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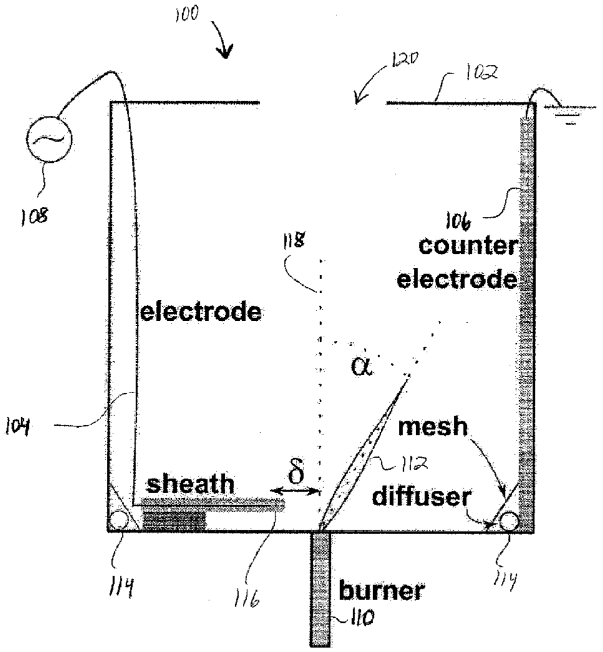

Figure 1.

(57) Abstract: Manipulation of flames is described using electric fields. In those instances in which electric fields are used, the electric fields may be time-varying gradient electric fields, and in some instances may be oscillating electiic fields. The manipulation may include extinction, suppression, control of mixing of the flame, concentration, and/or bending, among other types.

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MANIPULATION OF FLAMES AND RELATED METHODS AND APPARATUS

RELATED APPLICATIONS

This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application Serial No. 61/491,836 filed May 31, 2011 entitled "CONTROL AND EXTINCTION OF FLAMES BY OSCILLATING ELECTRIC FIELD GRADIENTS" and U.S. Provisional Application Serial No. 61/559,677 filed November 14, 2011 as Attorney Docket No. H0498.70424US00 and entitled "MANIPULATION OF FLAMES AND RELATED METHODS AND APPARATUS," the entire contents of both of which is incorporated herein by reference.

GOVERNMENT FUNDING

Research leading to various aspects of the present invention were sponsored, at least in part, by the Department of Defense under DARPA Award #w911nf-09-1-005. The U.S. government has certain rights in the invention.

BACKGROUND

Combustion processes, and the flames associated therewith, are common. Yet, our understanding of fire, and how to control it remains incomplete.

BRIEF SUMMARY

According to one aspect, manipulation of flames using electric fields is described. The manipulation may be performed by applying a time-varying gradient electric field to the flame. The flame may be any of various types, as the present aspect is not limited in this manner.

According to another aspect, a method comprises extinguishing a flame by applying an oscillating gradient electric field to the flame. According to another aspect, a method comprises suppressing a flame by applying an oscillating gradient electric field to the flame. According to another aspect, a method comprises bending a flame by application of an oscillating gradient electric field to the flame. According to another aspect, a method comprises controlling mixing in a flame by application of an oscillating gradient electric field to the flame. According to another aspect, a method comprises concentrating a flame by application of an oscillating gradient electric field to the flame.

Further aspects and embodiments are described below.

BRIEF DESCRIPTION OF DRAWINGS

Various aspects and embodiments of the technology will be described with reference to the following figures. It should be appreciated that the figures are not necessarily drawn to scale. Items appearing in multiple figures are indicated by the same or a similar reference number in each of the figures in which they appear.

FIG. 1 illustrates a non-limiting embodiment of a system which may be used to manipulate a flame by application of a time-varying electric field to the flame.

FIG. 2 shows a graph of the values of the probability of extinction, P, and the angle of deflection (α) in degrees as a function of frequency in Hertz (Hz) for the voltage V= 20 kV of the signal applied to an electrode and the distance δ= 6 mm of the electrode from the a flame.

