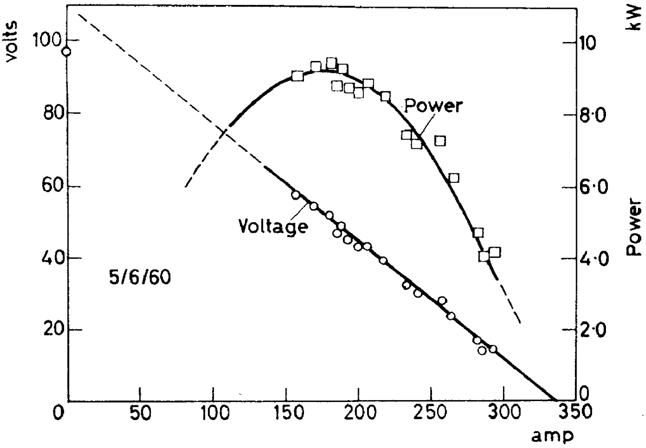

Figure 7. Test results on M.H.D. generator

ENERGY TRANSFER MECHANISMS

Quite clearly a generator based on this simple straight flow, crossed-field principle and utilizing a thermally ionized potassium seeded gas stream can be made to produce electricity. It is necessary, however, to take a closer look at the behaviour of a partially ionized high velocity gas stream in a magnetic field[26,27].

Only charged particles can interact directly with electric or magnetic fields and unless a mechanism exists for the transfer of kinetic energy from the neutral to the charged particles the efficiency of a generator can never exceed the fractional ionization since most of the kinetic energy of the gas stream is carried by neutral molecules.

Such a mechanism does exist in the metallic conductors of a conventional alternator where the energy transfer mechanism is *via* the positive ions in the crystal lattice. These conditions are not satisfied in a gaseous conductor; energy transfer can only result from attractive forces and collisions between particles.

Charged particles, in transferring their energy to an external load circuit are decelerated; for high efficiency the neutral particles in the gas stream must also be decelerated by some sort of energy transfer process with the charged particles.

Harris[27] has suggested a possible mechanism for energy transfer in such a system (for quite clearly some energy transfer does occur, otherwise the types of M.H.D. generator already working would be less efficient than they are in practice). He suggests that the free electrons in the system, on being subjected to a high applied field, experience large decelerating forces. Since the electron mass is low, and provided there is no energy transfer from other particles, the electrons are effectively brought to rest. The negatively charged " screen " so formed can then exert attractive (Coulomb) forces which contribute towards the deceleration of the positive ions: because of their large mass these ions are only slightly decelerated by the applied field. If the positive ions, in the absence of energy transfer from particles other than by Coulomb forces, can be effectively brought to rest, then there exists a dense screen of ions and electrons which can exert decelerating forces on the neutral particles by direct elastic collisions. The gas stream acts against the pressure of the " screen ", forces the charged particles through the applied field, constantly replenishes these charged particles and is itself decelerated. The net effect is a reduction in the kinetic energy of the flow and an equivalent electrical power induced in the external load circuit.

Unfortunately there is very little experimental evidence to prove or disprove this hypothesis and an electromagnetically driven shock tube is being used at Sheffield University to study deceleration effects on gas streams containing charged and neutral particles in an applied field (see *Figure 8*). A simple experiment using a similar system has been carried out by Bostick[28]. A plasma was projected through a vacuum across a magnetic field between two conducting plates. By connecting resistors of various values between the plates the plasma was slowed down with various degrees of deceleration. This is a simple demonstration of the conversion of the kinetic energy of the plasma directly into electrical energy and then dissipating it in the resistance.

