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ESL-TR-91-54

ELECTRIC FIELDS FOR FLAME EXTINGUISHMENT

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AIR FORCE CIVIL ENGINEERING SUPPORT AGENCY
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MARCH 1993

FINAL REPORT

JUNE 1991 - DECEMBER 1991

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ENGINEERING RESEARCH DIVISION
Air Force Civil Engineering Support Agency
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release.
Distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
ESL-TR-91-54

6a. NAME OF PERFORMING ORGANIZATION
Air Base Fire Protection &
Crash Rescue Systems Branch

6b. OFFICE SYMBOL *(If applicable)*
RACF

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
HQ AFCESA/RACF
Tyndall AFB, FL 32403-6001

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
ELECTRIC FIELDS FOR FLAME EXTINGUISHMENT

12. PERSONAL AUTHOR(S)
Thomas S. Call and Douglas B. Schwartz

13a. TYPE OF REPORT
Interim

13b. TIME COVERED
FROM 6/91 TO 12/91

14. DATE OF REPORT *(Year, Month, Day)*
March 1993

15. PAGE COUNT
24

16. SUPPLEMENTARY NOTATION
Availability of this report is specified on the reverse of front cover.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Ionic wind Fire extinguishment

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The objective of this work was to gain a better understanding of the interaction of an electric field with fire. Electric fields have been known to affect flames; this effort was initiated to determine the nature of this effect and to assess the practicality of using the phenomenon for firefighting. A literature search reviewed the theoretical background and preliminary lab experiments were conducted. An external electric field exerts two basic influences on a flame: the the "ionic wind" and direct disruption of the chain of combustion. The effect of the ionic wind depends upon the geometry of the electrodes, composition of the flame and the field polarity. We extinguished small diffusion and premixed flames with a high voltage electric field using various electrode configurations. In addition to the ionic wind effects that lead to extinction, an additional effect may be the stripping of charged radicals from the reaction zone, reducing the concentration available to sustain combustion. This effect also reduces the flame temperature, which reduces the combustion rate and may ultimately extinguish the flame.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
L.M. Womack

22b. TELEPHONE *(Include Area Code)*
(904) 283-3734

22c. OFFICE SYMBOL
HQ AFCESA/RACF

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE

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PREFACE

This report was prepared by Headquarters Air Force Civil Engineering Support Agency, Civil Engineering Laboratory, Air Base Fire Protection and Crash Rescue Systems Branch, Tyndall Air Force Base, Florida 32403-6001. The research took place from June 1991 to December 1991. Mr. Douglas B. Schwartz was the technical program manager.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be availiable to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of this work was to gain a better understanding of the interaction of an electric field with a fire, examine the extinguishing mechanisms due to a field, and project how this phenomenon might be exploited.

B. BACKGROUND

The search for improved or alternative fire suppression agents has gained urgency with the impending ban on production of the highly effective halon agents. Most firefighting agents suppress flames through a cooling action, acting as a heat sink to lower energy to where combustion is not sustained. Halons are the only "clean" agents in use that actually interrupt the flame chemistry for efficient fire suppression. Unfortunately, halons are also one of the most potent ozone depleting chemicals. Alternative agents are under study; however, non-ozone-depleting agents act only as heat sinks. Flame chemistry can be interrupted with bromine (which depletes ozone) or iodine (which can be toxic). As a result, the alternative agents under study are not as effective as the halons. Gaps in knowledge of the combustion process have hampered the search for and design of alternative or improved agents. More basic knowledge of how flames propagate and are extinguished is needed before effective agents can be found or designed with better than an educated guess.

C. APPROACH

In an attempt to fulfill this need and to aid in the search for a replacement for halons the Fire Protection Branch of the Air Force Civil Engineering Support Agency (AFCESA) initiated an investigation into alternatives to chemical-based fire extinguishment. A contract was awarded to Hughes Associates, Inc., to analyze previous work done on the interaction between flames and different types of energy fields with an emphasis on flame extinguishment. Of the ten energy fields considered, electric fields were found to have the most favorable effects. Hughes built a desktop demonstration device in which a radial high-voltage DC electric field was used to extinguish a Bunsen burner-type flame (Reference 1).

At this point an in-house effort was initiated to investigate this phenomenon in depth. This effort has taken two paths: a literature review to understand the theoretical background and review the known effects of an electric field on combustion, and some preliminary experiments in our fire research laboratory.

SECTION II

THEORETICAL BACKGROUND ON COMBUSTION AND FLAMES

A. CONCEPTS

The initial purpose of our literature search was not intended to be an exhaustive review of all the literature on the electrical effects on combustion, but simply to provide us with the background to start our in-house experiments. As it turns out, a large amount of work has been done in this area, and, at some point, an extensive literature search may be worthwhile. In the following we will briefly review some of the basics of combustion, the structure of flames and the sources of ions in flames. Then we will look at some of the theoretical and experimental work done on the mechanical and chemical effects of an electric field on a flame.

B. COMBUSTION

In order to better understand the effects that an electric field has upon a flame we'll briefly review some of the physics and chemistry of fire.

Combustion can be defined as an exothermic (heat-producing), self-sustaining reaction that involves the simultaneous oxidation of a fuel and reduction of an oxidant. The most common reaction of this type is the reaction of a hydrocarbon based fuel with atmospheric oxygen, producing excess energy in the form of radiated energy, much of which goes into propagating and sustaining combustion of other reactants. A large amount of work has been done concerning the physics and chemistry of hydrocarbon flames, which is our primary interest. The following discussions will thus be primarily concerned with flames of a gas-phase or vapor-phase fuel either premixed with air or mixed at the combustion zone.

The process of combustion is a complex reaction involving the interaction of temperature, fuel, oxygen, and the chain reactions of the combustion process (Reference 2). These interrelated processes involved in a fire of a gas or liquid fuel can be visualized as a tetrahedron (Figure 1). For combustion to occur, these four basic elements must freely interact and in the proper proportions. If, for example, the temperature is too low, or there is too little or too much oxygen, the reaction will not be self-sustaining. Likewise, if the chain of chemical reactions is interfered with, combustion will cease. Typical firefighting approaches have been to break up the tetrahedron along the juncture of its sides, removing the fuel, oxygen, or heat. We want to look at the possibility of interrupting the chemical chain reaction. We will now take a close look at the chain reactions of combustion, which will also provide some clues as to why an electric field can have an effect on flames.