FIG. 3 shows the dependence on electric field frequency of the probability of extinction, P, of a methane/air conical diffusion flame as a function of the peak voltage of the sinusoidal voltage signal applied to the electrode.

FIG. 4 shows the dependence of the critical electric field frequency (in Hz) at which flame extinction ensues on the peak voltage (in kV) applied to the electrode, as obtained from the data shown in FIG. 2.

FIG. 5 illustrates dependence on electric field frequency of the probability of extinction, P, of a methane/air conical diffusion flame as a function of the distance between the tip of the metal electrode and the mouth of the burner.

Fig. 6 shows the dependence of the critical frequency on the distance between the tip of the Pt electrode and the mouth of the burner as obtained from the data shown in Figure 4.

FIG. 7 illustrates a non-limiting example of a configuration for concentrating a flame using an electric field.

FIGs. 8A-8D each illustrate a photograph of a non-limiting configuration for concentrating a flame with an electric field as well as a plot of temperature data resulting therefrom.

FIG. 9 illustrates a non-limiting configuration in which a time-varying electric field may be used to suppress a flame.

FIG. 10 illustrates a non-limiting example of a configuration which may be used to increase flow of a fluid by creating a plume.

FIGs. 11A and 11B illustrate non-limiting examples of a suitable configuration for the electrode 104 and sheath 116 of FIG. 1.

FIG. 12 illustrates a non-limiting example of a configuration which may be used to suppress or extinguish flames using a combination of thermal quenching and electric fields.

FIG. 13 illustrates a non-limiting example of a configuration in which a mobile electrode may be used to manipulate a flame.

DETAILED DESCRIPTION

According to various aspects of the present application, methods and apparatuses for manipulating flames are provided. The manipulation may take various forms, including, but not limited to, extinguishing a flame, suppressing a flame, bending a flame, controlling mixing of the flame, and concentrating the flame. Such manipulation may be useful in various applications in which control of a flame is desired.

According to a first aspect of the present application, a flame may be manipulated by applying an electric field to the flame. The electric field may be a time-varying electric field, and in some embodiments may be an oscillating electric field (e.g., oscillating between a positive electric potential and a negative electric potential). Moreover, in some embodiments the electric field may have a gradient associated therewith, rather than being a uniform electric field. In some embodiments, the electric field may exhibit a gradient in three dimensions, though not all embodiments are limited in this respect. Thus, according to a non-limiting embodiment of the present aspect, a flame may be manipulated with an oscillating gradient electric field. The electric field may be applied to the flame with one or more electrodes, as non-limiting examples.

The aspects described above, as well as additional aspects, are described further below. These aspects may be used individually, all together, or in any combination of two or more, as the technology is not limited in this respect.

Manipulation of Flames Using Time-Varying Electric Fields

According to a first aspect, manipulation of flames is accomplished using time-varying electric fields. In one embodiment, the time-variation may be sinusoidal, and the electric field may be an oscillating electric field. The electric field may, in some embodiments, have a gradient, which may facilitate achieving certain types of manipulation. Various non-limiting examples are described further below.

Manipulation of flames using a time-varying electric field may depend, at least partially, on some parameters of the flame as well as some parameters of the electric field. For example, flame parameters which may influence whether, and to what extent, the flame may be manipulated by application thereto of a time-varying electric field include the amount of soot in the flame and the size of the flame source (e.g., the size of the burner used to create the flame if a burner is used). Parameters of the electric field that may impact the effectiveness of manipulation include the field strength, field gradient, and field frequency (e.g., in those embodiments in which an oscillating electric field is used). The distance of the electric field source (e.g., an electrode) from the flame as well as the electrode configuration may also impact the effectiveness of manipulation.

Applicants have appreciated that flames are charge neutral polarizable media. The effect of electric field stimulation on a flame can be understood by considering the concentration of ions that is present in most flames, which may range, for example, from approximately 10^8 to approximately 10^{11} ions per cubic centimeter (ions/cm^3). Despite their low concentration, the driven motion of these ions in response to an external electric field, and the consequent transfer of momentum to neutral molecules, imparts upon the flame a collective behavior. For sufficiently strong electric fields, this process can result in macroscopic gas flows–so-called ionic or electric wind–with speeds of up to ten meters per second. When placed in the proximity of a flame, the resulting gas flows may serve to manipulate the flame. However, not all embodiments described herein relating to manipulation of flames with electric fields are limited to manipulation arising from generation of an electric wind, as other physical mechanisms may also or alternatively be implicated. In fact, in at least some embodiments, manipulation of a flame is achieved without an ionic wind.

