

# ELECTRICAL CONDUCTIVITY OF SEEDED HYDROCARBON COMBUSTION PRODUCTS

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This paper presents a review of experimental and theoretical investigations at I.I.T. Delhi, on electrical conductivity of the seeded combustion products of some hydrocarbon fuels, likely to be used as working fluids in open-cycle MHD power generators. The results are of direct relevance to the MHD programme in India.

## INTRODUCTION

FOR a given temperature of the sink (atmosphere), the efficiency of a conversion process is an increasing function of the temperature of the source (i. e., the highest temperature attained by the working substance in a cycle). The efficiency of conventional turbo-machinery is limited by the highest usable temperature of steam, viz., 760 °C. Since combustion occurs at much higher temperature, it is extremely desirable to have a process, in which the working substance has a maximum temperature (in the thermodynamic cycle) as near the temperature of combustion as possible, so that the efficiency of conversion can be maximized. One of the proposed processes to this end, is the magnetohydrodynamic (MHD) power generation. The working gas in the MHD concept, can conveniently enter the system at a high temperature of the order 2600 °K, if hydrocarbon combustion is the source of energy; products of combustion at such temperatures have high conductivities, when seeded with salts of alkali metals (which have low ionization potential).

An open-cycle steam-MHD plant offers many attractions and is being seriously investigated by scientists all over the world. In the open-cycle MHD generator, seeded combustion products of a hydrocarbon fuel are accelerated through a nozzle and are then allowed to enter a duct, subject to a transverse magnetic field. The exhaust gases coming out of the duct are still extremely hot ( $\cong 2000$  °K), and are used for preheating of the oxidant and for generating electricity by a conventional steam power plant. The design of the MHD generator duct, the heart of this plant, requires a detailed knowledge of the electrical transport properties of seeded products of combustion of different types of hydrocarbon fuels burnt in air/oxygen. Our efforts have, therefore, been confined to the experimental and theoretical investigation of the electrical conductivity of some selected fuel/oxidant systems for evaluating their performance as working fluids in open-cycle MHD generators. This communication presents a review of the work carried out at I.I.T., Delhi.

Our early experimental investigations were confined to the study of the dependence of the electrical conductivity of the seeded combustion products of easily avail-

able fuel/oxidant systems (under stoichiometric conditions and at atmospheric pressure) on temperature and the amount of seed added. The seed was added in the form of an aqueous solution of  $K_2CO_3/KOH$ . The following systems were studied:—

- (i) Oxy-Acetylene system seeded with  $K_2CO_3$  (Sawhney *et al.*, 1976).
- (ii) Air-Acetylene system seeded with  $K_2CO_3$  (Sodha *et al.*, 1977).
- (iii) Oxy-LPG (Liquified-Petroleum-Gas) seeded with both  $K_2CO_3$  and  $KOH$  (Hussain *et al.*, 1977).

The experimental results for electrical conductivity of these systems were found to be in good agreement with the theoretical predictions; which validates our experimental set-up and the theory.

India has large reserves of coal and it is, therefore, necessary to develop MHD technology based on fuels derived from coal gasification, because direct combustion of coal poses severe material problems. A pilot MHD power plant of 5 MW capacity is being developed on a national level in India; the proposed plant utilizes watergas (resulting from gasification of coal) as the working fuel. We have therefore, investigated the electrical conductivity of the seeded combustion products of a suitable mixture of LPG and acetylene, such that the combustion products of the mixture simulate the seeded combustion products of a watergas-oxygen (Naidu *et al.*, 1977) system. Further, experimental investigations have been made to study the dependence of electrical conductivity of seeded combustion products of hydrocarbon fuels on their  $C/H$  ratio (Naidu *et al.*, 1978), the amount of seed added and the flame temperature. Nomograms have been plotted to illustrate variation of conductivity with these parameters; these can be used to predict the conductivity of any oxy-hydrocarbon system, characterised by a given  $C/H$  ratio.

The electrical conductivity of seeded combustion products of bituminous coal/air-oxygen (Hussain *et al.*, 1977 *a,b*) systems were analytically evaluated over a range of parameters of interest to the MHD power systems; however, since the material problem associated with coal are formidable at present, this investigation has not been followed up experimentally. In the next section is described the analytical method of evaluation of the composition of combustion products, the electron density and the electrical conductivity of the hydrocarbon systems. The next two sections contain respectively a description of the experimental set-up used during the investigations, and a discussion of the results obtained.

#### CALCULATION COMPOSITION OF SEEDED COMBUSTION PRODUCTS

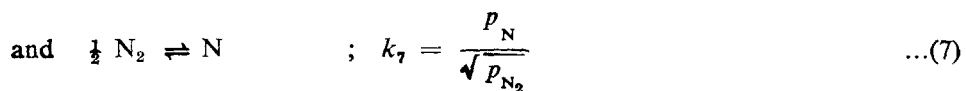
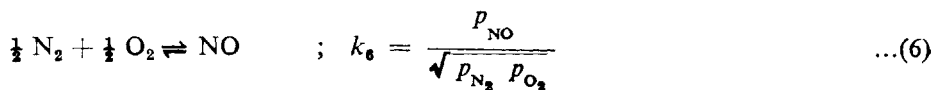
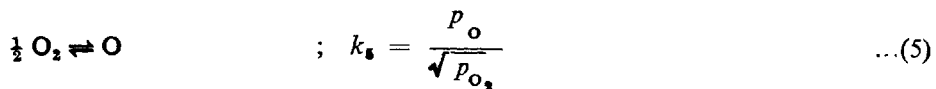
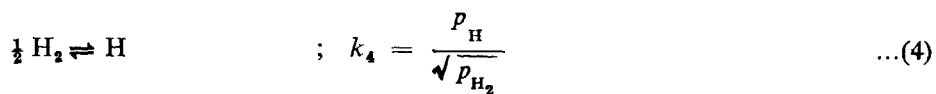
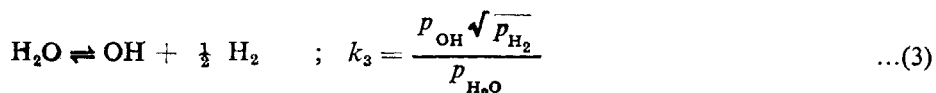
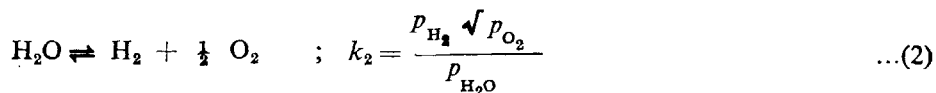
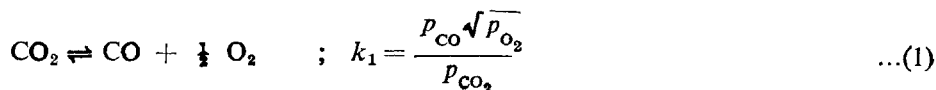
The electrical conductivity of seeded combustion products of a hydrocarbon (with air or oxygen as oxidant) system depends upon the composition of the flame and its temperature. Hence, it is important to determine these physical parameters so as to be able to evaluate the electrical conductivity of the system. For the determination of the fractional composition of the combustion products at a given temperature, the method used by Myers *et al.* (1958) and Venkataramani and Das (1975) is adopted here as follows:—

MHD generators employ working fluids with temperature above 2000 °K. At such high temperatures, dissociation of the combustion products takes place; this is an important factor to be considered. Enormous amount of energy is used in the dissociation process, thereby limiting the flame temperature. Since the flame gases

are essentially a mixture of compounds of carbon, oxygen, hydrogen and nitrogen; hence, the combustion products of a hydrocarbon system, in general, would mainly consist of the following constituents:

$\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2\text{O}$ ,  $\text{O}_2$ ,  $\text{N}_2$ ,  $\text{OH}$ ,  $\text{H}$ ,  $\text{O}$ ,  $\text{NO}$  and  $\text{N}$ .

The chemical equilibrium reactions to be considered for these constituents are :



where  $p$  denotes the partial pressure of a given constituent in atmosphere, and  $k_1$  to  $k_7$  denote the equilibrium constants of the corresponding reactions. These equilibrium constants depend on temperature and their values are available in Table 12.2 of Gaydon and Wolfhard (1974) (Table I). These equilibrium equations are seven in number. Since there are eleven unknowns in the system, four additional equations are required for a complete solution. Three more equations are obtained by determining the ratios  $n_{\text{C}}/n_{\text{O}}$ ,  $n_{\text{H}}/n_{\text{O}}$  and  $n_{\text{N}}/n_{\text{O}}$  from the given elements of the reactions, where  $n_{\text{C}}$ ,  $n_{\text{H}}$ ,  $n_{\text{N}}$  and  $n_{\text{O}}$  are the number of gram atoms of carbon, hydrogen, nitrogen and oxygen respectively. However, the reactions mentioned above yield, in general, the following expressions for these parameters :