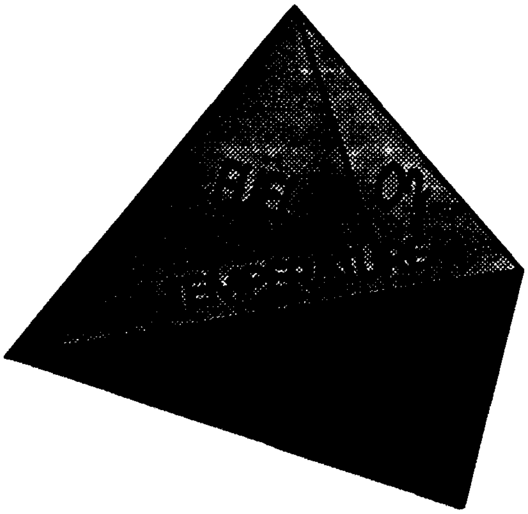

Figure 1. Fire Tetrahedron

If we look at the burning of hydrogen and oxygen to form water, this chemical reaction is written as[1]

$$2H_2 + O_2 \dashrightarrow 2H_2O. \qquad [1]$$

This reaction puts out between 58 and 68 kcal/mole, depending on the final state (gas or liquid) of the water. At first glance this appears to be a simple reaction. However, as pointed out in Reference 3, from an examination of the explosive and flammability limits of a stoichiometric hydrogen-oxygen mixture under different pressures and temperatures, and careful consideration of the chemical kinetics involved, this reaction actually proceeds through a number of simultaneous, interdependent chain reactions. There are four types of chain reactions that occur: chain initiation, chain propagation, chain branching, and chain termination. These can be generically written as (References 3 and 4),

$RE + (M)$	----->	$R^{\cdot}$	chain initiation	[2]
$R^{\cdot} + M$	----->	$I + (P)$	chain propagation	[3]
$R^{\cdot} + M$	----->	$\alpha R^{\cdot} + M^{*}$	chain branching, $\alpha > 1$	[4]
$R^{\cdot} + M$	----->	$P + M$	radical destruction, chain termination	[5]

where RE is a reactant, M is a molecule, $R^{\cdot}$ is a radical, I is an intermediate product, and P is a final reaction product. The parentheses around M and P mean that they may be involved in the reaction but not necessarily, and the asterisk * indicates an excited internal energy state.

The chain initiation reaction is usually highly endothermic (heat-absorbing). This is why a high activation energy is needed to start the combustion process. The

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[1] Reactions will be numbered in square brackets [ ], and equations in parentheses ( ).

chain propagation reactions are slightly exothermic or endothermic, but there is not much energy difference between the products and reactants in this reaction. The chain branching reaction is slightly endothermic with low activation energy. The energy to drive the overall reaction comes from the chain termination reactions which are highly exothermic.

There are several important results here. Radicals are involved in all but the initiation reaction above, therefore the number of radicals available influences the overall reaction rate. The chain branching reaction produces a net increase in the number of radicals. So, depending on the value of the chain branching reaction multiplicative factor a, the reaction shifts from a slow process to the explosive type we associate with fire. In Reference 3 it is shown how the time to complete a reaction can vary from 30 years for a straight chain reaction to 10^{-6} seconds with $\alpha=2$. The fact that radicals are involved in combustion is important to us because radicals, being charged species, can be affected by an external electric field.

If we now go back to the hydrogen-oxygen reaction, examples of the four chain reactions are (References 3 and 4):

$M + H_2 + O_2 \text{--->} H_2O_2 + M^* \text{--->} 2OH^{\cdot}$ chain initiation [6]
$H_2 + M \text{--->} 2H^{\cdot} + M$ [7]

$OH^{\cdot} + H_2 \text{--->} H_2O + H^{\cdot}$ chain propagating [8]
$H^{\cdot} + O_2 + M \text{--->} HO_2^{\cdot} + M$ [9]

$O^{\cdot} + H_2 \text{--->} OH^{\cdot} + H^{\cdot}$ chain branching [10]
$H^{\cdot} + O_2 \text{--->} O^{\cdot} + OH^{\cdot}$ [11]

$H^{\cdot} + OH^{\cdot} + M \text{--->} H_2O + M$ chain terminating [12]
$H^{\cdot} + H^{\cdot} + M \text{--->} H_2 + M$ [13]
$O^{\cdot} + O^{\cdot} + M \text{--->} O_2 + M$ [14]

All three of the above terminating reactions are exothermic, with heats of formation between 104 and 120 kcal/mole.

The chain reactions described so far are for the simple case of hydrogen and oxygen. There are at least 18 separate reactions involved in the burning of the simple hydrocarbon methane, CH_4, in pure oxygen (Reference 5). When methane is burned in air, the presence of nitrogen initiates still more reactions and formation of additional radicals.

C. FLAMES

With the above idea of the reactions that are occurring in a flame, we'll now examine two simple flame situations, a premixed flame and a diffusion flame. There are numerous variables of interest in these two systems, such as the rate of propagation of the flame front, the temperature of the flame and the temperature profile, the structure of the flame front, the ion and radical concentration and profiles, and the constitution of the reaction products. It is beyond the scope of this paper to discuss the methods for calculating and measuring all the above quantities. For a complete discussion see References 3 or 6.

A premixed flame occurs when the fuel and the oxidant are completely mixed prior to reaching the flame front. The flame from a simple lab Bunsen burner is an example of a premixed flame. Figure 2 shows a profile normal to a flame front. Several quantities of interest, such as the temperatures and velocities in the various regions of the flame are shown. If all the heat evolved from the reactions is used to raise the temperature of the product gases, the final temperature T_f is called the adiabatic flame temperature. This is a function of the difference between the heats of formation of the reactants and those of the final products (Reference 3). The overall rate of propagation (S_u) of such a flame is dependent on the sum of the local reaction rates. A first attempt to calculate the flame propagation rate would be to divide the flow rate of the reactant gases by the cross sectional area of the flame (Reference 6),

$$S_u = F / A \qquad (1)$$

where S_u is the velocity of the flame, F is the mixture flow rate and A is the area of the flame front. This approach would work with a two dimensional flame, i.e. one that is perfectly flat. However, there are obvious three-dimensional, cone-shaped zones in a burner flame. Various optical techniques have defined different regions in the flame as shown below. The calculations for actual flame front velocity and final temperature are fairly complex and can be found in References 3 or 6.