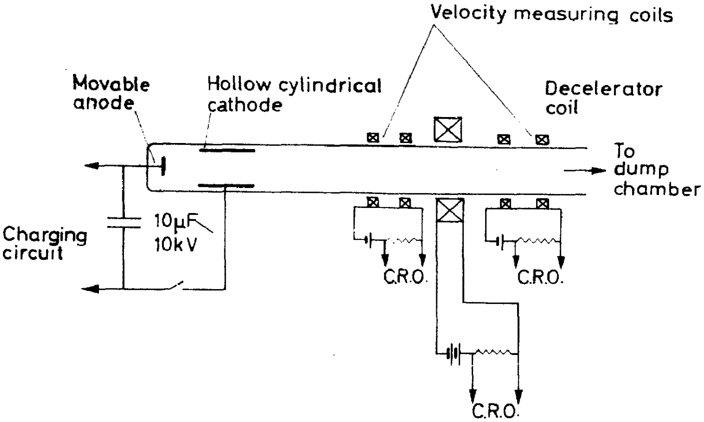

Figure 8. Electromagnetic shock tube experiment proposed by Harris

A better understanding of these energy transfer processes is desirable.

The simple cross flow type of M.H.D. generator which we have considered has several obvious disadvantages. One is the fact that it produces d.c. rather than a.c. and another is the difficult problem of current collection *via* electrodes in such a system. Various solutions to these and other problems have been suggested by different workers[26,27,29–31]. By and large, the solutions suggested involve the use of more sophisticated thermodynamic cycles and current collection systems which eliminate some of the losses which are bound to occur when electrodes are used in the working fluid stream.

One interesting possibility, shown in *Figure 9*, relies on induction methods for current collection and eliminates electrodes in the system. It relies on coupling between circumferential alternating currents set up in the gas and induced currents in an external co-axial coil. The circumferential gas currents may be produced by an alternating radial magnetic field and the jet would need to be annular with a central axial pole piece.

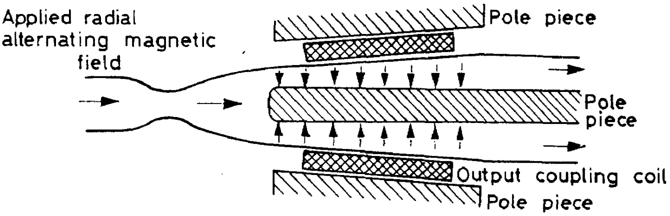

Figure 9. Induction magnetohydrodynamic generator

An attractive alternative is to use a pulsed jet with the gas moving along the axis of a large aircoil core through which current is passing. If the product of jet conductivity and pulse frequency is sufficiently large, there will be a change of effective inductance of the coil, owing to the reduced penetration of magnetic flux into its core area, when the pulse of conducting gas is introduced. An inductance change of a few per cent can be expected at pulse frequencies of several hundred cycles per second. If a direct current is initially flowing in the coil this inductance change corresponds to a change of stored energy and it can be shown that there is a net extraction of energy from a pulse of the jet when it passes through the coil.

The operation of a pulsed combustion system is quite feasible, indeed it is sometimes embarrassingly simple, as those concerned with oil-firing boilers know. So called " chugging " frequencies of around 100 c/sec occur, the propagating mechanism being very probably aerodynamic in nature. We are currently carrying out work on pulsating systems, similar to those developed by Reynst, in which conbustion occurs at constant volume rather than constant pressure resulting in more intensely ionized pulse systems with frequencies of about 100 c/sec.

This type of pulsed system can be used in conjunction with an energy converter based on the parametric amplification principle[27].

If in an inductance–capacitance electrically-resonant circuit, either element is varied periodically at twice the resonance frequency, electrical oscillations are built up and energy is obtained from the inductance-changing mechanism; this is termed parametric amplification. The system has the important advantage of being self-exciting. The condition for build-up of electrical energy is:

$$2f\,\delta L > R$$

where f is the frequency of electrical oscillations, δL is the change in inductance and R is the total load resistance. A jet of periodic conductivity at repetition frequencies of 500 to 1000 c/sec is required.

