Fire Extinguishment of Pool Flames by Means of a DC Electric Field

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Abstract

The application of an electric field to a combustion system can produce large and potentially useful effects. Such are reducing carbon formation, affecting flame velocity, extending flammability limits, increasing flame luminosity, flame stabilizing, extinguishing etc. When a strong electric field is applied between a sharply curved and a plane, a gap length is reached at which the gas near the sharp curved surface breaks down at a voltage less than the spark-breakdown voltage for that gap length. This local breakdown is in the form of a glow discharge which at atmospheric pressure is usually called corona. Positive ions are formed and accelerated toward the cathode. Collisions between these ions and neutral gas molecules transfer momentum to the bulk gas, resulting in a directional body force (corona wind). Under normal conditions, this kind of electro-fluid-dynamics device (EFD) can produce winds' velocities up to 8-12 m/s. The present study is concerned primarily with the ion effect on pool fires. In these systems the fuel surface was used as the cathode and several special designed positive probes have been examined. Some designs showed remarkable high performances as compared to mechanical-fluid-dynamics devices (conventional blowers). Systematic measurements of the velocity profile and chemical composition of the wind resulted from each device were recorded. A careful comparison revealed that not only the chemical composition of the wind is important but also (and perhaps mainly) the velocity profile of the wind. Sixty centimeters width pool flames of isopropanol, gasoline and diesel fuels were easily extinguished with the new device.

Introduction

The effect of an electric field on a flame has been studied extensively for many years. Jaggers and von-Engel[1] observed that when a dc electric field acts across a vertical tube filled with a mixture of methane or ethylene and air at atmospheric pressure, the speed of flame propagation was shown to rise well above its value in zero field. They concluded that when an electric field is applied, the free electrons acquire a sufficient energy to transfer molecules and radicals from the lowest to higher vibrational states by collisions, and this gives rise to an increase in the reaction rate thus the burning velocity. Bowser and Weinberg[2] have used a similar apparatus and reached a conclusion that axial dc fields (parallel to the direction of flame propagation) do not produce any appreciable changes in burning velocity. Fox and Mirchandani[3], on the other hand, have used a propane-air flat flame stabilized on a water-cooled porous disk and noticed that upon application of a negative axial electric field (negative burner) the flame speed increases. The flame speed decreases in positive electric field. However, they found that a wide variety of results can be obtained depending on the electrode geometry, cooling, material and burner dimension. They reported that microscopic examination of the luminous region of the flame indicated no observable distortion or dimensional change upon application of the electric field. However, other effects such as flame acceleration, flow of burned gas toward the upper electrode (for positive burner) and an increasing in the secondary flow of ambient air around the flame were noticed. Gulyaev et al.[4] studied the effect of axial electric field on propane-butane flames formed at the mouth of a 10 mm single-tube burner. An axial electric field was created by applying a voltage to a ring electrode, 50 mm in diameter, located 50 - 100 mm above the burner mouth. A transverse field was produced by applying a voltage to a metal-grid cylindrical electrode installed coaxially with respect to the burner. They found that an axial electric field has a weak effect on flame geometry. However, when a transverse electric field with a positive polarity (positive burner), was applied prior to the extinction, the flame plume was opened to form a flower shape with about four to six lobes. For a negative polarity the flame plume tends to become more stabilized.

Gulyaev et al.[4] assumed that in the flame preparation zone. there exists a region of positive ion location while near the luminous zone, on the other side of the flame front, negative ions predominate. Then. they esplaincd, when a positive field is applied. positive ions move to the exterior portion of the flme and negative ions move into the interior. Motion of neutral particles (ion wind) occurs in the direction corresponding to that of the ions with the least mobility (the positive ions). The ion wind attracts hot combustion products and active centers to the peripheral portion of the flame, which in turn cools down the reaction zone. When a negative potential is applied, the ion wind is directed toward the axis and enhances flame stabilization.