According to one non-limiting embodiment, a flame may be extinguished by application thereto of a time-varying gradient electric field. The electric field may be applied by an electrode placed in proximity to the flame. Various types of electrodes may be used. According to one embodiment, a rod-shaped electrode may be used (e.g., a wand-shaped electrode). According to one embodiment, a point electrode, e.g., from a wire, may be used. According to another embodiment, a wire electrode may be used. Alternatively, plate shaped electrodes may be used in some embodiments. The electrode may be covered/insulated in some embodiments, for example to minimize or prevent formation of a corona on the electrode. The electrode may have any suitable size, shape, and material to provide a desired electric field. As will be appreciated from the following non-limiting examples, manipulation of flames (e.g., extinction) may be achieved according to some non-limiting embodiments with one or more electrodes (e.g., with one electrode, two electrodes, three electrodes, or more). Extinction may occur when lift off is achieved, which may represent the displacement of the combustion zone of the flame from the burner.

In some embodiments, the electrode (or electrodes) used to apply a time-varying electric field may be stationary. In other embodiments, the electrode(s) may be mobile. Further explanation of a non-limiting example of the use of mobile electrodes to apply a time-varying electric field to a flame is provided in FIG. 13.

A non-limiting example of a configuration in which a flame may be extinguished using an oscillating gradient electric field is illustrated in FIG. 1. The illustrated system 100 includes a chamber 102, an electrode 104, a counter electrode 106, an electric signal source 108, a burner 110, and a flame 112. Diffusers 114 are also included to introduce oxygen into the chamber. A sheath 116 (e.g., made of borosilicate glass or any other insulating material) encloses at least one end of electrode 104 proximate the flame. The electrode 104 may be spaced from the flame by a distance δ.

A non-limiting example of a suitable configuration for the electrode 104 and sheath 116 is illustrated in FIGs. 11A and 11B, which include various dimensions. It should be appreciated that other configurations are also possible.

As shown, the flame 112 may be deflected from the vertical 118 by an angle α in response to application thereto of an oscillating gradient electric field from the electrode 104. The electric field may have any suitable frequency and magnitude to deflect the flame by a desired angle α, as the various aspects described herein are not limited to use of electric fields having any particular magnitude and/or frequency. For purposes of explanation, some non-limiting examples are described further below.

It should be appreciated that the illustrated electrode configuration is non-limiting. While a wire-shaped electrode is illustrated, other shapes may be used, including rod-shaped electrodes, and in some embodiments plate shaped electrodes, though these are only non-limiting examples. In the illustrated configuration, the resulting electric field may exhibit a gradient in three dimensions, though not all embodiments are limited in this respect. The configuration may allow for achieving larger fields strengths and/or field gradients than may be possible in configurations in which the electric field gradient is limited to only two dimensions. Thus, a configuration in which a gradient is exhibited in three dimensions may facilitate achieving various types of manipulation of a flame, such as extinction.

Also worth noting is that in some embodiments (e.g., the configuration of FIG. 1), the flame may be positioned substantially between the electrode and the counter electrode (e.g., the flame may be located on a line between the electrode and the counter electrode). Such a configuration may facilitate achieving the types of manipulation described herein.

Example 1

A non-limiting example of the operation of system 100 is now provided for purposes of illustration. It should be appreciated that the manner of operation and the specific parameters listed are non-limiting.