$$n_{\text{C}} = p_{\text{CO}_2} + p_{\text{CO}} \quad \dots(8)$$

TABLE I

*Values of equilibrium constants*

T°K	$K_1$	$K_2$	$K_3$	$K_4$	$K_5$	$K_6$
	$P_{CO} \times P_{O_2^{1/2}}$	$P_{H_2} \times P_{O_2^{1/2}}$	$P_{OH} \times P_{H_2^{1/2}}$	$P_H/P_{H_2^{1/2}}$	$P_O$	$P_{NO}$
	$P_{CO_2}$	$P_{H_2O}$	$P_{H_2C}$		$P_{O_2^{1/2}}$	$P_{N_2^{1/2}} \times P_{O_2^{1/2}}$
1200	$1.81 \times 10^{-8}$	—	—	—	$2.51 \times 10^{-8}$	$5.26 \times 10^{-4}$
1400	$1.01 \times 10^{-8}$	—	—	—	$0.95 \times 10^{-8}$	$1.92 \times 10^{-3}$
1500	—	—	—	—	$4.06 \times 10^{-8}$	$3.23 \times 10^{-3}$
1600	$2.07 \times 10^{-5}$	$6.31 \times 10^{-8}$	$2.0 \times 10^{-8}$	$5.10 \times 10^{-5}$	$1.45 \times 10^{-5}$	—
1750	$1.25 \times 10^{-4}$	—	—	—	$7.48 \times 10^{-5}$	$9.12 \times 10^{-3}$
1800	$2.13 \times 10^{-4}$	$5.20 \times 10^{-5}$	$2.3 \times 10^{-5}$	$3.45 \times 10^{-4}$	$1.22 \times 10^{-4}$	—
2000	$1.37 \times 10^{-3}$	$2.85 \times 10^{-4}$	$1.6 \times 10^{-4}$	$1.62 \times 10^{-3}$	$6.68 \times 10^{-4}$	$1.98 \times 10^{-3}$
2100	—	$5.85 \times 10^{-4}$	$3.6 \times 10^{-4}$	$3.11 \times 10^{-3}$	$1.39 \times 10^{-3}$	—
2200	$6.22 \times 10^{-3}$	$1.14 \times 10^{-3}$	$8.0 \times 10^{-4}$	$5.62 \times 10^{-3}$	$2.70 \times 10^{-3}$	—
2250	—	—	—	—	$3.68 \times 10^{-3}$	$3.64 \times 10^{-3}$
2300	—	$2.04 \times 10^{-3}$	$1.5 \times 10^{-3}$	$9.66 \times 10^{-3}$	$4.98 \times 10^{-3}$	—
2400	$2.18 \times 10^{-3}$	$3.55 \times 10^{-3}$	$2.9 \times 10^{-3}$	$1.54 \times 10^{-2}$	$8.70 \times 10^{-3}$	—
2500	$3.77 \times 10^{-3}$	$5.88 \times 10^{-3}$	$5.2 \times 10^{-3}$	$2.51 \times 10^{-2}$	$1.45 \times 10^{-2}$	$5.90 \times 10^{-3}$
2600	$6.26 \times 10^{-3}$	$9.40 \times 10^{-3}$	$8.9 \times 10^{-3}$	$3.83 \times 10^{-2}$	$2.32 \times 10^{-2}$	—
2700	—	$1.44 \times 10^{-2}$	$1.45 \times 10^{-2}$	$5.67 \times 10^{-2}$	$3.62 \times 10^{-2}$	—
2750	—	—	—	—	$4.43 \times 10^{-2}$	$8.76 \times 10^{-3}$
2800	0.156	$2.15 \times 10^{-2}$	$2.3 \times 10^{-2}$	$8.17 \times 10^{-2}$	$5.42 \times 10^{-2}$	—
2900	—	$3.14 \times 10^{-2}$	$3.5 \times 10^{-2}$	0.115	$7.96 \times 10^{-2}$	—
3000	0.34	$4.45 \times 10^{-2}$	$5.3 \times 10^{-2}$	0.158	0.113	0.122
3500	1.58	0.189	0.27	0.591	0.490	0.203
4000	5.0	0.562	0.91	1.60	1.47	0.298

\*After Gaydon and Wolfhard (1974)—Table 12.2

$$n_H = 2p_{H_2O} + 2p_{H_2} + p_H + p_{OH}, \quad \dots(9)$$

$$n_O = 2p_{CO_2} + p_{CO} + p_{H_2O} + 2p_{O_2} + p_{OH} + p_O + p_{NO} \quad \dots(10)$$

and

$$n_N = 2p_{N_2} + p_{NO} + p_N, \quad \dots(11)$$

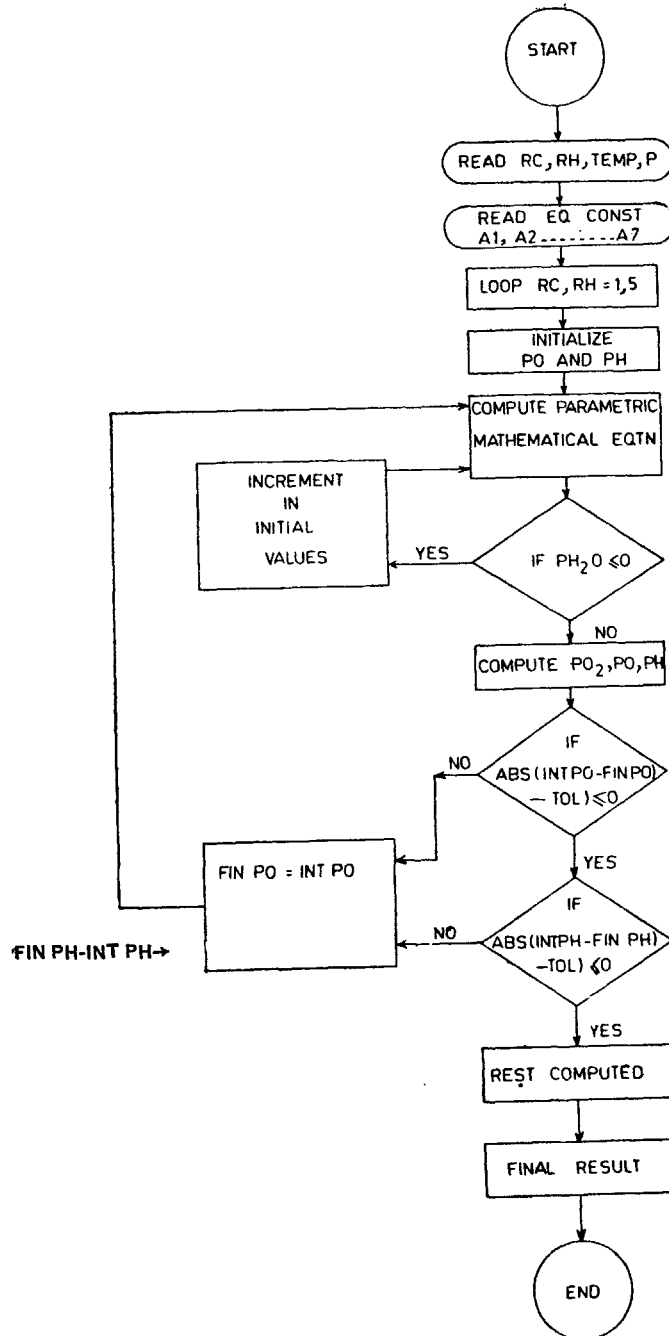
The remaining equation is the total pressure equation :

$$P = \sum_{i=a}^l p_i, \quad \dots(12)$$

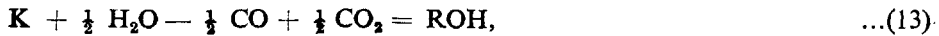
where  $p_i$  is the partial pressure of each of the several constituents in the equilibrium mixture.

A simultaneous solution of these equations is obtained with the help of a computer (ICL-1909), a flow chart for the programme used is given in *Appendix-I*.

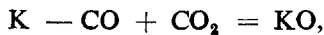
Flow Chart for Composition Calculation



Injection of the potassium seed to the flame gives rise to KOH and KO in the combustion products. Knowing the composition of eleven constituents and using the values of the equilibrium constant of reactions (13) and (14) from Janaf thermochemical Table (1975)



$$K_{\text{KOH}} = 1.794 \times 10^{-1} \theta^{-0.674} \exp\left(\frac{6.375}{\theta}\right)$$



$$K_{\text{KO}} = 5.068 \times 10^3 \theta^{-0.812} \exp\left(\frac{-32.90}{\theta}\right), \quad \dots(14)$$

where

$$\theta = \left( \frac{\text{Temperature in } ^\circ\text{K}}{1000} \right) \quad \dots(15)$$

One can calculate the composition of these constituents in the combustion system.

#### ELECTRON DENSITY AND ELECTRICAL CONDUCTIVITY

It is well known that the conductivity  $\sigma$  of a gas is given by :

$$\sigma = e n_e \mu, \quad \dots(16)$$

where  $e$ ,  $n_e$  and  $\mu$  represent the electronic charge, the electron density and the electron mobility respectively; the contribution of ions to the conductivity is negligible on account of their heavy mass. After determining the composition of the combustion products as described in the last section, the following procedure is used to evaluate the electron density and the electrical conductivity of the various hydrocarbon systems.

*Electron Density* — At temperatures ( $> 2000$  °C) of interest in MHD power generation, the gaseous components of the working fluid are non-conducting. The conductivity of the gas arises from the ionization of the low ionization potential materials like potassium or caesium. In order to calculate the electrical conductivity of the gas, it is necessary to estimate the degree of ionization of the gas, and hence, its electron density. The ionization of the seed atom occurs due to the thermal ionization at such temperatures and the degree of ionization is determined by the well known Saha's equation. During our investigations of the conductivity of the hydrocarbon systems, the gases were seeded only with potassium in the form of aqueous solution of  $\text{K}_2\text{CO}_3/\text{KOH}$ .

If K denotes the potassium atom, then its thermal ionization reaction can be written as :



with its equilibrium equation

$$K_e = \frac{[\text{K}^+][e]}{[\text{K}]}, \quad \dots(18)$$

where  $K_e$  is its equilibrium constant in concentration units; [ ] are particles per c.c.

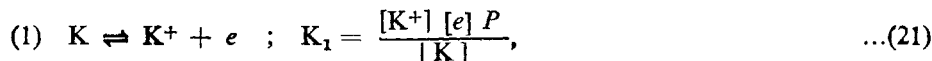
Using the third law of thermodynamics the equilibrium constant  $K_e$  can be expressed in terms of the ionization potential of potassium and other well known universal constants. However, it is found convenient to express the equilibrium constant in terms of partial pressures rather than the concentration. The constant  $K_e$  is converted to the constant  $K_p$  through the equation:

$$P = n k T, \quad \dots(19)$$

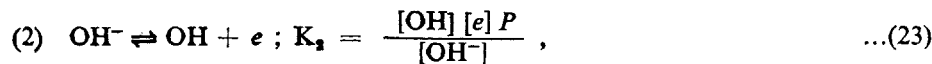
where  $n$  denotes the number density of particle,  $k$  is Boltzmann's constant and  $T$  is the gas temperature,. In the case of ionization of the potassium seed atom, the expression for  $K_p$  can be written in the following form :

$$\text{Log } K_p = - \frac{5036}{T} E + \frac{5}{2} \text{Log } T - 6.4829. \quad \dots(20)$$

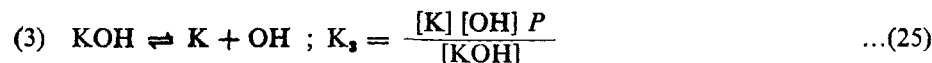
In the presence of the combustion products of hydrocarbon, the calculation of the degree of ionization and hence the electron density should take into account the reduction of the ionizable seed due to the formation of hydroxides and the electron attachment to the electronegative and other species in the flame. Therefore, the relevant reactions for potassium seed and their equilibrium constants are given by (Frost, 1961) (Womack, 1969) :



$$\log K_1 = - \frac{5036}{T} V_i + \frac{5}{2} \text{Log } T - 6.48, \quad \dots(22)$$



$$\text{Log } K_2 = - \frac{5036}{T} E + \frac{5}{2} \text{Log } T - 5.58, \quad \dots(24)$$



$$\begin{aligned} \text{Log } K_3 &= - \frac{5036}{T} V_{\text{KOH}} + \frac{5}{2} \text{Log } T - \text{Const.}, \\ &\approx \frac{5036}{T} \left( V_{\text{H}_2\text{O}} - V_{\text{KOH}} \right) + \log K_{\text{H}_2\text{O}} - 0.716, \quad \dots(26) \end{aligned}$$

where [ ] in the above equations denotes the partial pressure of various constituents in atmosphere,  $V_i$  in eqn. (22) is the ionization potential of K, taken as 4.34 eV.  $E$  is the electron affinity of OH, the values of which range from 2.1 eV to 2.65 eV. The value of 2.1 eV is chosen for the electron affinity  $E$ , since it gives reasonable

agreement with measured values of the conductivity in oxygen combustion products.  $V_{\text{KOH}}$ ,  $V_{\text{H}_2\text{O}}$  are the energies of dissociation of KOH into K+OH, and H<sub>2</sub>O into H+OH, and are taken to be 3.74 eV and 5.16 eV respectively. The values of  $K_{\text{H}_2\text{O}}$  at different temperatures have been given by Lewis and Von Elbe (1951) and have been used in our analysis.