A diffusion flame is formed when the fuel and oxidant are initially separate and only come into contact at the flame front. Burning occurs in the zone where the two have diffused to essentially a stoichiometric mixture. Candle flames, open pool fires, and gas jets are examples of diffusion flames.

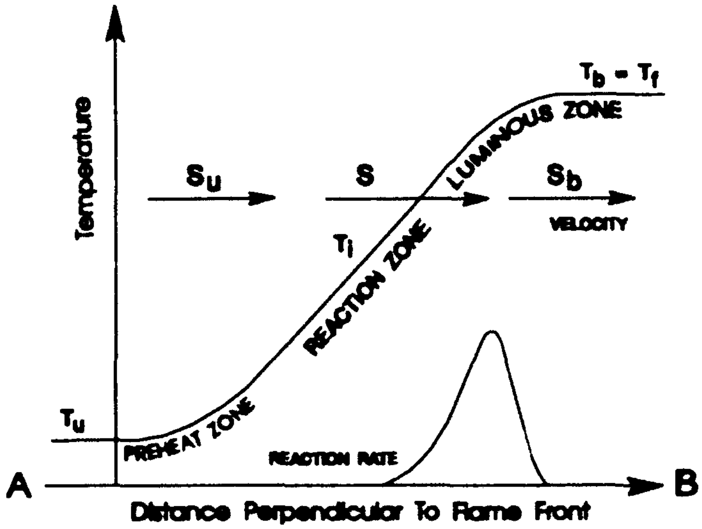

Figure 2. Cross Section of a Laminar Flame(3)(6)

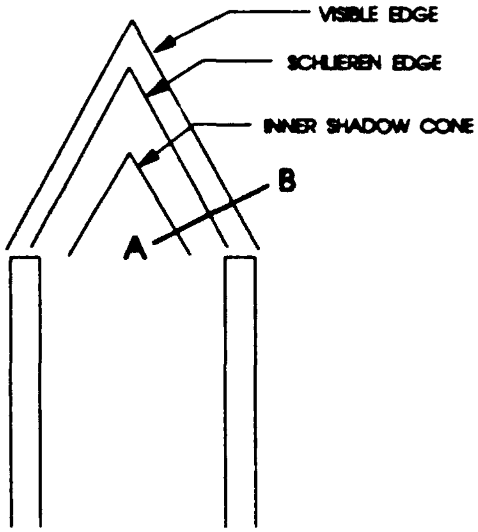

Figure 3. Optical Fronts in a Bunsen Burner (3)

D. ION SOURCES IN FLAMES

The importance of ions in a flame from our perspective is that they are the components that can be acted upon by an electric field. Reference 6 discusses in detail the relevant processes in a flame that can produce ions. They are:

1. Ionization by collision
   $A + B \dashrightarrow A^+ + B + e^-$
   $A + e^- \dashrightarrow A^+ + e^- + e^-$

2. Electron transfer
   $A + B \dashrightarrow A^+ + B^-$

3. Ionization by transfer of excitation energy
   $A + B^* \dashrightarrow A^+ + B + e^-$

4. Chemi-ionization
   $A + B \dashrightarrow C^+ + D + e^-$
   $A + B \dashrightarrow C^+ + D^-$

A large amount of work has been done to identify the ion species present in a flame and the mechanisms responsible for their production. The various methods for measuring ion concentrations and identity, from the use of probes to mass spectrometry, are discussed in detail in Reference 6. Hydrocarbon flames show the following general results:

1. The rate of ion generation depends on flame temperature and mixture composition but is independent of pressure. A 100° K increase in flame temperature increases the ion generation rate from two to four times. In a very lean flame, 3×10^{13} ions/sec-cm^2 were produced, whereas in a near stoichiometric mixture, 6×10^{14} ions/sec-cm^2 were produced (Reference 6).

2. In all hydrocarbon flames the positive ions CH_3^+, H_3O^+, CHO^+, and $C_3H_3^+$ are present. Arguments are put forth (Reference 6) that CHO^+ and $C_3H_3^+$ are the primary chemi-ions, thus being parent ions from which all the other ions are formed either by charge transfer reaction or ionization by electron collision. The positive ion concentration in a cross section normal to a flame is shown in figure 4. H_3O^+ is found in the highest concentration, but it reaches its greatest concentration downstream of the concentration peaks of the other positive ions, indicating that it is not a primary ion but formed later (Reference 6).

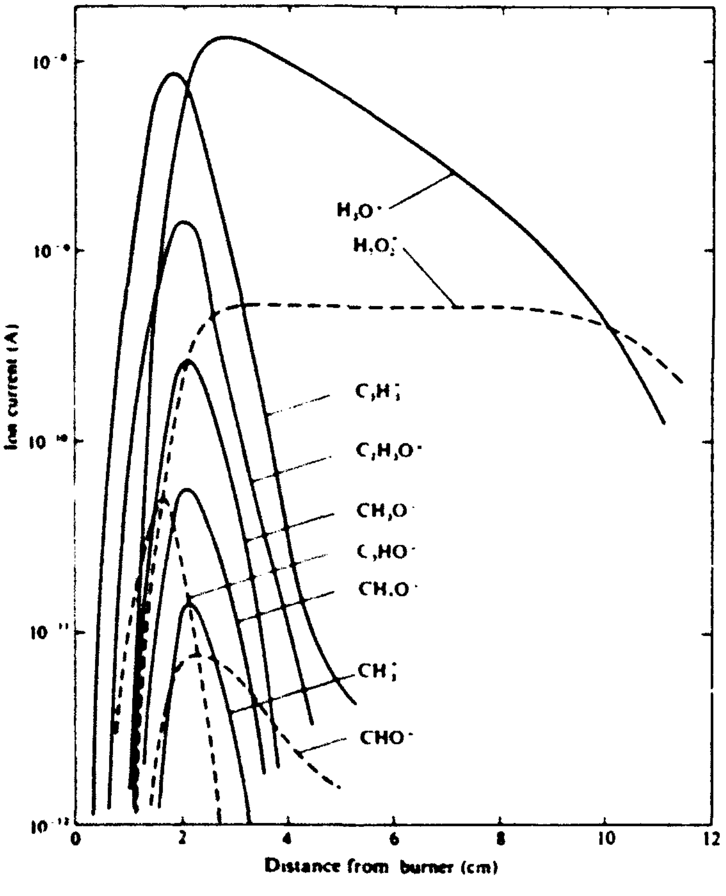

Figure 4. Positive Ion Concentrations (Reference 6).