A rather different way of producing a pulsed system has been suggested by Thring[31]. It consists of separating the working fluid and the electrical conductor in the conventional M.H.D. system by inserting a grid injection system across the tail end of the combustion chamber just before the gases begin to accelerate to high velocities in the divergent throat of the nozzle. This injection system is double, with alternate nozzles connected to supplies of pure oxygen and fuel. It is possible to arrange a pulse feeding system for these two materials; short bursts of gas which have different composition, burn with pure oxygen and are seeded with potassium to give high conductivity, are inserted into the high velocity gas stream. The combustion of this subsidiary flow striation can be delayed so that it is actually releasing heat all the way through the expansion process in the nozzle and in the generator section giving, in addition to thermal ionization, direct flame ionization. The rest of the gas can work through the most appropriate thermodynamic cycle. Thus, there are thin conducting layers passing through the magnetic field right across the electrode collection system (if the system is the conventional straight flow crossed-field type). The diffusion of heat and matter between hot conducting layers and the driving fluid during the millisecond or so that it travels through the magnetic field will not be very great; several layers of strongly ionized material will be passing through the field at any given time, each layer being acted on by the applied magnetic field and acting, therefore, as a break to the unionized driving fluid.

This system, in which the conducting and driving fluids are separated and effectively go through different thermodynamic cycles, presents several interesting possibilities and modifications of the more conventional systems.

METHODS OF ENERGY CONVERSION BASED ON SHOCK TUBE SYSTEMS

The use of shock tubes for the production of plasma has already been mentioned. Electromagnetically driven shock tubes are more convenient but tend to give a less well defined shock than the more conventional pressure and combustion driven systems. A good deal of work on magnetohydrodynamic flow has been carried out using shock tubes of one sort or another and many of the results are of direct application to energy conversion systems. Pain and Smy[32,33] have worked on a combustion driven shock tube and extracted 0·32 MW for a period of 100μ sec from the shock-ionized region. The flow velocity in a 5 cm internal diameter Pyrex tube was about 4000 m/sec (Mach 20) and the applied field strength was 10,000 gauss, the plasma temperature was 12,000°K and the degree of ionization was about 20 per cent. Load currents of up to 18,000 amp were drawn and maximum power was obtained with a matched external load. It was shown that the generator has an internal impedance equivalent to its own electrical resistance in series with a resistance arising from its behaviour as a compressible fluid. Drum camera photographs showed that the shock was reflected at the field region. The values of the electrical conductivity of the plasma obtained in these experiments (about 3000 mho/m) show that the plasma resistance is controlled by electron motion; they are also in good agreement with those found by other methods. It was noted in the experiments that boundary layer effects were apparently absent when large currents were flowing: Joule dissipation of a large current rapidly heats a cold boundary layer and reduces its resistance. No change in the surface finish of polished copper and brass electrodes was observed.

Various suggestions have been made for incorporating the basic principles of the shock tube into an energy conversion system. Thring[31] has suggested a system which is in effect, a shock tube with combustion driver sections at each end. An oscillating shock system is then set up in an applied field and current taken off from electrodes set in the system in the usual way. Cowley[26] has suggested a modification of this system in which the end of the shock tube is set in an annular magnetic field system so as to give a strongly reflected shock. This principle would be used to produce an oscillating slug of plasma from which power could be extracted in a parametrically excited circuit.

A simple analogue in which the oscillating shock wave is replaced by a metal cylinder moving backwards and forwards in a magnetic field driven by two internal combustion 2-stroke cylinders has recently been constructed at Sheffield University. Current is extracted from the cylinder by induction methods.

The obvious advantages of a series of highly ionized shocks following one after another through a magnetic field has been used by Thring in a recent proposal. He suggests that the combustion system of an M.H.D. generator should be arranged in such a way as to drive a continuous stream of shocks along the exhaust stream of combustion products. This kind of periodically detonating combustion system is already known although it is usual to eliminate it rather than encourage it.