Assuming that the charge is conserved and that the hydroxyl ion mole fraction is not affected by the addition of seed, the simultaneous solution of the above equations leads to the following expression for the electron concentration :

$$[e] = \left( \frac{K_1 [K]_s}{P} \right)^{1/2} (1 + \phi_2)^{-1/2} \left( 1 + \phi_3 + \frac{K_1}{[e] P} \right)^{-1/2}, \quad \dots(27)$$

where  $\phi_2 = \frac{[\text{OH}] P}{K_2}$  ,

and  $\phi_3 = \frac{[\text{OH}] P}{K_3}$  .

Using eqn. (27) for the electron concentration, the electron density in  $m^{-3}$  can be expressed as :

$$n_e = \frac{7.335 \times 10^{27} [e] P}{T}, \quad \dots(28)$$

where  $T$  is the temperature in  $^{\circ}\text{K}$  and  $P$  is the pressure in atmosphere.

*Electron Mobility* — The electron mobility  $\mu$  without a magnetic field is given by Frost (1961)

$$\mu = \frac{4\pi e}{3m} \int_0^{\infty} F(v) \frac{d}{dv} \left( \frac{N v^3}{\nu_t} \right) dv, \quad \dots(29)$$

where  $e$ ,  $m$ ,  $v$ ,  $\nu_t$  and  $N$  are the electronic charge, mass, velocity, total collision frequency, and molecular density respectively,  $4\pi v^2 F(v) dv$  is the number of electrons per unit volume, having velocities between  $v$  and  $v + dv$ . If  $\nu_{en}$  denotes the total collision frequency, for momentum transfer, of electrons with neutral molecules and  $\nu_{ei}$  the effective electron collision frequency with ions due to Coulomb's scattering, then the total electron collision frequency  $\nu_t$  is given by :

$$\nu_t = \nu_{en} + \nu_{ei} \quad \dots(30)$$

At temperatures of interest, the electrical conductivity of the plasma arising from the electron-ion Coulomb scattering is found to be very small for the low ionization obtained in these cases and hence, the total electron collision frequency  $\nu_t$  is essentially because of the electron-molecular collision frequency  $\nu_{en}$ . Frost (1961) has given approximate analytical expressions, Table-II of his paper reproduced below describes the ratio of the collision frequency  $\nu_{en}$  to the molecular density  $N$  as a function of the electron energy  $u$ , in eV, for various gases of interest in MHD power generation, i.e., account is taken of the variation of the collision cross-section of particle with energy. For a given temperature, taking the composition of the combustion products as calculated earlier, the fractional composition for a given gas



TABLE II

Approximate analytical expressions for  $\nu_{en}/N$  for MHD gases as a function of electron energy,  $u$ , in eV.

Gas	$10^{14} \times \frac{\nu_{en}}{N} \text{ s}^{-1} \text{ m}^{-3}$
H <sub>2</sub> O	10 $u^{-1/2}$
CO <sub>2</sub>	1.7 $u^{-1/2}$ + 2.1 $u^{1/2}$
CO	9.1 $u$
O <sub>2</sub>	2.75 $u^{3/2}$
O	5.5 $u^{1/2}$
H <sub>2</sub>	4.5 $u^{1/2}$ + 6.2 $u$
H	42.0 $u^{1/2}$ - 14 $u$
N <sub>2</sub>	12.0 $u$
OH	8.1 $u^{-1/2}$
K	160

is multiplied by its  $\nu_{en}/N$  value from Table I of Frost (1961) and such contributions are added for all the gaseous constituents present. In a similar manner  $\nu_{en}/N$  for a given seeding ratio of K is obtained. The electron collision frequency can then be expressed as :

$$\frac{\nu_{en}}{N} = b_1 u^{-1/2} + b_2 u^{1/2} + b_3 u + b_4, \quad \dots(31)$$

where  $b_1$  to  $b_4$  are coefficients. The coefficient  $b_4$  relates to the contribution from the seeding. In case the seeding is small, the first term in the above expression is found to be much larger than the rest of the terms; hence, we may express  $(1/\nu_{en})$  as :

$$\begin{aligned} \frac{N}{\nu_{en}} &= \frac{u^{1/2}}{b_1} \left( 1 + \frac{b_2}{b_1} u + \frac{b_3}{b_1} u^{3/2} + \frac{b_4}{b_2} u^{1/2} \right)^{-1} \\ &= \sum_{-b}^n a_i u^i, \quad b < 5/2 \end{aligned} \quad \dots(32)$$

Following Frost (1961), the mobility  $\mu$  of the electrons, satisfying a Maxwellian energy distribution, in equilibrium with the gas is obtained to be :

$$\mu = \frac{4e}{3\sqrt{\pi} mN} \sum_{i=-b}^n a_i \Gamma\left(\frac{5}{2} + i\right) \left(\frac{kT}{e}\right)^i, \quad \dots(33)$$

where  $e$  and  $m$  are the electronic charge and mass, respectively,  $k$  is the Boltzmann's constant and the coefficients  $a_i$  are determined, for each component of the combustion products by combining the calculated composition of the products and its  $(\nu_{en}/N)$  value from Table I of Frost (1961). The summation in eqn. (33) has to be

carried over all the components of the working gas including the seed material. The electrical conductivity is then obtained by making use of eqn. (16).

However, in case the amount of seed added is large, approaching its optimum value, the above method of Frost (1961) for evaluating the electrical conductivity needs modification; this has been done by us and the modified method of calculating the electrical conductivity is given below :

Around the optimum seeding, the term  $b_4$  becomes comparable to  $b_1u^{-1/2}$ , and for some systems even  $b_3u$  may also become comparable, and the binomial expansion can not be carried out. Under such conditions, it is preferable to expand eqn. (32) in the following binomial form :

$$\begin{aligned} \frac{N}{v_t} &= \frac{1}{b_1u^{-1/2} + b_2u^{1/2} + b_3u + b_4} \\ \frac{N}{v_t} &= \frac{1}{b_1u^{-1/2} + b_3u + b_4} \left[ 1 + \frac{b_2u^{1/2}}{b_1u^{-1/2} + b_3u + b_4} \right]^{-1} \\ &= \frac{1}{b_1u^{-1/2} + b_3u + b_4} - \frac{b_2u^{1/2}}{[b_1u^{-1/2} + b_3u + b_4]^2} \quad \dots(35) \end{aligned}$$

The combination of eqns. (29) and (35) yields the following expression for the electron mobility  $\mu$  in  $V^{-1}m^2 \text{ sec}^{-1}$ :

$$\mu = \frac{4 \times 10^{14}}{3N\sqrt{\pi}} \left( \frac{e}{m} \right) \left( \frac{kT}{e} \right)^{-5/2} [I_1 + I_2], \quad \dots(36)$$

where

$$\begin{aligned} I_1 &= \frac{2}{c^{5/2}} \int_0^{\infty} \frac{e^{-x^2} x^5 dx}{[b_1\sqrt{c} + b_4x + (b_3/c)x^3]}, \\ I_2 &= -\frac{2b}{c^3} \int_0^{\infty} \frac{e^{-x^2} x^7 dx}{[b_1\sqrt{c} + b_4x + (b_3/c)x^3]^2}, \\ c &= \frac{e}{kT}, \quad x = (cu)^{1/2}, \quad \text{and } u = m_v^2/2e, \end{aligned}$$

$e$  and  $m$  being the electronic charge and mass respectively. The flow chart given in *Appendix II* incorporates the evaluation of the electrical conductivity directly.

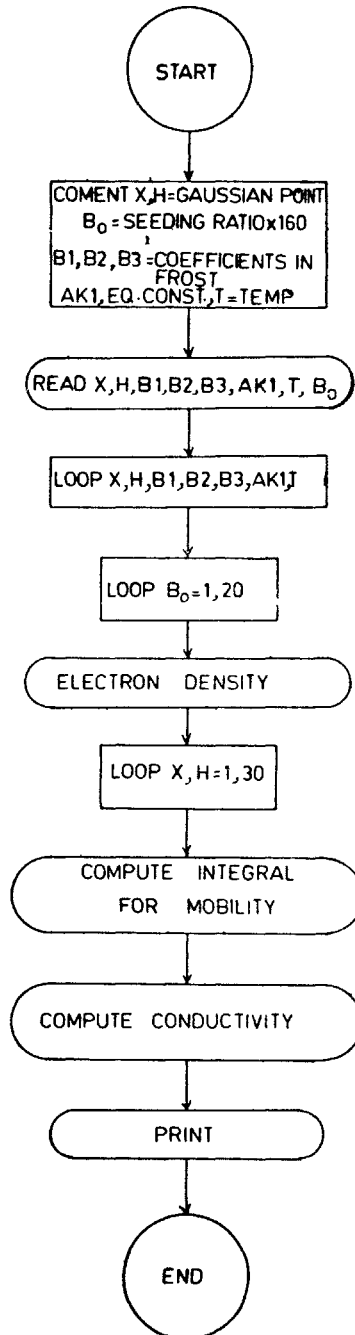
#### EXPERIMENTAL SET-UP

The experimental system consists of two parts :

(1) Burner and Flow unit; and (2) Diagnostic set-up.

A description for each of the components is given below :

Flow Chart for Conductivity Calculation



**Burner and Flow Unit**

The burner used for the combustion of a hydrocarbon fuel is made of a metallic pipe having a circular nozzle; different nozzles of diameter 3/8", 5/16", 5/32" and 3/16" are used during the investigations. The fuel and the oxidant (compressed to pressure of 3–5 atm), are allowed to pass through the burner which is so designed that the mixing is complete within it. The flow-rates of the gases to the burner are regulated with the help of gas flow-meters, such that the stoichiometric ratio of the gases (hydrocarbon and oxidant) remains unity during all measurements. A part of the oxidizer is passed through a sprayer which sprays an aqueous seed solution of  $K_2CO_3/KOH$  into the flame. The combustion products of the flame are then fed into a duct made of alumina ( $Al_2O_3$ ) bricks; the walls of the duct were joined with the help of castable refractory. The length and the rectangular cross-section of the duct were one meter and ( $4 \times 4$ ) respectively.