3. There is no agreement as to the abundance and identity of negative ions formed in a flame, or as to the process by which they would be formed. Some studies (Reference 7) indicate that negative ion formation is only significant in the

preheat zone, with the negative ion concentration decreasing rapidly in the reaction zone and almost zero in the products. Other work (Reference 6) has indicated that up to 99 percent of the negative charge in a flame is carried by free electrons, which means there is a very small concentration of negative ions.

4. The primary charge recombination reaction is $H_3O^+ + e^- \text{--->} H + H_2O$. This is a highly exothermic reaction with a ΔH of -145 kcal/mole.

In summary, from the known composition of the positive ions in a flame, and from thermochemical considerations, the primary mechanism for ion formation in a flame is chemi-ionization. In addition to the positive ions present in a flame, there is a high concentration of free electrons. The importance of this will show up when we discuss the effect of an electric field upon a flame.

SECTION III

ELECTRIC FIELD EFFECTS ON A FLAME

It has long been common knowledge that an external electric field has a dramatic visible effect upon a flame. Observations of the effects of a high-voltage field on a candle were recorded in 1814 by Brande (Reference 8). In 1924, Malinowski was able to extinguish flames with a high voltage field (Reference 9). Other effects that have been seen are various deflections and distortions of flames under different electric field/burner systems, destabilization of flames leading to extinguishment and, conversely, stabilization and augmentation of flames leading to wider flammability limits and higher flame temperatures. Since J.J. Thompson suggested in 1910 that electrons are involved with combustion, the debate has been whether or not the observed effects of an electric field and a flame are due to purely mechanical forces, the ionic wind, which disrupt the physical parameters of the flame, or if the electric field actually alters the flame chemistry (Reference 10). Both effects are occurring. Which one is dominant depends upon the geometry of the situation and the nature of the electric field. This is important to us because from a firefighting point of view, the possible chemical effects could be useful in developing new firefighting agents. We will now look in detail at some of the relevant work concerning the mechanical and chemical effects of an electric field upon a flame.

A. IONIC WIND

The ionic wind is the flow of ions and neutral gases which occurs when a flame is subject to an external electric field. The flow of neutral gases happens because the charged particles, which are directly subject to displacement due to the electric field, transfer their momentum to the more numerous neutral particles. We will now examine some of the details of this displacement of the charged particles and the ensuing results of their displacement.

Under the influence of an external electric field, the charged components of a flame will experience a translational force proportional to the electric field strength E and the charge q,

$$F = qE. \tag{2}$$

If the charged particle is small compared to the mean free path λ, the distance it travels between collisions with the mainly neutral gas components, and we assume that the particle starts at rest from each collision, then the kinetic energy gained between collisions is

$$q\lambda E = 1/2\ mv^2. \tag{3}$$

For more massive particles, the average effect of the collisions can be expressed as a retarding force proportional to the velocity,

$$qE = \beta v. \tag{4}$$

In both cases, the energy gained by the charged particle is transferred to the neutral gas. But the electric field continues to add energy to the charged particle. So, a balance is established between the energy gained by the particle from the field and lost to the neutral gas. Thus the charged particle assumes a constant drift velocity which is proportional to the electric field. In this case, the particle is said to have a constant mobility K, defined as (Reference 6),

$$K = E/v\,. \tag{5}$$

Mobility depends upon a large number of factors, from mass of the particle to the density of the gas. Lawton goes into extensive calculations of the mobilities of the different charged products. One important result is that the velocities of free electrons in a flame are 10^2 to 10^3 times greater than the velocities for positive ions. Therefore, in an electric field, the free electron concentration in a flame is negligible.

Due to this flow of ions and electrons, there is a current flow through the flame to the electrodes. If the field is constant in time, then a nonuniform distribution of charge will occur. Positive ions will build up near the negative electrode and negative ions and free electrons will build up near the positive electrode. By Gauss's law, this leads to a nonuniform electric field between the electrodes and across the flame. Again, Lawton has calculated the results of this effect and a graph of the electric field strength across a flame is shown in figure 5. Wolf and Ganguly (Reference 11) have also seen this effect in propane flames seeded with cesium ions.

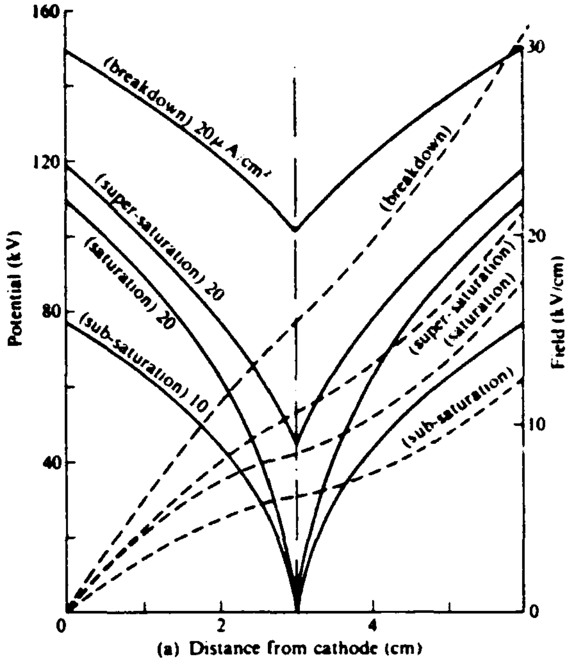

Figure 5. Field and Potential Distribution for a CH_4 Flame Between Electrodes 6 cm Apart (Reference 6).