The methane burner 110 was enclosed in a 0.1 m^3 cubic chamber 102 of 0.5 cm-thick panels of ROBAX®, a refractory, electrically insulating, and highly transparent glass ceramic. The top panel was instead a glass-filled PTFE sheet (0.32 cm x 61 cm x 61 cm) with a hole 120 (15 cm diameter) in its center, which served as a chimney for the combustion products. The burner comprised a cylindrical tube of machinable Al_20_3 (0.32 cm inner diameter; 2 cm outer diameter; 25 cm in length) and was lodged tightly into a hole in the center of the bottom panel of the chamber. Methane was introduced from the bottom hole of the burner through a one-way valve, and the flow was monitored by a gas flow meter. The methane flow was kept at 540±23 ml/min for all experiments reported here.

Air was introduced into the system via two flexible bubble diffusers (Flexible Bubble Wand, Marineland), which lined the bottom inside perimeter of the chamber. The diffusers were covered with a PTFE mesh (635um x 127um rhombic-shaped holes) to further diffuse the inlet air flow and connected to a compressed air tank through a flow meter. The air flow rate was maintained at 19±2 l/min for all experiments.

The electrode 104 was a Pt wire (0.5 mm diameter) with a rounded parabolic-like tip created via chemical etching, though the aspects described herein as utilizing a rounded parabolic-like electrode are not limited to the manner in which the electrode is created. Furthermore, other electrode geometries are also possible, as a rounded parabolic-like electrode tip is a non-limiting example. The electrode was encased in custom-made borosilicate glass sheath (2 mm thick on the sides of the wire, 5 mm thick at the tip). The purpose of the sheath was to (i) electrically insulate the flame from the electrode (e.g., to prevent arc formation between the electrode and the flame) and (ii) to prevent the formation of the so-called ionic wind emanating from the corona discharge at the electrode tip. The electrode was connected to an AC power amplifier (TREK 30/20A), driven by a signal generator (Agilent 33220A). The amplifier's output current and voltage were monitored with an oscilloscope (Tektronix TDS 2024D).

The electrode 104 was positioned horizontally at a height of 1.5 cm above the burner 110, and its tip was oriented towards the center of the burner (cf. Fig. 1) The sheathed electrode was supported by a stack of glass slides positioned 7 cm from the burner and fastened with insulating tape.

The counter electrode 106 was a 45 cm x 45 cm x 1 cm aluminum plate, fastened to the interior side of the chamber opposite the electrode and the flame. The distance between the electrode tip and the plate was $\delta = 25.5$ cm.

Before an experiment, the interior of the chamber was cleaned of soot. The flame and the air flow were turned on at least one hour before the beginning of the experiment to allow the thermalization of the setup. The temperature at the internal surface of the side panels of the box was found to stabilize at 39±2 °C.

The flame was subjected to AC fields using a sinusoidal waveform of various amplitudes (15-30 kV) and frequencies (10-2000 Hz). The distance between the tip of the electrode (i.e., the outer surface of the glass sheath) and the mouth of the burner was varied from 6 to 15 mm.

For a constant voltage and a distance $\delta < 11$ mm, as the frequency of the oscillation of the voltage (and therefore the electric field) was increased, the flame was increasingly deflected. This deflection of the body of the flame is constant in time and no obvious turbulence is observed. As the frequency is further increased and the deflection approaches 90° the flame is extinguished with increasing probability.

For a given voltage, V, frequency, f, and distance, δ, the angle of deflection α and the probability of extinction, P, were measured. Movies (at 1 frame per second) were collected of all events. The angle of deflection α of the flame for a certain set of experimental parameters was determined by averaging all of the stills (still images) from all events performed under those conditions. The resulting image was then analyzed to determine the major axis of "inertia" of the flame. The manner of analysis is described in the Appendix of the present application, though it should be appreciated that the various aspects of the technology described herein are not limited to the manner in which deflection is calculated, or to calculating deflection of the flame at all.

The probability of extinction, P, was estimated as the fraction of successful extinction events (within a set of 10-30) following the application of the field for 10 sec. If the flame was extinguished by the field, it was reignited, and the flame was left burning undisturbed for 30 seconds before attempting another extinction event. If the flame was not extinguished by the field within 10 seconds following the application of the field, the field was turned off. The flame was then left undisturbed for 30 seconds before starting another event. These 30 second pauses between events prevented correlation between events.