**Diagnostic set-up**

During the course of investigations measurements were made of : (a) The flame temperature, (b) seeding ratio and (c) the electrical conductivity of the seeded combustion products of the hydrocarbon system by using the following techniques :

*(a) Flame temperature*

The flame temperature of the hydrocarbon fuels which are used in the open-cycle MHD power generator, lies in the range of 2000—3000 °K. Depending upon the temperature of the flame either a thermocouple or (and) an optical pyrometer was used for its measurement.

*Thermocouple* — Flame temperatures upto 2000 °K were measured directly with the help of  $P_t - P_t - R_h$  (10 per cent  $P_1$ ) thermocouple; temperatures higher than 2000 °K were also estimated by extrapolation as described in the following. Temperature measurements were made at various points along the length of the duct. A plot was made from the values obtained at the different positions of the probes and the corresponding temperatures. The curve was extrapolated to determine flame temperatures beyond the range ( $> 2000$  °K) of the thermocouple. The flame temperatures determined by means of the thermocouple are accurate by  $\pm 30$  °K upto a temperature of 2000 °K, while the error is slightly higher in the extrapolated region ( $> 2000$  °K).

*Optical pyrometer* — Since the error in measurement by thermocouple of temperature beyond 2000 °K is large, an optical pyrometer was used to determine higher temperatures. To facilitate the measurement of such high temperatures a probe (diameter 0.5 mm) of tungsten was immersed in the gaseous system (inside the duct). The colour of the tungsten probe is then matched with that of the filament of the pyrometer through a red filter (of wave length 6000 Å); the flame temperature is then directly read from scale of the pyrometer.

A correction for the emissivity of the probe material was made in order to obtain the true temperature. The brightness temperature  $T_B$  measured with the help of optical pyrometer and the true temperature  $T$  are related by the relation (Dwight Gray, 1962):

$$\ln \epsilon(\lambda, T) = \frac{C_2}{\lambda} \left( \frac{1}{T} - \frac{1}{T_B} \right), \quad \dots 40$$

where

$$C_2 = 2.435 \text{ cm } ^\circ\text{K}$$

$\epsilon(\lambda, T)$  = emissivity of the source at wavelength (6000 Å) and temperature  $T$ .

Using the values of the emissivity given in (Dwight Gray, 1962), the true temperature  $T$  can be calculated from the above relation.

(b) *Seeding*

After ignition and before entering the duct an aqueous of  $\text{K}_2\text{CO}_3$  or  $\text{KOH}$  was sprayed into the flame as seed. As mentioned earlier, by changing the strength of the solution and size of the nozzle of the sprayer, different amounts of seed were injected into the flame; for higher seeding two sprayers were used simultaneously. The maximum strength of solution used was 50 per cent  $\text{K}_2\text{CO}_3$  and 70 per cent  $\text{KOH}$  by weight. The seeding in all cases has been measured in terms of percentage of seed by weight added to the gases; i.e.,

$$\text{Seed} = \frac{\text{mass of injected } \text{K}_2\text{CO}_3/\text{KOH per unit time}}{\text{mass of total gas flow per unit time}} \quad \dots(41)$$

(c) *Measurement of Electrical Conductivity*

The electrical conductivity of the seeded combustion products was determined by immersing a double probe of tungsten in the gaseous system (inside the duct). The length and the diameter of the tungsten probes were 2 cms. and 0.5 mm respectively and they were kept 3 mm apart. The probes were fixed mechanically with the help of copper holders in a fire brick, which could be placed at different positions (corresponding to different temperatures) along the length of duct. The potential difference across the probes was measured with the help of an electrometer with an internal impedance of  $10^{14}\Omega$ . The current through the probes was measured with the help of a microvoltmeter by noting the potential difference developed across a standard resistance of  $10\text{C}\Omega$ . put in series with the circuit. With this arrangement currents of the order of  $10^{-8}$  A could be detected. The internal resistance of the microvoltmeter was about  $10^8\Omega$ . Since the combustion products of the system consist mainly of water and carbon-dioxide (which do not react with tungsten) and a negligibly small amount of oxygen ( $< 0.1$  per cent), tungsten does not react appreciably with gas to change the temperature at the probes during the measurements; besides, a fresh set of probes was utilized after each run.

To determine the electrical conductivity of the seeded products experimentally, the ( $V$ - $I$ ) characteristics of the double probes of tungsten were measured. From the linear portion of ( $V$ - $I$ ) characteristics, the gas conductivity can be computed by the formula :

$$\sigma = \left( \frac{\Delta I}{\Delta V} \right) \left( \frac{l}{A} \right), \quad \dots(42)$$

where ' $l$ ' and ' $A$ ' are the effective length and face-to-face cross-sectional area between the electrodes. However, to remove the uncertainty in the value of ' $l/A$ ' the same set of probes was first inserted in a standard solution of  $\text{CuSo}_4$  (whose conductivity

was measured by a conductivity cell to an accuracy of  $\pm 5\%$ ), and  $I/A$  determined from the ( $V-I$ ) characteristics of the probes and the conductivity of the solution.

For the velocities of gas flow for which experiments were performed, the electric Reynold's number (Clements & Smy, 1969) is much less than unity and hence, there is negligible effect of the gas flow on the characteristics of the probes used.

The error in the experimental determination of electrical conductivity arises because of the errors in the measurement of potential difference  $V$  and the current  $I$  in the ( $V-I$ ) characteristics of the flame. During the course of our experiments, the error in the measurement of potential difference (measured with an electrometer) was approximately 4–8 per cent while the error in the measurement of current  $I$  (obtained by measuring the potential drop across the known resistance measured by a d.c. microvoltmeter) was in the range of 0.2–2.0 per cent. Besides, the some of our experimental investigations of the electrical conductivity have also been carried out for various C/H ratios of the working fuels. An approximate estimate shows that error  $\Delta\sigma_e$  arising due to an error in the measurement of ratio C/H is about 2 per cent. Hence, the cumulative error in the measurement of electrical conductivity is  $\approx 8$ –12 per cent.

However, there is variation in the value of the analytically calculated electrical conductivity arising because of the error in the measurement of flame temperature. This error  $\Delta\sigma_T$  in the conductivity due to an error  $\Delta T_g$  ( $\pm 50$  °K in the case of pyrometer) in the measurement of the gas temperature  $T_g$  is given by (Harris, 1963)

$$\frac{\Delta\sigma_T}{\sigma_T} \approx \left( \frac{eV_i}{2kT_g} \right) \left( \frac{\Delta T_g}{T_g} \right), \quad \dots(43)$$

where  $V_i$  is the ionization potential of the seed (4.34 eV for K),  $e$  is the electronic charge and  $k$  is the Boltzmann's constant. This yields a variation of 14–20 per cent in the electrical conductivity of the gas (for the temperature range of 2000–3000 °K).

## RESULTS AND DISCUSSION

The electrical conductivity of various hydrocarbon systems has been analytically evaluated by the method described earlier and its variation has been studied with the flame temperature and the amount of seed added. The results obtained for these systems are shown in the form of graphs; comparison has been made with the corresponding experimentally measured results. Since the experiments were carried out under stoichiometric conditions and at atmospheric pressure, conductivity values have also been calculated under the same conditions. The conductivity variations with these parameters have been analyzed and are described below in detail separately for each of the systems investigated, viz., Oxy-Acetylene (Sawhney *et al.*, 1976), Air-Acetylene (Sodha *et al.*, 1977), Oxy-LPG (Liquified-Petroleum-Gas) (Hussain *et al.*, 1977), simulated watergas-oxygen (Naidu *et al.*, 1977) and mixture of LPG-Acetylene Oxygen (Naidu *et al.*, 1978).

### (i) Oxy-Acetylene System

Fig. 1 illustrates the dependence of the calculated electrical conductivity of the seeded combustion product of an oxy-acetylene system on temperature for various amounts

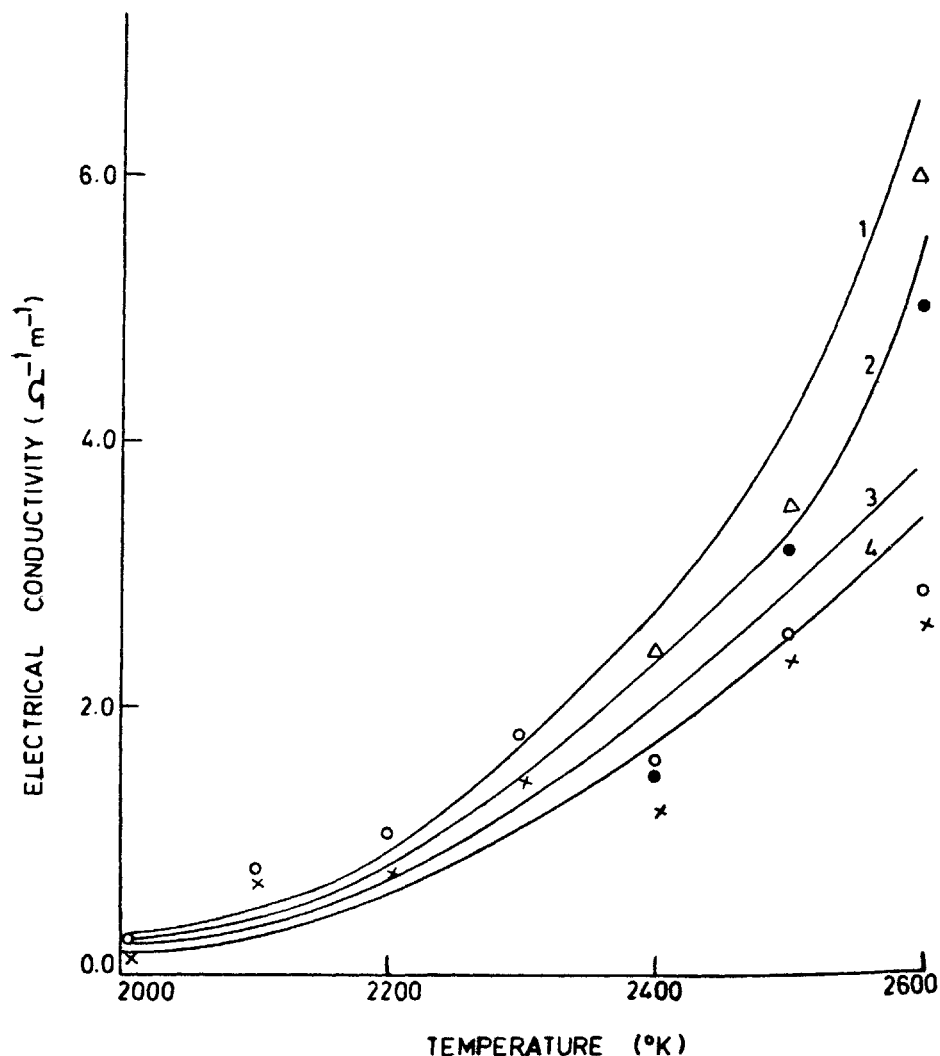


FIG. 1. Variation of electrical conductivity with temperature : Curve 1, theoretical curve for seeding  $4.4 \times 10^{-3}$ , experimental points  $\Delta$ ; curve 2, theoretical curve for seeding  $3.3 \times 10^{-3}$ , experimental points  $\bullet$ ; curve 3, theoretical curve for seeding  $2.4 \times 10^{-3}$ , experimental points  $\circ$ ; curve 4, theoretical curve for seeding  $2.1 \times 10^{-3}$ , experimental points  $\times$