The estinction of hydrocarbon flames which are subjected to a nonuniform electric field has been studied by Sher et al.[5]. A candle type burner having a hemispherical tip and a horizontal conducting plate situated above the flame have been used. The voltage between the burner head and the conducting plate was gradually increased until llame cxtinction was observed. It was round that the extinction occur in two phases. In the first as the applied voltage increases, the luminous zone stretches upward up to a critical field strength for which a sudden flame contraction occurs. In the second phase the flame gradually contracts as the voltage is increased and is finally completely extinguished. It is concluded that the interaction between the electric field and the flame is associated with electric forces which are applied to the polarizable intermediate species in the flame zone. These forces are directed, irrespectively of the voltage polarity, outward of the flame zone (mainly toward) the burner tip where the intensity of the electric field is higher. Thus this mechanism of estinction appears to be found only in srongly non-uniform fields.

On the contra?, when the electric field nonuniformity is too strong, which leads to corona inception, no extinction takes place and burning can even be enhanced. This effect was studied also by Bradley and Nasser.[9] The authors employed a brass tube burner having four pointed tips fed by a premised air-methane mixture. It was found that coronae increase the blowoff flow rate. The effect was ascribed to the introduction of excited species which panicipate in the flame reactions and influence their rates.

In the present work, a strong non-uniform electric field was applied between a sharply curved surface and a plane in order to produce a corona wind. The primarily concern of this study is to establish the mechanism of flame extinguishment by corona discharge source and to assess the application of such a device to extinguishing pool flames.

Theoretical Background

When a strong electric field is applied between a sharply curved and a blunt surface, a voltage is reached at which the gas near the sharp curved surface breaks down at a voltage less than the spark-breakdown voltage for that gap length. This local breakdown is in the form of a glow discharge which at atmospheric pressure is usually called corona Under some conditions. the corona may result in a gas movement in the electrode gap which is directed toward the blunt curved electrode irrespective of the polarity of the voltage applied. This effect is often called an "electric wind or a "corona wind". A simple theoretical analysis[7] can show that the velocity of the gas is proportional to the square root of the corona current which has been found in full agreement with experimental observations.[8]

When corona occurs, the space between the electrodes is characterized by two different regions; the ionization region in which ionization lakes place in a very thin layer in the vicinity of the sharp electrode, (typically less than 1 millimeter) and the drift region in which charged particles are accelerated toward the blunt electrode. The maximum current of a negative corona before breakdown occurs is typically much higher than in a positive corona (about twice) and that means a higher possible wind velocity (the wind velocity is proportional to the

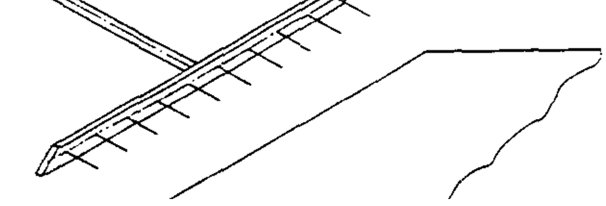

Figure 1 A series of sharp curved electrodes

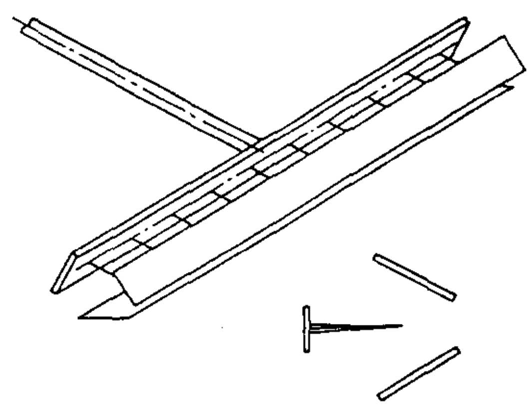

Figure 2 A series of points shielded with two naps.

square root of the electric current). Furthermore for a positive arrangement it has been observed[8] that the voltage at which corona occurs, increases with pressure and approaches the breakdown voltage at pressures of a few several hundred kilo-pascals. As a result corona wind cannot be produced anymore. The threshold of this transition depends on the medium type and electrode geometry. For air it varies from 0.2-0.1 MPa for a dull electrode to 1-1.5 MPa for a very sharp electrode. In a negative corona the voltage at which corona occurs practically never approaches the breakdown voltage and corona occurs at any pressure. and for devices operating at high pressures, negative corona is clearly preferable.