CLOSED CYCLE SYSTEM

Closed cycle systems are particularly attractive for use in conjunction with very high temperature reactors. Experimental work now under way at the C. A. Parsons Nuclear Research Centre[26] is based on an M.H.D. generator through which continuously filtered and purified helium with a small added concentration of caesium vapour is circulated in a closed loop. The gas temperature is raised to between 1500 and 2500°C, a metered flow of caesium vapour is introduced before the helium expands to a high velocity through a rectangular section supersonic nozzle. The supersonic flow of helium and ionized caesium passes through the generator duct and a subsonic diffuser to a recuperative heat exchanger and final cooler. The caesium is removed in a cold trap before the helium re-enters the circulator.

The chief problem with this type of system is quite clearly raising the gas temperature to 2500°C. This involves heat transfer to the gas through some sort of wall. The high temperature is necessary for two reasons; to achieve the necessary supersonic gas velocity through the generator duct, and also to give a high enough thermal ionization of the caesium vapour. An interesting modification[33] involves the surface ionization properties of caesium vapour in contact with solid tungsten. This principle has been used in diode conversion systems[34] where 100 per cent ionization of caesium vapour has been achieved in stationary plasma systems in contact with tungsten at about 1500°K. Substantially higher gas conductivities than are possible by thermal ionization alone are thus possible at lower gas temperatures if tungsten surfaces are introduced into the system.

CONCLUSIONS

The use of a high velocity, ionized gas stream to produce electricity in a generator which has no mechanically moving parts seems to be a practical possibility. Whether such generators can be developed sufficiently to compete with turbo-generators or nuclear power plants depends on the solution of a variety of problems.

The first and probably the most difficult problem is the production of a high velocity gas stream with a level of ionization giving at least 1 mho/m. We have seen that thermal ionization of added alkali metals is a possibility but not an economic one; the temperatures required also lead to materials problems. Methods involving the use of plasma jets tend to consume more power than is produced in the generator section. It may be possible to obtain high values of ionization when thermal methods are used in conjunction with surface ionization for special conditions, such as one encounters in closed cycle systems used in nuclear reactors.

The best solution to this problem would seem to lie in first obtaining a better understanding of the processes leading to the abnormally high ionization level found in the reaction zones of hydrocarbon flames and then to try to arrange combustion conditions to promote ion formation and to delay ion decay. The use of new techniques such as ion-beam mass spectroscopy and shock tubes, together with more conventional methods, are gradually leading to a better understanding of flame ionization.

The second problem is a better understanding of the energy transfer mechanism between charged and uncharged particles when a partially ionized gas is " braked " by passing it through a strong magnetic field. Energy transfer certainly occurs but a quantitative knowledge of the process is desirable.

The third problem arises from a solution of the first two problems and involves the design of the most efficient system for extracting the energy from the high velocity, high temperature gas stream and converting it into electrical energy, preferably alternating current. Clearly a more sophisticated thermodynamic cycle than that obtained in the simple linear, crossed field M.H.D. generator is to be desired and there are more convenient methods for current collection than simple electrode systems. It seems probable that a practical generator will incorporate the kinds of modification, once developed, suggested by Thring, Harris and other workers.

The problem of electrical engineering and materials technology involved are considerable; nevertheless, there is tremendous scope for ingenuity in devising better and more efficient M.H.D. generators. If the inventiveness applied to the improvement of turbogenerators during the last fifty years can be channelled into producing new methods of electricity generation it seems not unreasonable to expect that a practical and efficient M.H.D. generator will be developed.

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References

[1] A. Von Engel. *Ionized Gases*, Oxford University Press (1955).

[2] M. Faraday. *Experimental Researches in Electricity*, First Series, London (1832).

[3] R. J. Rosa and A. Kantrowitz. *Direct Conversion of Heat to Electricity*, Ed. Kay and Welsh, Chap. 12, Wiley (1960).

[5] J. J. Thompson and C. P. Thompson. *Conduction of Electricity through Gases*, 3rd Ed., Cambridge University Press (1928).

[6] H. A. Wilson. *Red. Mod. Phys.* **3**, 156 (1931).

[7] T. Heumann. *Spectrochim. Acta* **1**, 293 (1940).

[8] H. F. Calcote and I. R. King. *5th Intern. Symposium on Combustion*, p. 423, Reinhold Publ. Co., New York (1955).