of seed added. Fig. 2 shows the variation of the calculated conductivity with seeding at different temperatures. The corresponding experimentally measured values of the conductivity have also been indicated in these figures. The seeding has been indicated as weight percentage. Since the seed was injected in the aqueous form, the extra amount of water associated with the seed at high seeding made the flame unsteady, and measurements unreliable (not reported).

As is apparent from these figures, the agreement between the calculated and experimentally observed values of conductivity is reasonably good except for large seeding. For larger seeding, it is very likely that evaporation takes a longer time

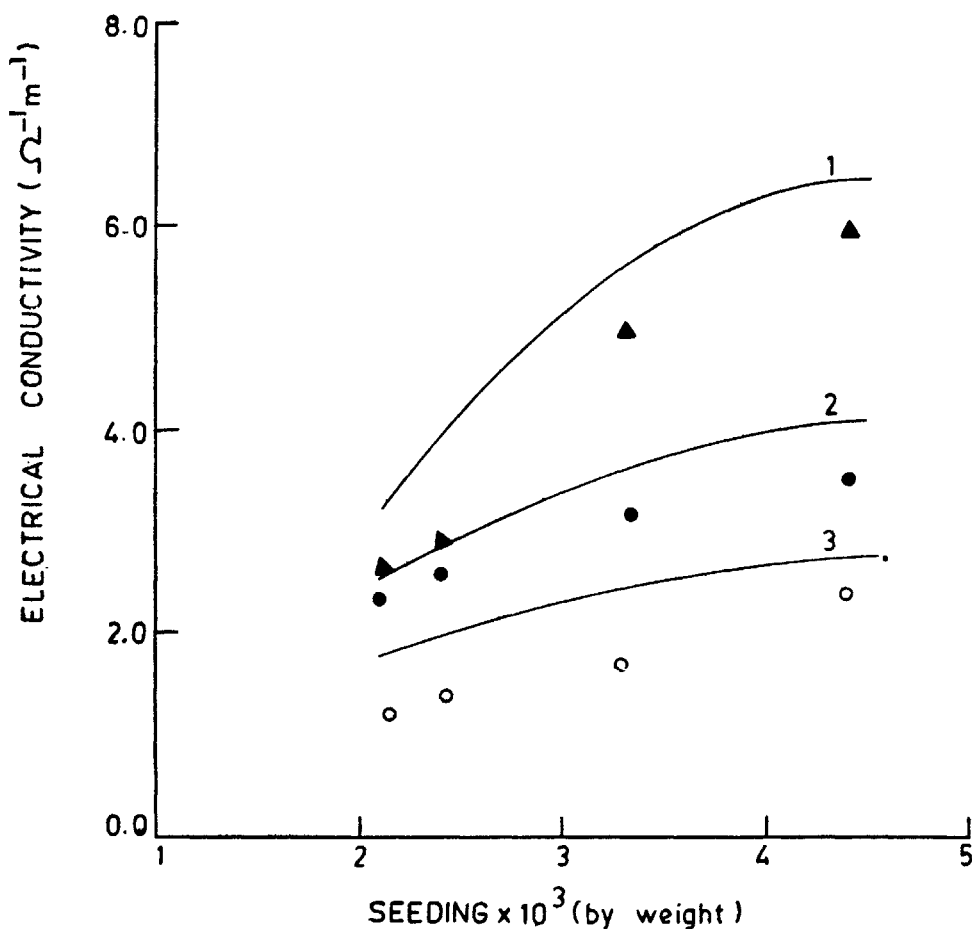


FIG. 2. Variation of electrical conductivity with seeding : Curve 1, theoretical curve for 2600 °K, experimental points  $\Delta$ ; Curve 2, theoretical curve for 2500 °K, experimental points  $\bullet$ ; Curve 3, theoretical curve for 2400 °K, experimental points  $\circ$ .

and cools the gas considerably when it is complete. Thus at high temperatures (beginning of the flame) all the seed which has been injected does not vaporize and, therefore, is not effective. Therefore, lower conductivity is expected than the calculated on the assumption that all the seed goes into the combustion products. This is indeed observed experimentally. More reliable data for high seeding can be obtained by using  $\text{K}_2\text{CO}_3$ , in the powder form or injected in the molten state. This, however, would present a different set of practical problems.

#### (ii) Air-Acetylene System

Fig. 3 illustrates the variation of the calculated electrical conductivity of the seeded combustion products of an air acetylene system with temperature for a seed of 0.34 per cent potassium by weight. Measurements of the electrical conductivity of the seeded combustion products of the air-acetylene system have also been made



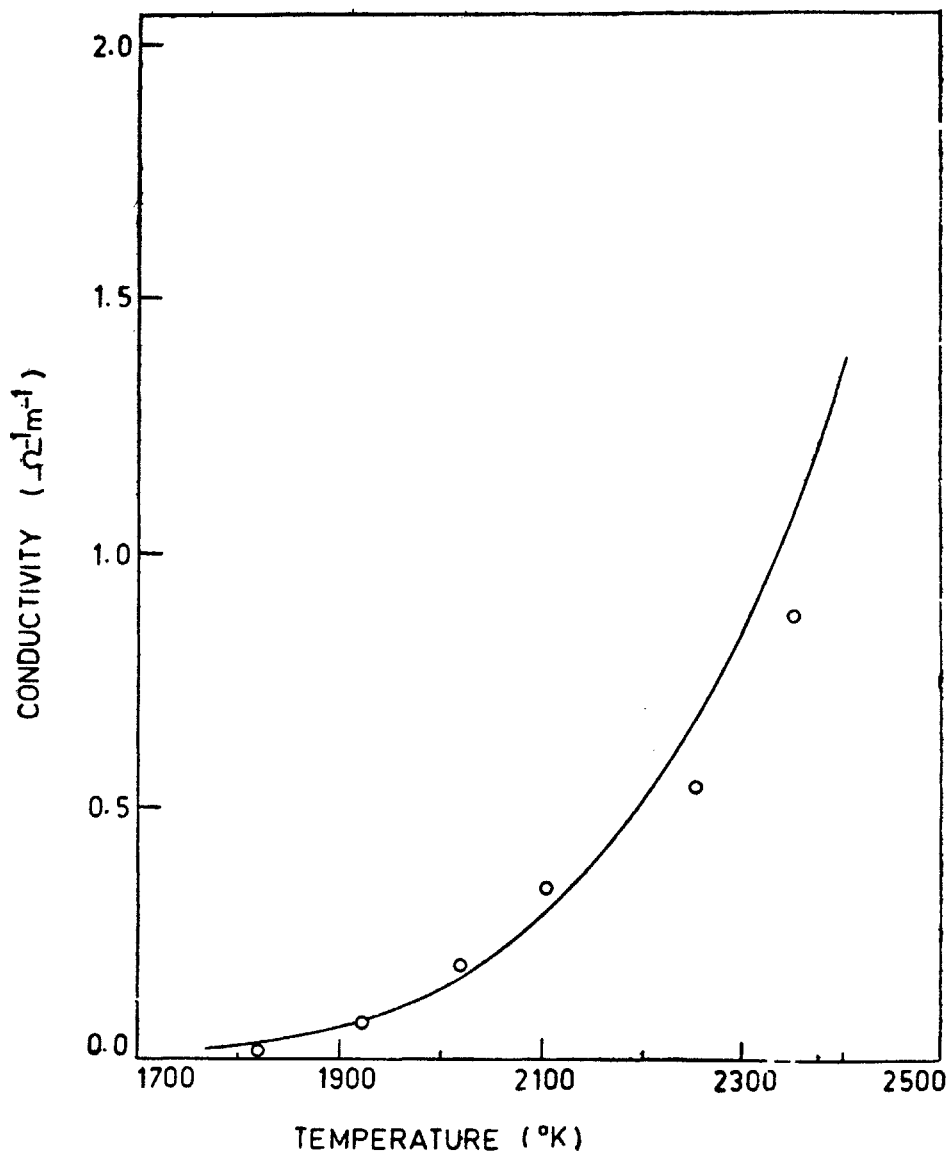


FIG. 3. Variation of electrical conductivity with temperature at seeding ratio of 0.34% by weight. The theoretical curve is shown by (—) and experimental points are shown by  $\circ\circ$ .

for a  $\text{K}_2\text{CO}_3$  seed of 0.30 per cent by weight (figure not reported). The variation of the conductivity with temperature is found similar to that represented by the curves of Fig. 3. It is found from the curves, that the conductivity values calculated by our method described earlier, are in reasonable agreement with those measured experimentally. It may be pointed out that the conductivity of the seeded combustion products of an air-acetylene system lies in the range  $1\text{--}10 \Omega^{-1} \text{m}^{-1}$  at a temperature of (2000–2500  $^{\circ}\text{K}$ ).