It is fairly understandable that corona wind due to its high velocity and sharp profile[6] may considerably influence mixing and heat transfer. thus the burning process. However, do the active species which are formed in the corona region and convected by the corona wind into the combustion region, play any significant role in the combustion process? Bradley and Nasser[9] addressed this question for corona source situated inside the flame, but no satisfactory conclusion was reached. For an external source, it was experimentally observed that the concentration of any of the three main products of a corona, namely, ozone, nitrogen oxides and ions, is in the order of tens of ppm[10,11], and their influence on the combustion process is quite limited if not insignificant at all.

It follows that the most probable mechanism of influencing a combustion process by an external corona source is the corona wind itself. This conclusion is to be supported experimentally by the present study.

Preliminary Observations

In order to gain a qualitative feeling about the effect of a corona wind on a pool flame, a simple experiment was carried out. An electrical conductive pool of 96 mm in diameter was filled with isopropanol (C_3H_7OH) to the top. A sharply curved electrode was situated at a distance from the fuel surface. A 10 kV high voltage source was applied between the fuel container (the blunt electrode) and the sharp curved one. Then the latter was moved slowly to find the location at which the effect is higher. At this location the voltage was gradually increased until the flame was extinguished. The following are the main conclusions from our observations:

a. The best effect was achieved when the sharp electrode was situated 25 mm above the pool rim with an inclination angle of 45°, while the electrode axis coincided with the radial coordinate of the pool.
b. The voltage at which extinguishment was achieved does not depend appreciably on the electrode polarity.
c. Extinguishment could not easily be achieved when the liquid surface was lower than 4 mm below the container rim.
d. Although a higher voltage was required to extinguish gasoline and diesel fuel, basically, similar effects were observed.
e. The tip sharpness and the material of the sharp electrode had no significant effect as long as its curvature radius did not exceed 0. 2 mm.
f. No extinguishment could be achieved with larger pool diameters.

An attempt to achieve extinguishment with larger pool diameters was made by introducing simultaneously a series of sharp curved electrodes as illustrated in Fig. 1. The optimal effect was obtained with 3 cm spaced electrodes but no complete extinguishment was achieved: flame tongues have always managed to cross back the pool along the electrodes' spaces. When a denser electrode array was used, a weaker corona wind was produced due to the unavoided interactions between two adjacent

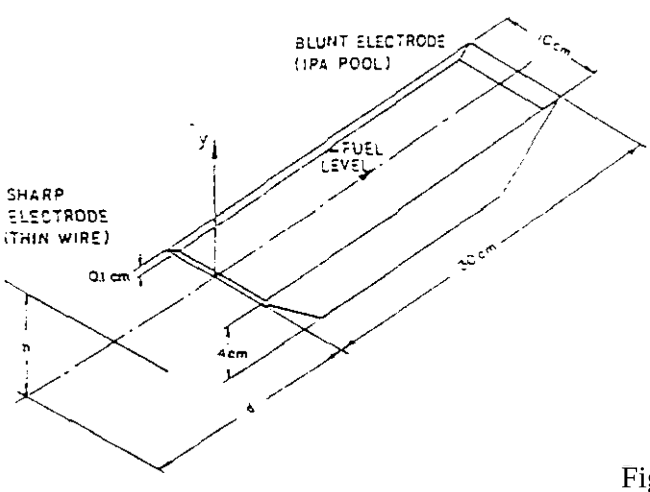

Figure 3 Experimental system.