The effect that interests us is the impact the ion flow, the current, has on the neutral gases. The momentum acquired by the ions from the electric field is transferred to the neutral gases by collisions. The force per unit area exerted on the gas is (Reference 6),

$$F = Ee(n_+ - n_-)\,, \tag{6}$$

where n is the density of the positive and negative particles. As shown above, the charge distribution in a flame is nonuniform, and the positive ions and electrons coexist only in the thin reaction zone where they are created, so the force per unit area in the region of an electrode is

$$F = Een, \tag{7}$$

where n is the number density of the ion attracted to that electrode. Also, the current density is given by (Reference 6),

$$j = EenK\,, \tag{8}$$

therefore,

$$F = j/K. \tag{9}$$

From this we see that the force is proportional to the current and inversely proportional to the mobility. Since the fuel and oxidant for flames are initially neutral, by the law of charge conservation the current flow due to the positive particles must be equal and opposite to the current flow due to the negative particles. Thus the predominant direction of the force on the neutral gas is by the particle with the lowest mobility, which is the positive ions. So, the ionic wind is primarily towards the negative electrode.

Let us now determine the maximum force that the ionic wind can exert. Since the mobility is fixed, the maximum current density will be a limiting factor. There are two limiting cases for the current density and total current. The first case, the saturation current density, j_s, occurs if the electrodes are far enough from the flame that ionization breakdown does not occur first. The saturation current is reached when the field is stripping the ions out of the flame as fast as they are being produced. The factors that affect this are flame size, composition, electrode geometry, and field strength. An example of this saturation current is shown below.

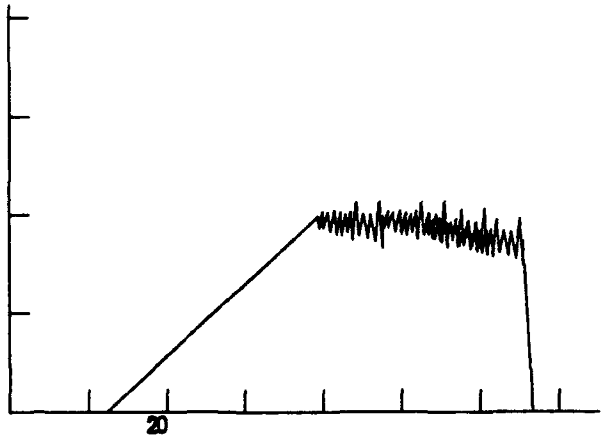

Figure 6. Current Versus Voltage.

In the linear ramp section of the plot, the flame acts like a simple resistor; the current follows Ohm's law. As the voltage is increased the speed of the ions increases, thus increasing the current flow until the ions are depleted as fast as they are generated.

The second case, the breakdown current density, j_b, occurs when the electric field strength reaches the breakdown strength in the gas. Since, as was shown above, the electric field is maximum next to the electrodes, j_b is primarily a factor of macroscopic quantities. This can be shown (Reference 6) to be

$$j_b = EK/8\pi a \tag{10}$$

where E is the breakdown field strength and a is the distance from the flame to the electrode. We have seen examples of both limiting currents in our lab.

Using the above maximum current density, Lawton has calculated for an average hydrocarbon flame the maximum static pressure, wind velocity at the electrodes, and force/unit volume to be

$$P_B = E_B /8\pi = 400 \text{ dyn/cm}, \tag{11}$$
$$v_B = E_B /2\,(2\pi\rho)^{1/2} = 550 \text{ cm/s}, \tag{12}$$
$$F_B = E_B/ 8\pi a = 800 \text{ dyn/cm}^2. \tag{13}$$

Lawton and Weinberg (Reference 6) performed numerous studies of and experiments on the effects of ionic wind on flames. They conclude that the aerodynamic effects alone of the ionic wind can explain the phenomena of flame distortion, variations in combustion rate, and increases/decreases in flame stability. They claim that there is no need to resort to explanations involving changes in the chemical processes of combustion. However, since their monologue was published, there has been work that both supports and questions their position.

B. CHEMICAL EFFECTS

The mechanical effect of the ionic wind upon a flame is an established fact. However, counter to the claims of Lawton and Wienberg, ionic wind effects do not completely explain the effects of an electric field upon a flame. Numerous experimental results have been seen that can not be completely explained, if at all, as due to an ionic wind. We will now examine some of the work that illustrates this and investigates the other possible effect the electric field could be having: an influence on the combustion chemistry.

Jaggers and von Engel (Reference 10) studied the effect of DC and AC electric fields on the burning velocity of different gas flames. In a vertical tube 120cm tall by 5cm inside diameter, the burning velocity was measured as a function of the fuel/air mixture ratio under various electric fields. For ethylene-air and methane-air flames, the application of a DC field of 0.5 kV/cm increased the burning velocity by close to a factor of two. Salamandra and Maiorov (Reference 12) found that in a horizontal tube the flame velocity of a dry gas mixture is raised by a factor of eight by the application of an electric field. However, for a wet gas mixture (1.8 percent water vapor by weight), the flame velocity with an electric field was only 2.5 times greater. Both groups saw physical perturbations in the flame front under the electric field and posited that an ionic wind effect may be increasing the flame surface area and thus the velocity, but Jaggers and von Engel also saw physical perturbations in flame fronts with no electric field. Salamandra and

Maiorov concluded that the increase in the flame velocity is due to "hydrodynamic effects," and hence the adding of water vapor basically reduced the ionic wind.

To eliminate the effects of the ionic wind, Jaggers and von Engel subsequently used a high frequency (HF) field of 5 MHz in their experiment. 5 MHz was chosen because for a field of frequency ω, the displacement Δx of an ion is

$$\Delta x = KE/\omega^2 \text{ or} \qquad (14)$$
$$\Delta x = eE/m\omega^2 \qquad (15)$$

depending upon whether mobility (K) or inertia (mass m) predominates. If Δx is less than the flame front thickness, then there will be no ionic wind effects. At 1 atm, 1500^0 K, the flame front thickness is approximately 10^{-2} cm, and K is of the order of 10 $cm^2/Vsec$. With E = 0.5 kV/cm, ω must be greater than 1 MHz in order that Δx be less than 10^{-3}cm, less than the flame front thickness. In the vertical tube apparatus with a 5 MHz field, there was a 20% increase in the flame velocity. Therefore, there is some effect on the flame chemistry increasing the flame velocity.

To insure that the effect seen was due to an increase in the flame front velocity S_u, Jaggers and von Engel measured the displacement of a flat floating flame in a 5 MHz electric field (see figure 7 below). The electric field was applied both transversely along the flame front and longitudinally across the flame front. In both cases, a displacement of the flame towards the burner was seen, indicating an increase in S_u. There was no change in flame shape or stability, indicating that there was no ionic wind.