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Manipulation of flames using time-varying electric fields may apply to various flame types (i.e., flames resulting from combustion of various types of fuels), unless otherwise stated, including liquid, gas, and solid flames, flames categorized as National Fire Protection Association (NFPA) Class A (e.g., paper, wood, plastic, etc.), Class B (liquid and gaseous fuel sources), and/or Class C, flames from gels, or any other types of flames. Ethanol, methanol, toluene, and hexane are non-limiting examples of liquid flame types to which one or more aspects of the present application may apply. In some embodiments, diffusion flames may be used. In some embodiments, flames having conductive particulates may exhibit the greatest degree of response to an applied electric field. The breadth in flame types to which the presently described techniques may apply is due at least in part to the fact that oscillating gradient electric fields operate on a minority component of the flame which has a characteristic which is shared across flames of the most diverse kinds: electric charge, and not on parameters such as fuel and oxidizer availability, heat, or the radical chain reaction. Thus, again, ethanol, methanol, toluene, and hexane are only non-limiting examples of fuel sources to which aspects of the present application may be applied. Other types of flames are also possible.

The electric field may have any suitable magnitude and frequency to extinguish a given flame. In some embodiments, such as that of FIG. 1, the electric field may be an alternating current (AC) electric field having a sinusoidal waveform. The signal generating the electric field may have any suitable voltage to generate a suitable magnitude electric field. As a non-limiting example, the voltage of the applied signal may be between 15-30 kV, between 10-50 kV (e.g., 10 kV, 15 kV, 20 kV, etc.), between 20-25 kV, or have any other suitable value. The frequency of oscillation of the applied signal (the signal applied to the electrode 104), and therefore of the electric field itself, may be, for example, between 10-2000Hz, between 100-50000 Hz, between 100-300 Hz, between 300-600 Hz, between 400-500 Hz, between 100-1000 Hz (e.g., 100 Hz, 200 Hz, 300 Hz, 400 Hz, 500 Hz, 600 Hz, etc.), or any other suitable value, as these are non-limiting examples. According to a non-limiting embodiment, an electric field having the following parameters may be used to manipulate, and in some instances extinguish, a flame: $E \approx 1$ MV/m, $dE/dr \approx 10^8$ V/m^2, and $f \approx 1000$ Hz). Other values are possible.

The electric field may have any suitable gradient. According to some embodiments, the gradient may be a three-dimensional gradient, while in others the gradient may exist in fewer than three dimensions (e.g., two dimensions). The gradient may range, in some non-limiting embodiments, between approximately $dE/dr \approx 10^6$ V/m^2 and $dE/dr \approx 10^{10}$ V/m^2 (e.g., $dE/dr \approx 10^7$ V/m^2, $dE/dr \approx 10^8$ V/m^2, $dE/dr \approx 10^9$ V/m^2, etc.). Other gradient values are also possible.

The distance from the electrode generating the electric field to the source of the flame (e.g., to a burner when a burner is used) may take any suitable value. According to some embodiments, the closer the electric field source is to the flame the more easily the flame may be extinguished. According to some embodiments, the source electrode may be between approximately 5 mm and 30 mm from the source of the flame (e.g., between 6 mm and 15 mm, between 10 mm and 25 mm, etc.), or any other suitable distance.

The impact of the electric field characteristics and the distance from the electrode to the flame on the deflection and extinction of flames is illustrated in some non-limiting example graphs, and now explained. Generally, both the angle of deflection, α, and the probability of extinction, P, increase with increasing frequency. More specifically, the dependence of P on frequency exhibits a threshold-like behavior, whereby the flame is reliably extinguished primarily, and in some situations only, above a certain "critical" frequency, which we define as the frequency at which $P = 50\%$.

FIGs. 2 and 3 illustrate data indicative of this generalization. Figure 2 shows a graph of the values of P and α (in degrees) as a function of frequency (in Hz) for $V = 20$ kV and $\delta = 6$ mm. Above the graph is a set of three pictures of the flame 210 taken at the indicated frequencies (20 Hz, 310 Hz, and 400 Hz), showing the increasing deflection in the flame 210 with increasing frequency. The positions of the burner 212 and of the electrode 214 are also indicated.