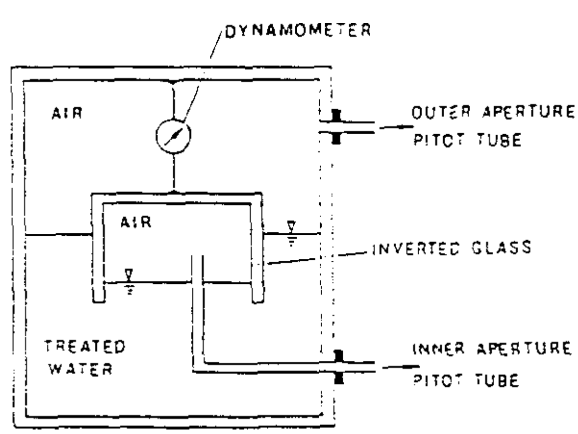

Figure 4 A schematic layout of the workshop made apparatus used to measure the pressure difference of the pitot tube.

electrodes. An attempt to shield the electrodes (Fig. 2) did not lead to substantially better results.

In order to find corona-wind device which will facilitate the extinguishment of larger pool flames, many electrode types were examined. The most effective device was found to be constructed from a simple thin wire which was situated in parallel to the fuel surfaces as shown in Fig. 3. For the same electric current, the wire electrode produced a more uniform flow pattern as compared to a series of sharp electrodes.

In order to evaluate the influence of the corona ions on the extinction, the corona wind was shielded by two grounded electrodes similar to those shown in Fig. 2. No effect on the flame shape was observed.

Experimental Set-Up

The experimental system is shown schematically in Fig. 3. It consists of a shallow metal container, 30 x 10 x 4 cm having 45' inclined head and tail edges. The container is filled with isopropanol (C_3H_7OH) fuel up to 1 mm below its top, and connected to the low ripple high-voltage direct-current power supply thus acting as the blunt electrode. The sharp electrode is a thin steel wire, 0.2 mm in diameter, which is situated in parallel to the fuel surface at a distance of d cm from the head edge and h cm above the fuel level. An x-y coordinate system is fixed to the head edge as shown. Ignoring edge effects, such an arrangement provides a two-dimensional system for all the relevant quantities.

Three sets of experiments were performed as follows:

1. Cold experiments - a parametric study to investigate the effect of various parameters on the velocity profile of the corona wind. These include electrode polarity, voltage, current, the wire distance d and its height above the fuel level, h.

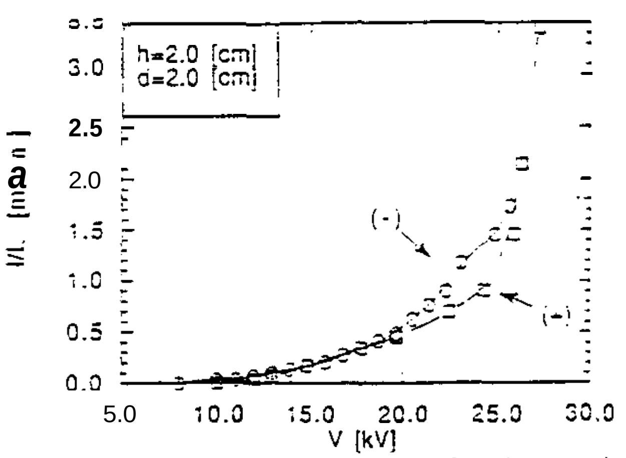

Figure 5 Typical current-volt. characteristics for both polarities. L is the pool width.

2. Hot experiments - the pool has been ignited and the effect of the wire location on the flame shape was studied.
3. A comparative study - the velocity profile of the corona wind has been simulated by a carefully designed nozzle which was mounted on a suitable mechanical blower. The effect of the two devices on the flame behavior was compared.

Results

1. Cold Experiments

The velocity profile of the corona wind above the fuel surface was measured by using a thin pitot tube, 1 mm in diameter. The pressure difference was determined by the aid of a workshop made apparatus (Fig. 4) which consists of an inverted glass immersed in treated water in which detergent was added to reduce the surface tension. In this apparatus the small pressure difference, in the order of 0.1 mm H_2O is applied to an area of 25 cm^2 and the resultant force (0.0025N) is balanced by a dynamometer having an accuracy of 0.0001N.