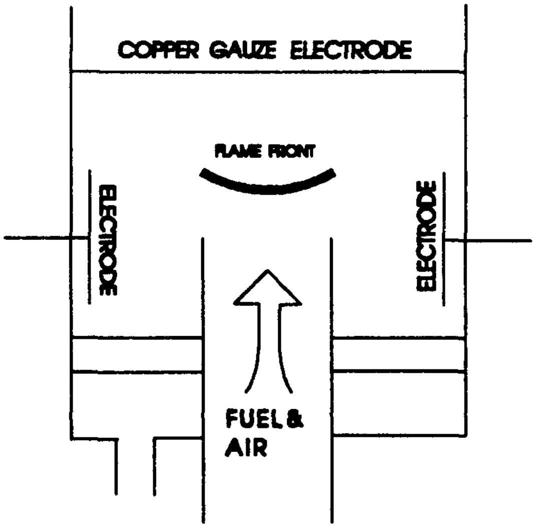

Figure 7. Floating Flame Burner (Reference 10).

Jaggers and von Engel concluded that the effects seen are due to a change in the electron collision process in an electric field. They state that the chain branching reaction

$$H^{\cdot} + O_2 \dashrightarrow OH^{\cdot} + O^{\cdot} \qquad [15]$$

controls the overall rate of reaction, and therefore the flame speed S_u. The rate of the reaction above is influenced by the vibrational energy level of O_2, indicated by υ. The free electrons in a flame pick up translational energy which through the interaction

$$O_2(\upsilon=n) + e^{-} \dashrightarrow O_2(\upsilon=n+1) + e^{-} \qquad [16]$$

is then passed on to the O_2 population as an increase in internal vibrational energy υ. This then increases the rate of the chain branching reaction [15] which then increases S_u. Therefore, the electric field increases the free-electron temperature, which in turn increases the vibrational energy states of O_2, and the increase in S_u is due to the increase in the overall reaction rate.

Tewari and Wilson (Reference 13) also did an experimental study of the effects of high frequency electric fields on flame propagation rates. They measured the growth rate of flame kernels induced by a high-energy laser pulse in mixtures of methane/air and methane/argon/oxygen. The application of a 6 MHz, 1.67 kV/cm(rms) field resulted in increased flame propagation rates in both mixtures, but there was less of an effect seen in the methane/argon/air mixture. Tewari and Wilson then argue that if the effect seen is due to an electron energy exchange mechanism, it should have been greater in the mixture with argon. The free electron density in the flames of the two mixtures is the same. Since N_2 is a strong absorber of electron energy, replacing N_2 with Ar should have increased the efficiency of the electron-O_2 energy exchange. This would then lead to a greater increase S_u. But the reverse is seen. So, they concluded that other modes of energy exchange must be occurring.

Shebeko (Reference 14) analyzed the work of Tewari and Wilson and concluded that the electron energy is absorbed by the N_2, but is then passed on by energy exchange collisions to the O_2. Collisions of N_2 with excited electrons leads to increased vibrational energy levels υ' of N_2,

$$N_2(\upsilon'=0) + e^{-} \dashrightarrow N_2(\upsilon'>0) + e^{-}. \qquad (16)$$

Then, through an energy exchange collision some of this internal energy is transferred to the O_2 population,

$$N_2(\upsilon') + O_2(\upsilon=0) \dashrightarrow N_2(\upsilon'-1) + O_2(\upsilon=1). \qquad (17)$$

Thus, this population of vibrationally excited O_2 increases the rate of the chain branching reaction [15] as discussed above, which increases S_u.

Gulyeav, Popkov and Shebeko (Reference 15) looked at the effects of a DC electric field on premixed propane/butane/air flames. Their work is especially interesting in that they focused special attention on flame extinguishment. The experimental setup consisted of a metal burner 10 mm in diameter, surrounded by a cylindrical metal mesh, 70 mm in diameter and 200 mm tall. The burner formed one electrode and the mesh cylinder the other. The lower edge of the mesh was 20-30 mm below the burner mouth. The maximum gas flow rate for a sustainable flame, Qmax, was used as an index of the stability of the flame. Qmax versus applied voltage for various excess oxidant ratios above stoichiometric were measured. A positive voltage applied to the mesh led to a stabilization of the flame and higher maximum flow rates. A negative voltage produced significant changes in the flame geometry and a lower Qmax. The perturbations of the flame grew with applied voltage, leading to a "flower" form with 4-6 lobes immediately before being extinguished.

Gulyaev, Popkov and Shebeko explained the effects seen as caused by the ionic wind. In the preheat zone of a flame, positive ions predominate; in the luminous zone, negative ions predominate. If a negative voltage is applied to the mesh, the hot positive ions are drawn to the outside of the flame and the negative ions are attracted to the center. The ionic wind is outward since the positive ions have a lower mobility than the negative ions, which are predominantly free electrons. The ionic wind thus draws hot combustion products and reaction centers out of the reaction zone, cooling the flame. At sufficiently high voltages (0.1 to 0.5 kV/cm) this cooling leads to flame extinction. Conversely, with a positive voltage on the mesh, the ionic wind is in toward the axis of the flame. This leads to flame stabilization.

In a similar setup, using a mesh cylinder 9.5 cm in diameter by 20 cm high, Gulyaev, Popkov and Shebeko (Reference 16) investigated the combined effects of an inert gas (nitrogen or argon) and an electric field on a flame. In this case, the flame stability was characterized by the minimum flow rate Qmin. As expected, the addition of N_2 or Ar required an increase in the fuel-air mixture Qmin. Both N_2 and Ar have an extinguishing effect on a flame. The addition of the electric field on the flame-N_2 combination unexpectedly stabilized the flame, decreasing Qmin. In the flame-Ar case, the fire extinguishing effect of Ar was intensified. They explained this by stating that there are three effects that could be going on here. First, the inert gas cools the flame. Second, the ionic wind due to the electric field also cools the flame, and, third, the N_2-electric field combination increases the combustion rate, as Shebeko put forth above. In the situation with N_2, this third effect outweighs the first two. With Ar, the first two combine in some way to produce a fire extinguishing effect greater than the sum of the two; some kind of synergism occurs.