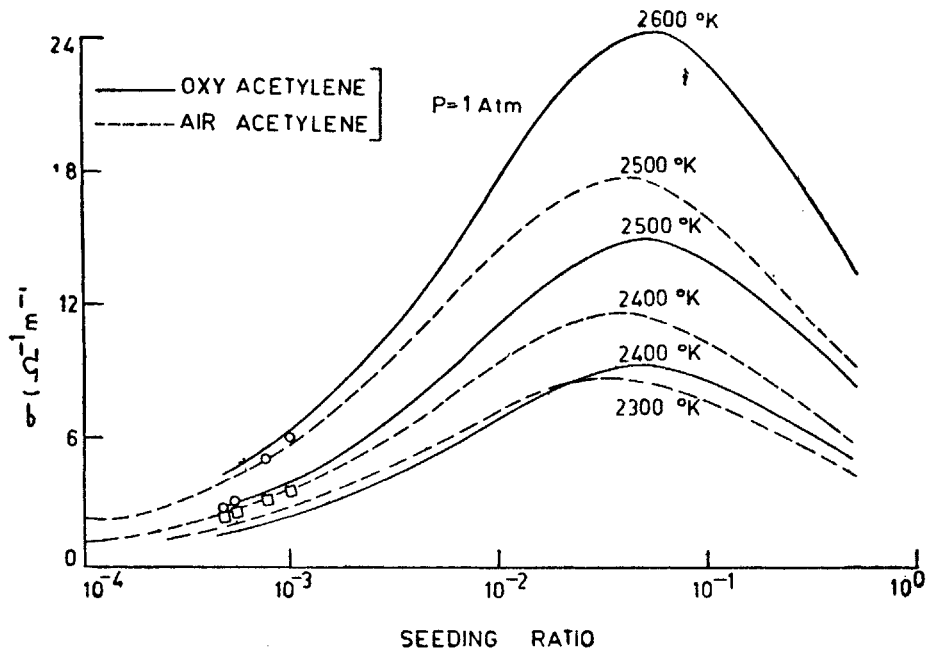


FIG. 4. Variation of the electrical conductivity of the oxyacetylene system (—) and air-acetylene system (---) with the seeding ratio expressed in mole fraction at atmospheric pressure and various attainable temperatures. Experimental points of oxyacetylene system are (i) At 2600 °K ○○: (i) At 2500 °K : □□.

In order to estimate the optimum values of the seeding ratio to obtain maximum conductivity, analytical studies have been made the variation of the electrical conductivity of these systems with the amount of seed added. Fig. 4 shows the variation of the electrical conductivity of the seeded combustion products of air-acetylene and oxyacetylene systems, calculated by the present analysis, with the amount of 'K' seed ('K' expressed in terms of mole fraction) added at various temperatures of the flame. The solid lines represent the conductivity variations of the oxy-acetylene system while the dashed curves indicate the results obtained for the air-acetylene system. The electrical conductivity of these systems is first found to increase with increasing seeding ratio, but starts decreasing when the seeding ratio is very high; thus showing a maximum conductivity for an optimum value of the seeding ratio. It is apparent from these curves that the maximum conductivity at various temperatures of an air-acetylene system occurs when the amount of 'K' added lies in the range of 3.5–4.5 per cent mole fraction, while for an oxy-acetylene system the optimum seeding lies in the range of 4.0–5.5 per cent mole fraction of 'K'. The experimental results for the electrical conductivity of these systems, obtained during our investigations, are also shown on the graph. It is obvious from the curves that the optimum amount of seed, corresponding to maximum conductivity, is very large as compared to the amount of 'K' seed (added in the form of aqueous solution of  $K_2CO_3$ ) which can be conveniently added in the experiments.

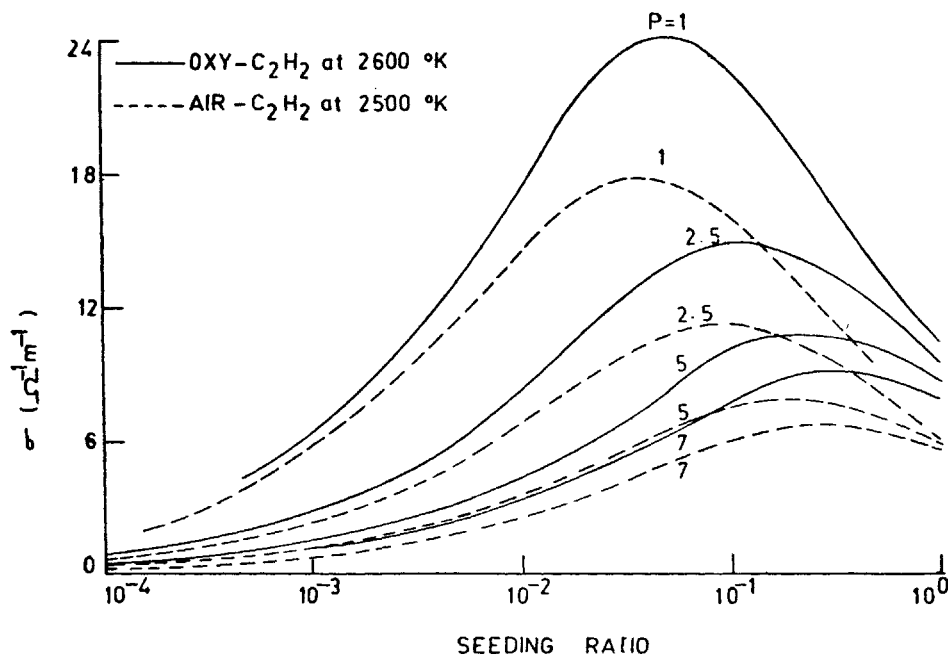


Fig. 5. Variation of the electrical conductivity of the oxyacetylene system (—) at 2600 °K and the air-acetylene (---) system at 2500 K with seeding ratio (expressed in mole fraction) at various pressures.

Fig. 5 represents the variation of the electrical conductivity (calculated) of the seeded combustion products of the air-acetylene and oxy-acetylene systems, under stoichiometric conditions, with the amount of seed added at various pressures. The conductivity of both the working gases is found to decrease with pressure. Further, the optimum values of the seeding ratio for maximum conductivity are found to increase with increasing pressures.

### (iii) Oxy-LPG System

In the present investigations of the transport properties of seeded combustion products of various fuels, for evaluating their suitability as a working fluid in MHD generators, the electrical conductivity of seeded combustion products of liquified-petroleum gas (LPG) is studied because of its ease of availability. The liquified petroleum gas (LPG), used mainly for household applications and being manufactured by the Hindustan Petroleum consists of low boiling hydrocarbons and has the following average composition by weight (Data supplied by the manufacturer) : normal butane ( $C_4H_{10}$ ), 41.5 per cent; isobutane [ $CH(CH_3)_3$ ], 18 per cent; propane ( $C_3H_8$ ), 13.7 per cent; isobutene [ $CH_2 : C(CH_3)_3$ ], 9.5 per cent; trans -2-butene cis-2-butene [ $CH_3 : CH : CHCH$ ], 7 per cent L-butene [ $CH_3CH_2CH : CH_2$ ], 4.3 per cent ; 1:3-butadiene [ $H_2C : CH_2CH : CH_2$ ], 4 per cent; Propylene ( $C_3H_6$ ), 1.5 per cent and a very small percentage of other low hydrocarbons.

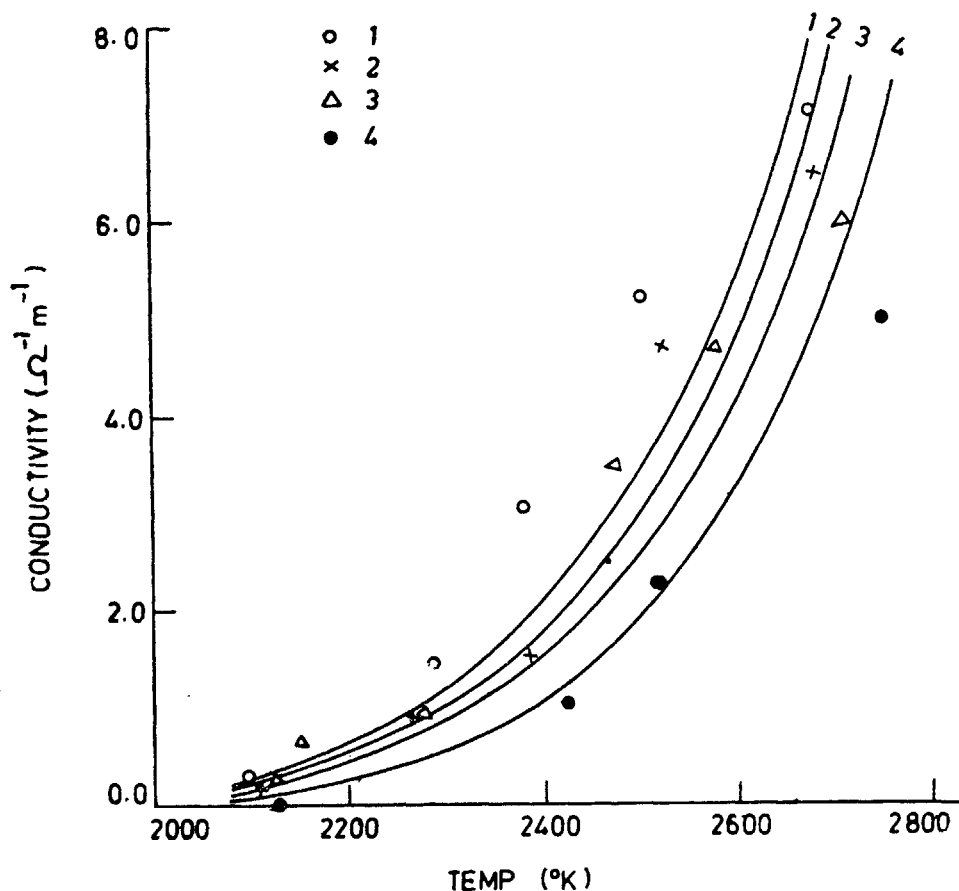


FIG. 6. Variation of electrical conductivity with temperature for different amounts of  $\text{K}_2\text{CO}_3$  seeding (by weight) [Theoretical curves (—) : (1),  $1.42 \times 10^{-3}\%$ ; (2),  $1.03 \times 10^{-3}\%$ ; (3),  $0.82 \times 10^{-3}\%$ ; and (4),  $0.42 \times 10^{-3}\%$ .]

Fig. 6 shows the temperature variation of the calculated electrical conductivity of the combustion products of an Oxy-LPG system seeded with  $\text{K}_2\text{CO}_3$ , for various amounts of seed added, along with some experimentally measured values. Fig. 7 shows similar conductivity variations when the gases are seeded with KOH. The injection of KOH seed into the flames results in the creation of extra OH ions as a consequence of which the electrical conductivity of the system decreases (in the region of the hump in Fig. 7). As the temperature rises further, it is well known that the OH ion concentration decreases with temperature causing an increase in the electrical conductivity at higher temperatures. As is apparent from Figs. 6 and 7, the agreement between the calculated and experimentally determined values of the electrical conductivity is found to be reasonably good. It may be noted that the measured value of the electrical conductivity for an Oxy-LPG system lies in the range of 6–8  $\Omega^{-1} \text{ m}^{-1}$  for seeding ratio of 1.0–1.5 weight per cent of potassium.