[9] T. Kinbara and J. NaKamura. *5th Intern. Symposium on Combustion*, p. 285, Reinhold Publ. Co., New York (1955).

[10] H. F. Calcote. *Combustion and Flame* **1**, 385 (1957).

[11] I. R. King. *J. Chem. Phys.* **27**, 817 (1957).

[12] H. F. Calcote. *Aerochem. Research Lab. Technical Publication No. 15* (1960), also *8th Intern. Symposium on Combustion*, Williams Wilkins & Co., Baltimore (1960).

[13] H. F. Calcote. *3rd Intern. Symposium on Combustion*, p. 245, Williams Wilkins & Co., Baltimore, (1949).

[14] K. G. Payne and F. J. Weinberg. *Proc. Roy. Soc.* (*London*) **A250**, 316 (1959).

[15] E. R. Andrew, D. W. E. Axford, and T. M. Sugden. *Trans. Faraday Soc.* **44**, 427 (1948).

[16] H. Belcher and T. M. Sudgen. *Proc. Roy. Soc.* (*London*) **A201**, 480 (1950); **A202**, 17 (1950).

[17] H. Williams. *7th Intern. Symposium on Combustion*, p. 256, Butterworths, London (1959); *8th Intern. Symposium on Combustion*, Williams Wilkins & Co., Baltimore (1962).

[18] P. F. Knewstubb and T. M. Sugden. *7th Intern. Symposium on Combustion*, p. 247, Butterworths, London (1959); *Proc. Roy. Soc.* (*London*) **A255**, 520 (1960).

[19] J. Deckers and A. Van Tiggelen. *7th International Symposium on Combustion*, p. 254, Butterworths, London (1959); *8th Intern. Symposium on Combustion*, Williams Wilkins & Co., Baltimore (1962).

[20] A. G. Gaydon and H. J. Wolfhard. *Flames, their Structure, Radiation and Temperature*, 2nd ed., Chapman and Hall (1960).

[21] B. Lewis and G. von Elbe. *Combustion, Flames and Explosions of Gases*, Academic Press Inc., New York (1951).

[22] R. W. Smith, J. Manton, and S. R. Brinkley. *Rept. Inst. U.S. Bur. Mining* No. 4983 (1953).

[23] V. I. TverdoKhlebov. *J. Exp. Theoret. Phys. U.S.S.R.* **30**, 252 (1956).

[24] H. Eyring, N. R. MuKherjee, T. Fueno, and T. Ree. *8th Intern. Symposium on Combustion*, Williams Wilkins & Co., Baltimore (1962).

[25] S. Way and R. L. Hundstad. *Westinghouse Research Lab. Scientific Paper 6*—40,509—2—P3; *8th Intern. Symposium on Combustion*, Williams Wilkins & Co., Baltimore (1962).

[26] B. C. Lindley. *2nd Symposium on Engineering Aspects of M.H.D.*, University of Pennsylvania, March (1961).

[27] D. J. Harris. *J. Inst. Elec. Eng.* (*London*) **7**, 84 (1961).

[28] W. H. Bostik, E. Harris, and R. Theus. *U.C.R.L.* 4719, see *Plasma Dynamics*, Ed. Chauser. Pergamon Press (1960).

[29] M. W. Thring. *Inaugural Lecture*, Sheffield University (1953); *J. Inst. Fuel* (1954).

[30] M. W. Thring. *New Scientist* **6** (149) 522 (1959).

[31] M. W. Thring. *Direct Electricity From Fuel Combustion*, The Abingdon Lecture delivered at Esso Research (1961).

[32] H. J. Payn and P. R. Smy. *Proc. Phys. Soc.* (*London*) **76**, 849 (1960); *J. Fluid Mech.* **9**, 390 (1960).

[33] D. J. Harris. Private communication.

[34] W. B. Nottingham. *Direct Conversion of Heat to Electricity*, Ed. Kaye and Walsh, Wiley (1960).