The Russians refer to similar work that was done using a diffusion flame instead of a premixed flame. In that case, with N_2 added, only the positive fire extinguishing synergism effect was seen. This is explained by the fact that the excitation of the internal degrees of freedom, vibrational in this case, is greatest for the relatively lower temperature reactions. This means the electric field will have the most effect on combustion rate in the low temperature region of the flame front. A low temperature zone of a flame front with both fuel and oxidizer in comparable concentrations occurs only in premixed flames. In this case the combustion rate is controlled by the reaction rate, so the electric field effect upon the reaction rate can take place. In a diffusion flame, the low temperature regions are deficient in either fuel or oxidant, which then becomes the combustion rate limiting factor.

C. SUMMARY OF LITERATURE REVIEW

From this literature search, the following conclusions can be drawn:

1. The combustion of hydrocarbons is a complex reaction that occurs through branched chain reactions involving radicals.

2. The *primary radicals in a flame which can be acted upon by an* electric field are the positive ions. There are negative ions and free electrons in a flame but their concentration is much lower than that of the positive ions.

3. An electric field produces an ionic wind, the effects of which vary depending upon the geometry of the burner and electrodes, composition of the flame, and polarity of the field.

4. The electric field interacts in some manner with the combustion chemistry. One theory is that the electrons pick up energy which through an exchange collision is transferred as vibrational energy to either N_2 or O_2, which then has an impact on the reaction rate of $H^{\cdot} + O_2 \text{--->} OH^{\cdot} + O^{\cdot}$, a major reaction influencing the combustion of hydrocarbons.

SECTION IV

IN-HOUSE WORK

A. GENERAL OBSERVATIONS

In our laboratory we have looked at the electric field extinguishment effects on a flame. We have done some preliminary investigations into various electrode/flame configurations and the observable physical effects upon the flame. Since we are still in the process of equipping our lab, we lacked some instrumentation and equipment.

Almost all of our work has been with diffusion flames of natural gas. One of the most prominent effects that we have seen is the attraction of the luminous part of the flame to the negative electrode. This was seen with point, plate, and cylindrical electrodes. This seems counter to what is stated in the literature that negative ions predominate in the luminous zone. We were able to extinguish these flames in several configurations.

B. PLATE AND POINT ELECTRODES

We succeeded in extinguishing flames with a high-voltage field using various electrode configurations. Square aluminium plates 51 mm on a side and aluminium rods 2.4 mm in diameter were placed on opposite sides of a flame (see figure 8) and connected to a variable high voltage (0-30 kV) power supply. The burner in this case was simply a thick-walled glass tube 7.25 mm OD x 2.8 mm ID. As the voltage was increased, the electrode spacing would be increased if arcing occurred before the flame was extinguished. With a flame 52 mm high, and the rod electrodes 45 mm apart, as the voltage was increased the yellow, luminous section of the flame was attracted to the negative electrode while the blue section of the flame was attracted to the positive electrode. As the field strength was increased, at a certain point the yellow luminous part of the flame would disappear, leaving only the blue section. The ionic wind at this point was obvious because the blue flame would be so laterally displaced towards the positive electrode that the flame just barely touched the edge of the burner tube. At 15.1 kV, roughly 34 kV/cm, the flame was extinguished. Similar results were seen using the square plate electrodes, but there were more problems with arcing and greater voltages were required to extinguish the flame.

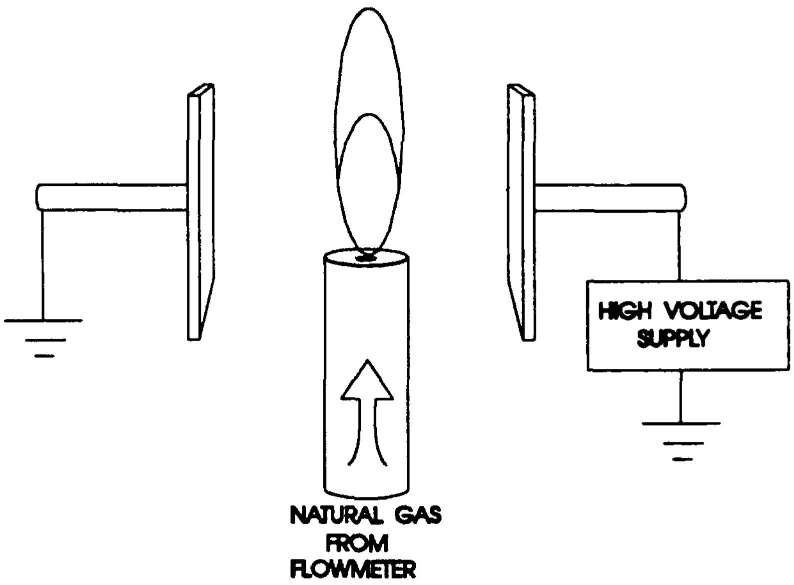

Figure 8. Plate Electrode Setup.

C. CYLINDRICAL ELECTRODES

One of the most successful electrode configurations for extinguishing the flame was a cylindrical stainless steel mesh as the negative electrode and a metal burner as the other electrode, as Gulyaev. Popkov, and Shebeko used. The setup is depicted below (Figure 9).

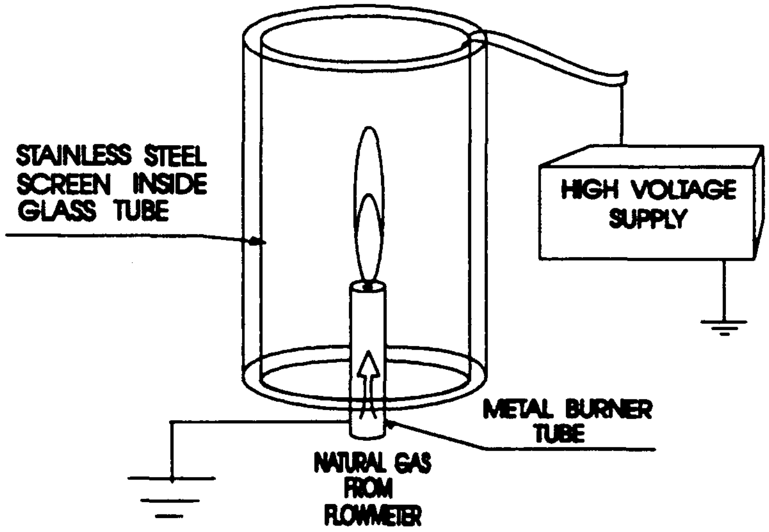

Figure 9. Cylindrical Electrode Setup.