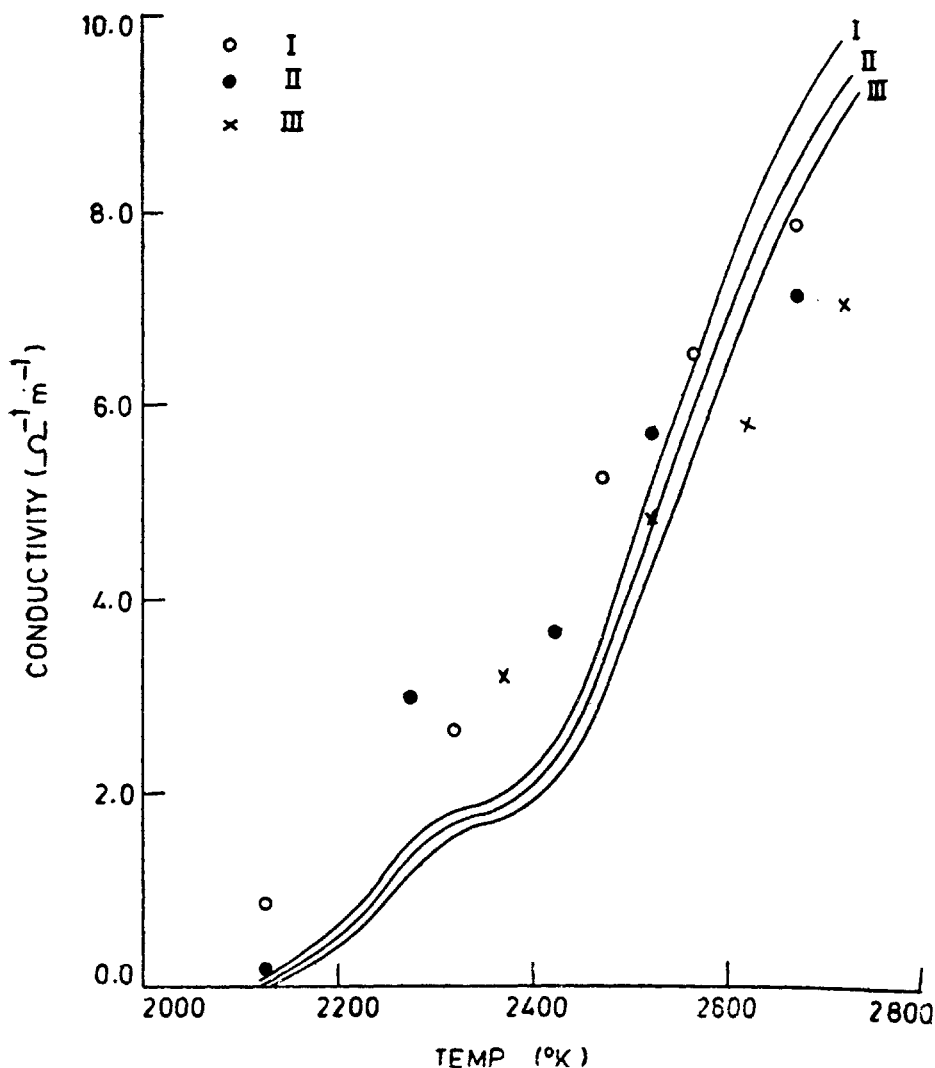


Fig. 7. Variation of electrical conductivity with temperature for different amounts of KOH seeding (by weight) [(1),  $2.44 \times 10^{-2}$ ; (2),  $1.77 \times 10^{-3}$ %; and (3),  $1.47 \times 10^{-3}$ %]

Fig. 8 illustrates the variation of the calculated electrical conductivity of the seeded combustion products of an Oxy-LPG system with the amount of K seed (K expressed in terms of mole fraction) added at different flame temperatures. The optimum seeding ratio for maximum conductivity of an Oxy-LPG system is found to lie in the range 4–6 per cent mole fraction for different temperatures. The values of the electrical conductivity determined during the experimental investigations (with  $K_2CO_3$  as seed) are also shown in Fig. 8.

(iv) *Simulated Oxy-Watergas System*

In an attempt to investigate the conductivity of a watergas system, it was found difficult to fabricate a mini watergas plant. Hence, the concept that a suitable mixture

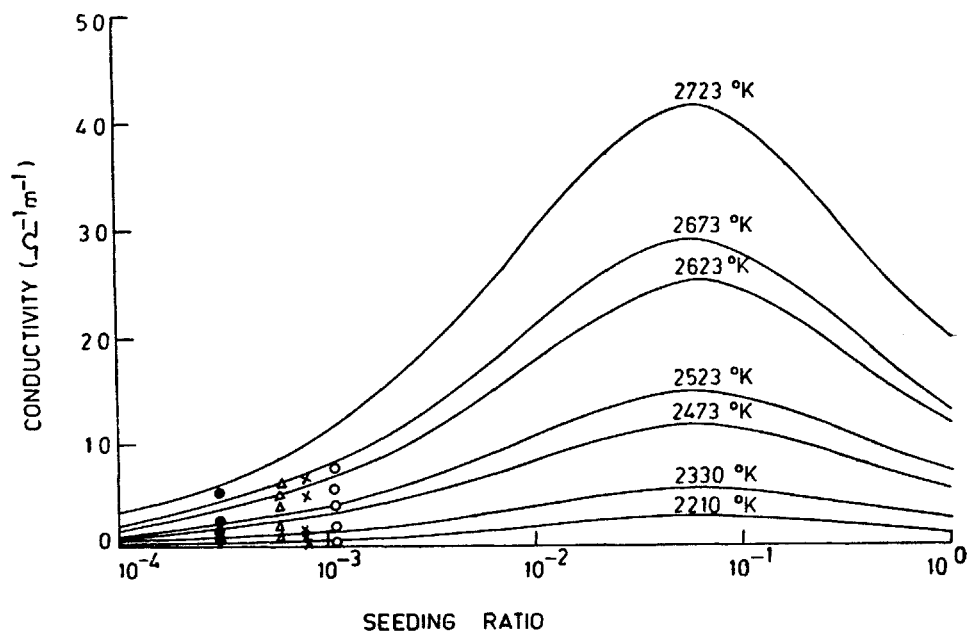
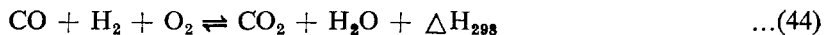
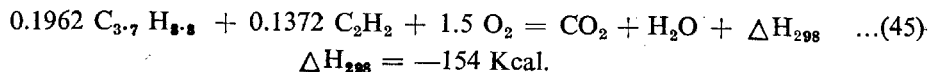


FIG. 8. Variation of the electrical conductivity of oxy-LPG system (seeded with  $K_2CO_3$ ) with the seeding ratio (expressed in mole fraction) at atmosphere pressure for various attainable temperatures. [—, theoretical curves; experimental points of oxy-LPG system  $\circ$ :  $1.10 \times 10^{-4}\%$ ;  $\times$ ,  $8.01 \times 10^{-4}\%$ ;  $\Delta$ ,  $6.38 \times 10^{-4}\%$ ; and  $\bullet$ ,  $3.12 \times 10^{-4}\%$ ]

of liquified-petroleum-gas (LPG) and acetylene being burnt with oxygen under stoichiometric conditions, the combustion products simulate those of a watergas/oxygen system. The stoichiometric combustion reaction of watergas with oxygen is :



The standard heat of this reaction at 25 °C or 298 °K ( $\Delta H_{298}$ ) is  $-125$  Kcal, while for the case of LPG and acetylene :



(It is assumed that complete combustion takes place in the above reactions).

It can be seen from eqn. (45), that the ratio of  $CO_2$  and  $H_2O$  in the combustion products of an Oxy-LPG-acetylene system is the same as in the case of Watergas-oxygen system [Eqn. (44)]. eqn. (45), therefore, specifies that acetylene, LPG and oxygen should be mixed in the ratio 0.1962 : 0.1372 : 1.50 in order that the combustion products of this mixture simulate those of a watergas/oxygen system; the C/H ratio of the acetylene-LPG mixture is 0.5, the same as in the case of watergas. Since, the standard heat of reaction is greater in eqn. (45) than in the eqn. (44); it is expected that an Oxy-LPG-acetylene system would result in higher combustion temperature as compared to that for a watergas/oxygen system. Hence, along the

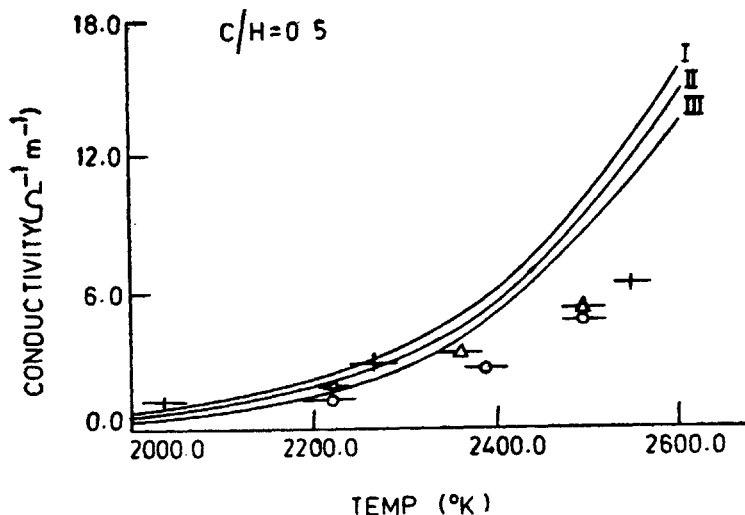


FIG. 9. Variation of electrical conductivity with temperature [continuous curves represent theoretical variation while error bars attached experimental points indicate the uncertainties]

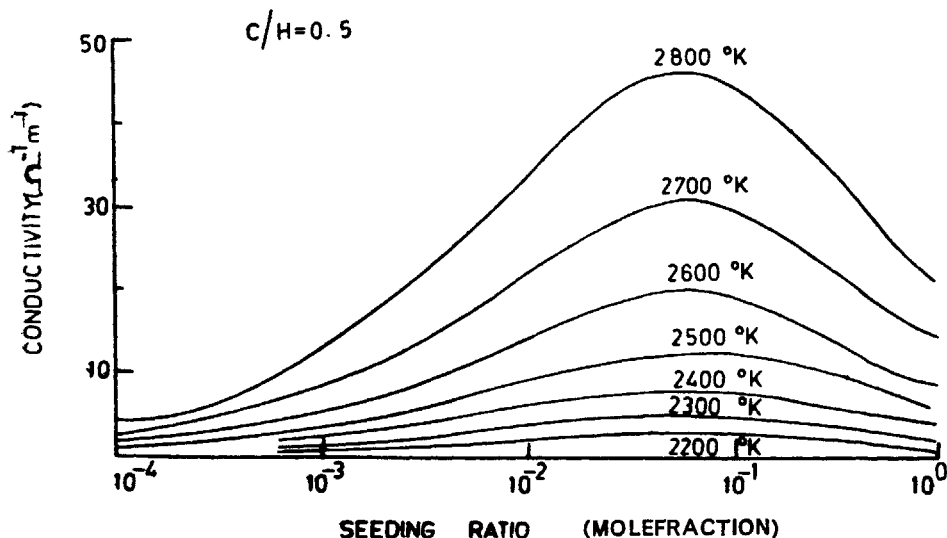


FIG. 10. Variation of the electrical conductivity of water-gas/oxygen system (seeded with  $K_2CO_3$ ) with seeding ratio at atmospheric pressure and various attainable temperatures.

length of the duct, as the temperature falls down, the transport properties of an Oxy-LPG-acetylene system would approach that of a water-gas/oxygen system.