Fig. 5 shows typical current-voltage characteristics for the two polarities. It seems that the negative polarity arrangement (negative sharp electrode) results in a higher current to an extent, thus a higher corona wind. However, while the average velocity is higher, the peak velocity along the y axis (Fig. 6) seems to be lower by about 20%. These characteristics have been found to be independent of the wire diameter in the range of 0.05 to 0.5 mm, and the wire material (steel and copper), and are in full agreement with other available data.[6,8]

The effect of the wire location on the current-voltage characteristics is shown in Fig. 7. It seems that in general, for a given voltage, the current increases with the view angle (higher h to d ratio. However above h/d = 2, no noticeable increase has been observed.

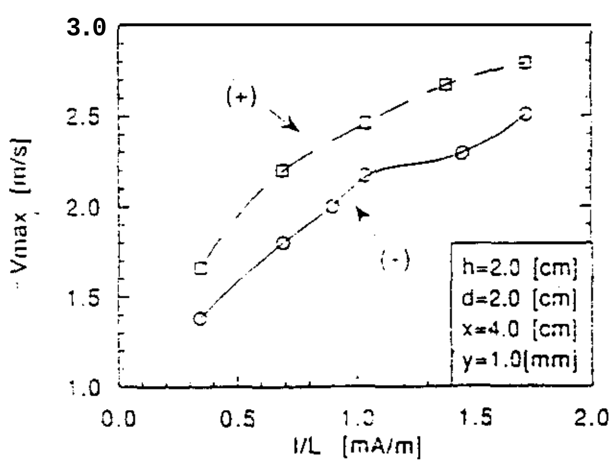

Figure 6 Peak velocity vs. electric current for both polarities. L is the pool width.

A typical velocity profile of the corona wind above the fuel surface is shown in Fig. E. It seems that the velocity profile is characterized by a remarkably high velocity gradient near the fuel surface. The velocity peaks at 1 to 3 mm above it and then decreases moderately. Owing to the shear stresses. the peak velocity decreases with the distance from the leading edge and the velocity profile is flattened. A higher electric current results in a higher peak velocity ana thinner flow stream while maintaining the special structure of the velocity profile.

?. Hot Experiments

In this set of experiments, the pool has been ignited and the effect of various parameters on the flame shape was studied. Among these parameters are the h to d ratio; electric current and electrode polarity. Since the aim of this study is to investigate the effect of the electric field on the extinction of pool flames. the flame regression dong the pool the has been selected to characterize the effectiveness of the system. A systematic study has revealed that the flame regression depends only on the peak d u e of the velocity profile. Any arrangement which could provide a higher peak velocity has performed a higher effectiveness. In order to achieve a complete extinction, the wire should be advanced slowly (approx. 0.1 m/s) at an elevation of about 2 cm above he fuel level. A lower wire might result in a local breakdown leading to reignition, or alternatively would limit the maximum voltage which might be insufficient to expel the flme. A higher wire would need a higher voltage which may be found to be impractical. The use of the flaps (Fig. 2) yields lower sensitivity to breakdowns.

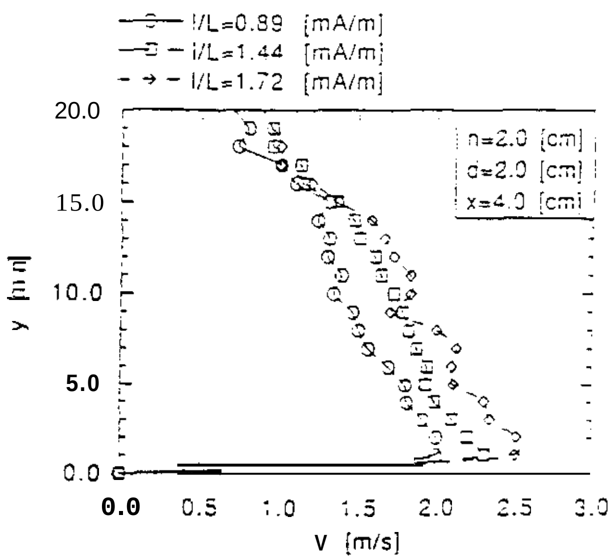

Figure 7 Electric currcnt vs. voltage fur a positive corona (positive wire).