With the mesh as the negative electrode, the results we saw were similar to Reference 15 in that perturbations of the flame were evident and increased with voltage, sometimes taking on lobes. Extinguishment occurred between 5 to 7.5 kV.

Figure 6 is a typical graph of current versus applied voltage. Current starts to flow as voltage is increased above a threshold. Current continues to increase with voltage, until at a certain voltage, which appears independent of gas flow rate, the luminous part of the flame disappeared and the maximum or saturation current j_s was reached. The flame is very unstable at this point and is reflected in the unstable current flow. This instability increases as the voltage is increased until the flame goes out. A plot of the voltage required to extinguish the flame as a function of gas flow is shown in Figure 10. The low point of the curve is the flow rate at which the flame just reaches the top of the screen.

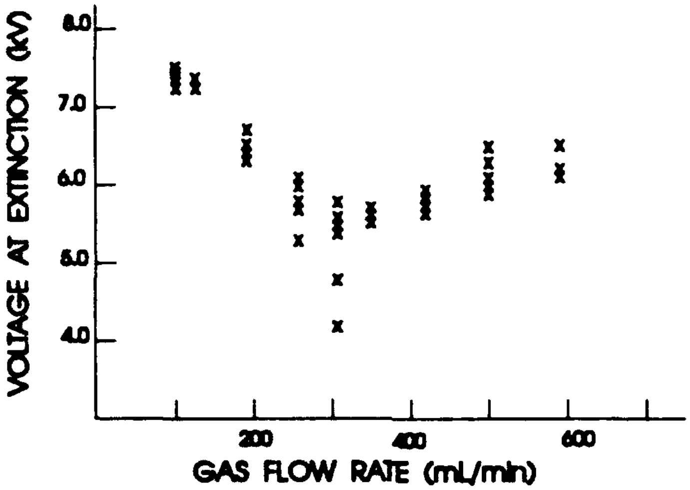

Figure 10. Extinction Voltage Verses Gas Flow Rate for Setup in Figure 9.

An explanation of the reduction and disappearance of the luminous part of the flame may be that we are stripping out the carbon and carbon forming centers from the flame before they get hot enough to glow. Lawton and Weinberg observed a similar phenomena and collected the carbon from the flame on the negative electrode. However, we do not see a precipitation of carbon onto the screen as the negative electrode. If the polarity of the voltage is reversed, the flame is stabilized and the breakdown current j_b is reached before the flame is extinguished. With this situation, carbon deposits are very evident on the burner top.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY AND CONCLUSIONS

The thrust of this effort was to gain a better understanding of the interaction between the process of combustion and electric fields. Two approaches were taken: a review of the literature and some preliminary in-house laboratory investigations.

The theory of combustion was reviewed, and it was discussed that the combustion process itself consists of initiating, propagating, branching, and terminating chain reactions. Radical species are crucial to these reactions. It is most likely that an electric field exerts an effect upon a flame through the radicals.

The literature review revealed two possible mechanisms by which an electric field influences a fire: the ionic wind and a chemical effect. The ionic wind is the movement of radicals and neutral gases due to the electrostatic forces on the radicals and their subsequent collisions with the neutral gases. Whether the ionic wind aids in stabilizing a flame or extinguishes it depends upon the flame-electrode geometry. The chemical effect described is one which aids in combustion. Energy is added to the combustion process by an electric field by raising the energy level of the free electrons which is then ultimately transferred to O_2, increasing the reaction rate of the branching chain reaction [15] and thus the overall combustion rate.

Our laboratory work confirmed that it is possible to extinguish small, Bunsen burner-sized diffusion and premixed flames with various electrode configurations. Our observation that the luminous section of the flame is attracted to the negative electrode contradicts the statements in the literature that negative ions predominate in the luminous zone. Diffusion flames take less voltage to extinguish than premixed flames. The configuration of an outer cylindrical negative electrode with the burner forming the positive electrode appears to be the most effective so far. In addition to the ionic wind effects that lead to extinction, an additional chemical effect may be that since the radicals are stripped from the reaction zone by the field, the number of radicals available is decreasing and possibly interrupting the reactions. This effect also reduces the flame temperature, which reduces the combustion rate and may ultimately extinguish combustion.

B. RECOMMENDATIONS

The first goal we would like to pursue in our laboratory is to gauge the relative importance of mechanical and chemical effects of the electric fields. We will attempt to isolate the flame from the ionic wind through the use of various electrode geometries, or perhaps air jets to simulate the ionic wind. Another approach is the use of an alternating current to disrupt the flame chemistry. If chemical effects alone can significantly disrupt the flame, further research would be directed at uncovering the nature of these effects with a view to practical application.

Other research should take several paths. Other researchers are pursuing electric fields research, though not specifically for application to flame extinguishment. The literature review revealed that Dr. Bish Ganguly of the Aeropropulsion Laboratory at Wright-Patterson AFB was using electric fields as a diagnostic tool to study combustion. A visit was made to Dr. Ganguly, where we found a sophisticated laser spectroscopy setup that he has been using to study soot formation. Laser spectroscopy is a powerful tool to nonintrusively measure various physical quantities in a flame, such as local electric field strength and temperature. Through laser spectroscopy of flames of different reactants we could look for the existence or lack of specific combustion products and measure the specific species concentrations and temperatures (using Raman scattering) under different external electric field strengths and configurations. We would also like to compare accuracy of field measurements taken with our in-house equipment versus Dr. Ganguly's more elaborate setup.

In addition to research to uncover the chemical basis of the phenomenon, we will be evaluating the effect from an application point of view and do experiments oriented to finding the practical usefulness of using electric fields to extinguish flames. To do this we will need to expand our instrumentation to include means of analyzing combustion products and viewing flame fronts, such as Schlieren photography.

Little of the past investigation of electric field effects was directed toward fire suppression. With additional knowledge of combustion and suppression effects under electric fields, more effective firefighting agents may be designed and effective fire protection continued.

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