Fig. 9 represents the variation of the calculated electrical conductivity of the seeded combustion products of an Oxy-LPG-acetylene system ( $C/H = 0.5$ ) with temperature for different amount of seed added. The experimentally measured values of the electrical conductivity at different temperatures for the corresponding seeding ratios are shown on the graph; the lengths of the small lines (parallel to the temperature axis) represent the uncertainty in the measurement of the flame temperature

with the help of optical pyrometer. As is apparent from this figure, the agreement between the calculated and experimentally observed values of conductivity is found to be reasonably good except at higher temperatures as observed with other systems.

Fig. 10 shows the variation of the conductivity, calculated analytically, with seeding for different temperatures. Optimum values of electrical conductivity at different temperatures are found to occur when the seeding ratio lies in the range of 5–8 per cent mole fraction of potassium.

(v) *Hydrocarbons with varying C/H*

The dependence of the electrical conductivity of an oxy-hydrocarbon system on the C/H ratio of the fuel (other conditions like temperature and pressure remaining the same) is also experimentally investigated. Such an investigation helps to determine the electrical conductivity of any seeded hydrocarbon system likely to be used as a working fluid in an MHD generator. As it is inconvenient to use different hydrocarbon fuels in order to have working fluids with different C/H ratio, instead, used here is a mixture of easily available hydrocarbons, viz., acetylene ( $C_2H_2$ ) and liquified-petroleum-gas ( $C_{3.7}H_{8.8}$ ), in different proportions and burnt the mixture with oxygen at atmospheric pressure under stoichiometric conditions.

Combustion reaction for the mixture can be written as :

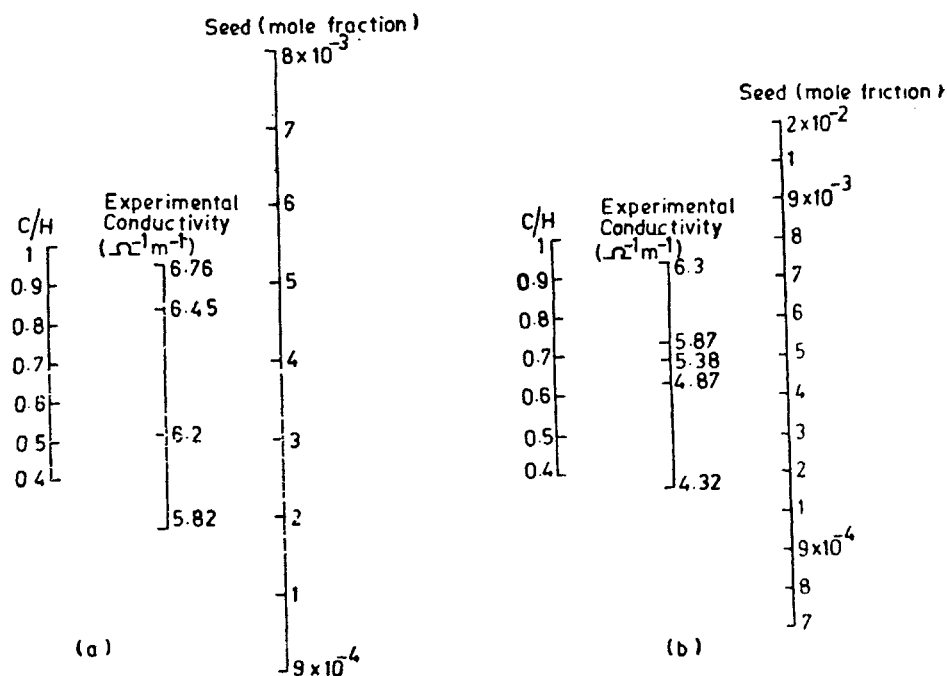
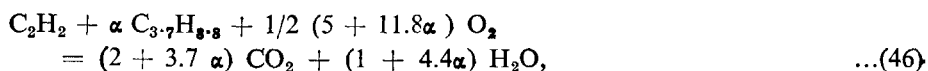


FIG. 11. Parallel line nomograms between C/H ratio seed (in mole fraction) and measured electrical conductivity (a) for temperature 2550 °K; (b) for temperature 2450 °K.



the (C/H) ratio  $\beta$  given by :

$$\beta = (2 + 3.7\alpha)/(2 + 8.8\alpha). \quad \dots(47)$$

Any hydrocarbon (characterized by a given  $\beta$ ) may be simulated by choosing a desired ratio of LPG to acetylene, i.e., the parameter  $\alpha$  in the above equations; the amount of oxygen required for stoichiometric combustion can be obtained from eqn. (46). In our experiments, the combustion products were seeded with an aqueous solution of  $K_2CO_3$ .

In Fig. 11(a) and (b), the experimental results for electrical conductivity of this system have been illustrated by nomograms. In these figures, two parallel axes representing C/H ratio and the amount of seed added are drawn, separated by an arbitrary distance. A reference line representing experimentally determined values of electrical conductivity is drawn midway between the two axes. The line joining the experimental value of C/H ratio and seeding, during one measurement, cuts the conductivity line at a point corresponding to its experimentally measured conductivity. Similar lines have been drawn for the measured conductivity during other measurements. As is evident from the figures, the reference line or conductivity line is not linear in scale throughout. However, the conductivity line is assumed to

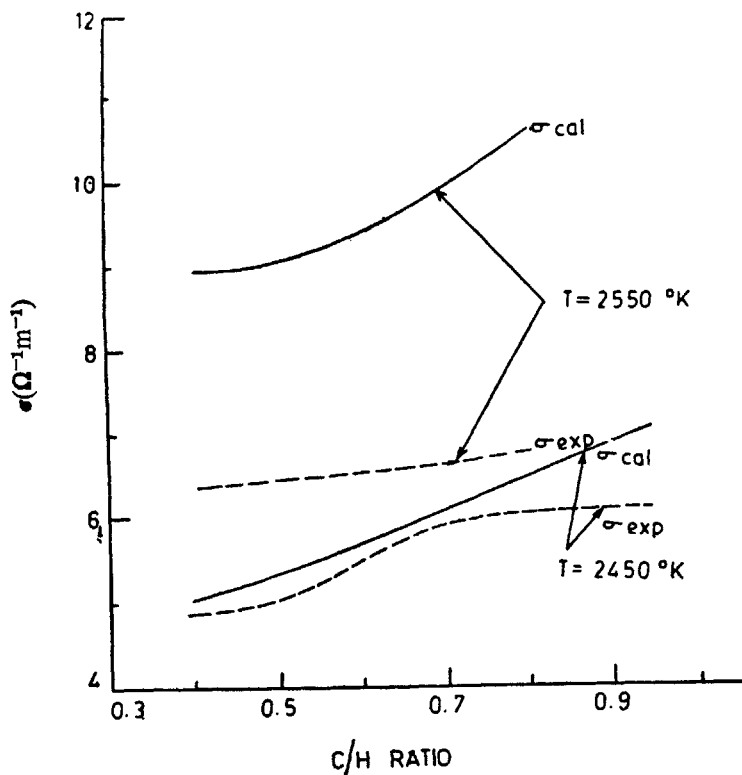


FIG. 12. Variation of electrical conductivity with C/H ratio, at fixed seeding (on mole fraction) of  $6 \times 10^{-3}$  at temperature  $2550 \text{ }^\circ K$  and  $2450 \text{ }^\circ K$ .

represent the value of conductivity on a linear scale between its two neighbouring points. The line joining the C/H ratio of a given hydrocarbon fuel with the desired seeding cuts the reference line at a point to give its electrical conductivity. The value of the electrical conductivity found from these nomograms for a particular C/H ratio and seeding is found to agree within seven per cent of the measured conductivity. Such nomograms have been drawn for various flame temperatures; Figs. 11(a) and (b) show two nomograms for typical flame temperatures of 2550 °K and 2450 °K respectively. During our experiments, the C/H ratio was varied from 0.4 to 1.0 and seeding (by mole fraction) from  $9 \times 10^{-4}$  to  $2 \times 10^{-2}$ . The conductivity of the seeded combustion products of a given hydrocarbon fuel can, hence, be determined from these nomograms for the values of C/H ratio and seeding in the range given above.

For a particular seeding ratio (say  $6 \times 10^{-3}$ ) the electrical conductivity of the flame was determined from the nomograms shown in Figs. 11(a) and (b) for various values of C/H ratio. Fig. 12 shows the variation of the conductivity (determined from the nomograms) with C/H ratio for the abovementioned temperature; the values of conductivity calculated analytically are also shown on the graph. The agreement between the calculated and experimental values of electrical conductivity (determined from these nomograms) is found to be good, specially at lower flame temperatures (<2450 °K). At higher flame temperatures, the experimental values of the conductivity are smaller than the calculated ones.

These investigations show that the electrical conductivity of a given hydrocarbon fuel increases appreciably ( $\approx 50$  per cent) with increasing C/H ratio at lower temperature while at higher temperatures the increase in the value of electrical conductivity is smaller ( $\approx 25$  per cent). This, in general, agrees with the theoretical investigations of the earlier workers (Freck, 1964; Goldenberg *et al.*, 1968; Zielinski 1968).

#### CONCLUSION

It is interesting to note from the results mentioned above that the electrical conductivity of the seeded combustion products of most of the hydrocarbon fuels investigated by us lies in the range  $1.0\text{--}10.0 \Omega^{-1} \text{ m}^{-1}$  (for temperatures 2000–2800 °K) which is of interest in MHD power generation. It is considered that the data obtained during the course of this work would be important and of direct relevance to the future MHD programme, in general and for India in particular.

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