3. Comparative Study

In order to re-assess the assumption that the only effect of the electrical field is the producing of an aerodynamic wind, the spatial velocity profile of the ionic wind has been simulated by a carefully designed nozzle which was installed on a suitable blower. Fig. 9 compares the two resulted profiles. The regression distance was found to be quite comparable within an acceptable deviation. A quantitative comparison was made by analyzing gas samples taken at different locations. The samples were analyzed by a mass spectrometer for hydrogen, and by a gas chromatograph for the other species. Beyond the unavoided errors which stem from h e difficulties associated with sampling a fluctuating flow, there is not much difference between samples taken from the blower and corona systems.

It is of fundamental interest to compare the extinguishment efficiency of the blower and the corona devices. Our expeiments clearly snow that for a similar velocity profile the electric power consumption of the blower *is 5* to 8 times lower than that of the corona. This agrees with the theoretical analysis and expeimental observations of Bondar and Bastien[12] and Sigmond[7], which noted even a lower power conversion efficiency. namely less than 2%.

Therefore, when considering an application in an atmospheric environment, the corona extinguisher is far inferior to the blower system. However, the corona device is a unique and useful source of wind in special cases, e.g., in hot and aggressive environment.

Conclusions

1. Extinguishment of pool flames has been rendered possible by means of corcna

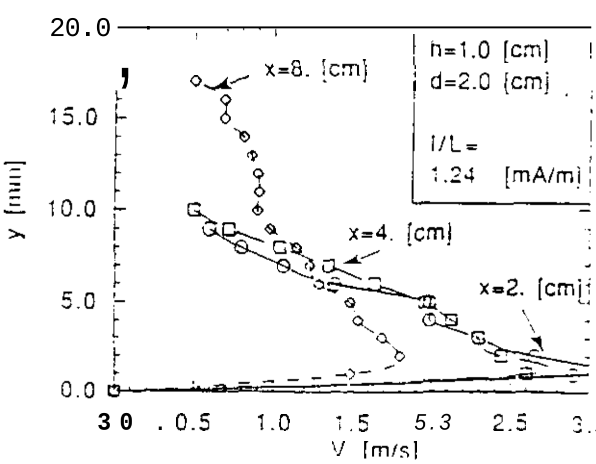

Figure 8 The development of the velocity profile for a positive corona Electric current to pool width ratio = 0.75 mA/m, and hid = *0.5*.

discharge.
2. This effect seems to be a pure aerodynamic one. The ions and other traces produced by the corona bear no impact on the flame extinguishment.
3. The electromechanical efficiency of a corona dischage is very low, however, for unique applications, such as flame extinguishing within an aggressive (corrosive) or hot environments, this method should be favorably considered.
4. The most efficient corona device for the extinguishment of pool flames appears to be a thin wire moving parallel to the liquid surface at the rate of about 10cm/s. The remarkable extinguishig capability is explained by the unique sharp velocity profile associated with a maxium high velocity of up to 3 m/s which occurs 1 to 3 millimeters above the liquid surface.

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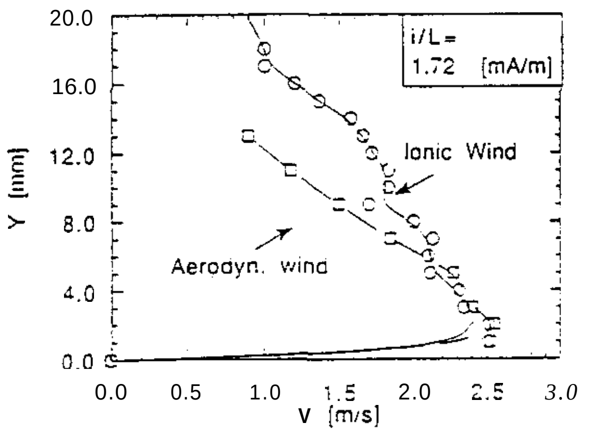

Figure 9 Velocity profile of aerodynamic wind produced by a blower vs. that produced by a corona.

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