The probability of extinction, P, increases with increasing voltage of the applied signal, and therefore with increasing electric field strength. FIG. 3 illustrates a graph showing a non-limiting example of data supporting this statement. This plot shows the dependence on frequency (in Hz) of the probability of extinction, P, of a methane/air conical diffusion flame as a function of the peak voltage of the sinusoidal voltage signal applied to the electrode. No extinction was observed for $V < 16$ kV within the range of frequencies experimentally tested.

The critical frequency, f_c, decreases with increasing voltage (see also FIG. 4, which shows the dependence of the critical frequency (in Hz) at which flame extinction ensues on the peak voltage (in kV) applied to the electrode, as obtained from the data shown in FIG. 2), in a manner that can be fitted by a decaying exponential (see FIG. 4): ($f_c = ae^{-bV}$, where f_c is the critical frequency, V is the voltage of the applied signal, $a = 1.1 \times 10^5$ Hz and $b = 0.28\ V^{-1}$) or with a power law (see FIG. 4) ($f_c = cV^{-d}$ with $c=3.2 \times 10^9$ Hz and $d=5.4$).

FIG. 5 illustrates dependence on frequency (in Hz) of the probability of extinction, P, of a methane/air conical diffusion flame as a function of the distance between the tip of the metal electrode and the mouth of the burner. The data represent five distances: 6 mm, 10 mm, 11 mm 12.5 mm and 15 mm. It can be seen that P decreases with increasing distance. The extinction behavior is similar for $\delta = 6$, 10, and 11 mm, while there is no extinction for $\delta > 12.5$ mm. While at 11 mm of distance, the response of the flame to the field is repulsive, at 12.5 mm the response is a mixture of attractive and repulsive, with the flame becoming shorter and wider, as if stretched horizontally by the field. The critical frequency of suppression may be independent of distance, as long as the distance is sufficiently small to elicit the suppressive "response" (see Fig. 6, which shows the dependence of the critical frequency (in Hz) on the distance (in mm) between the tip of the Pt electrode and the mouth of the burner as obtained from the data shown in Figure 4). Such behavior may arise from a very sharp distance dependence (e.g., a power law with large exponent) of the effective force operating on the flame.

Extinction of a flame by application of a time-varying electric field thereto, when P = ~50%, may progress in stages. The flame is initially strongly deflected (~70-90 degrees). The flame loses all traces of soot emission (possibly due to cooling, or more plausibly due to the efficient removal of soot particles from the hot zone). The flame front oscillates erratically at about 2-5 cm from the burner, as if pushed by two opposing driving forces. On one side the flame propagation which drives the flame front back to the burner. On the other side, the effective force generated by the electric field is pushing it away from the burner. This behavior fades as P increases to 100% with increasing frequency. In such conditions extinction happens within the first second of the application of the field. At frequencies much lower than the critical frequency (P~0), the flame remains "attached" to the burner and is only deflected.

Though the various aspects described herein are not limited to utilizing any particular physical mechanism for extinguishing flames, it is noted that in at least some embodiments the extinction of the flame may be caused at least in part by forcing the combustion region away from the fuel source using an oscillating gradient electric field. The electric field may accelerate the ions within the flame, resulting in a transfer of momentum having a non-zero net average, and thus leading to repulsion of the flame from the electrode applying the electric field. When the speed of repulsion of the flame is less than the speed of propagation of the flame to the burner, the flame may not be extinguished but rather may be deflected. When the speed at which the flame is projected away from the burner (the fuel source) is greater than the speed at which the flame can propagate to the burner (which happens to be approximately 1 m/s for a CH_4/air diffusion flame), the flame may be blown off the fuel source and thus extinguished.

The behavior of flames in response to the application of a time-varying electric field may be due, at least in part, to the Ponderomotive Force. The Ponderomotive force, F_p, may take the form:

$$Fp = \frac{-q^2 \nabla_o (E_o^2)}{4m\omega^2[1 + (\lambda/mw)^2]}$$

where m and q are, respectively, the mass and charge of the particle, E_o is the magnitude of the electric field given by $E(r,t) = E_o(r)\cos(\omega t)$, and λ is a damping factor which accounts for the viscous drag due to the surrounding fluid (e.g., air).

The Ponderomotive Force may cause ions of either polarity (positive or negative) to be repelled from the electrode applying the oscillating gradient electric field. The particles may oscillate and drift towards regions of low electric field density. When the amplitude of the oscillations is small with respect to length scales of the electric field gradients, the oscillation center moves as if acted upon by a force, which is the so-called Ponderomotive Force. The Ponderomotive force acts symmetrically on both positive and negative charged species, may require oscillating electric fields in at least some situations, and generally increases with increasing field gradients. The Ponderomotive Force may also act most effectively in at least some embodiments on large particles, such as soot in a flame.

It is also noted that the manipulation of flames using oscillating gradient electric fields, as described herein, need not require contact between the electrode(s) applying the electric field and the flame.

As should be appreciated from the foregoing, application of a time-varying gradient electric field may bend (or deflect) a flame, for example prior to extinguishing the flame. Thus, according to one embodiment, a flame may be manipulated by bending the flame via application of a time-varying (e.g., oscillating) gradient electric field thereto. The field have any suitable frequency, magnitude, gradient, and spacing from the flame to generate a desired degree of bending. Similarly, a flame may be squashed (e.g., minimized) or stretched if a time-varying electric field is applied parallel to the direction of the flame.

According to another non-limiting embodiment, mixing of a flame may be controlled at least in part by application thereto of a time-varying gradient electric field. As explained previously, application of a time-varying gradient electric field to a flame may generate motion of ionic particles within the flame, which may itself give rise to collective motion of the flame, for example as a result of ionic particles of the flame transferring momentum to neutral particles of the flame. The resultant motion may enhance, or alternatively suppress depending on the conditions, mixing of the flame. Thus, various applications in which control over flame mixing is desired may be realized.

According to another non-limiting embodiment, concentration of a flame may be achieved by application of a time-varying gradient electric field thereto. FIG. 7 illustrates a non-limiting example of a configuration which may be used. As shown, an electric field source may be configured substantially parallel to the direction of flow of the flame. For example, a burner 702 may have an electrode 704 configured with respect thereto such that an electric field 706 is generated in a direction substantially parallel to the direction of propagation of the flame 708. A time-varying applied signal 710 (e.g., an alternating current (AC) signal) may be applied to the electrode to generate the electric field. A grid 712 may be positioned a distance *d* from the top of the burner. The distance *d* may be between approximately 5-15 cm (e.g., 10 cm), or have any other suitable value, as these are non-limiting examples. Application of the electric field may result in concentration of the flame across a smaller area of the grid 712 than would occur absent the electric field. Thus, in some non-limiting embodiments, the width (from left to right in FIG. 7) of the flame 708 may be greater when no electric field is applied than when the electric field 706 is applied (i.e., the electric field 706 may "shrink" the width of the flame, thus concentrating the flame). A non-limiting example of operation of the configuration of FIG. 7 is now described, together with results therefrom in FIGs. 8A-8D.

Example 2

FIGs. 8A-8D illustrate the setup of an apparatus conforming to the general configuration of FIG. 7, and which may be used to concentrate a flame. The bottom photograph in each of FIGs. 8A-8D illustrates the physical setup, showing a perspective view of the metal grid. The dark spot in the center of the metal grid represents the area of the grid contacted by the flame. As described further below, it can be seen that the area changes depending on the parameters of the applied electric field. The top image in each of FIGs. 8A-8D represents a thermal image taken of the metal grid for the corresponding physical setup.

The setup comprises a ceramic burner flowing ~ 1 L/min of methane. The methane is lit. The flame is then arrested by the thick metal grid placed flat above the flame. The grid functions as the ground, while a ring electrode is applied to the burner.

FIG. 8A illustrates the scenario in which no electric field is applied. The maximal temperature observed on the top of the grid was 631° C.

FIG. 8B illustrates the scenario in which a voltage of 18 kV at 100 Hz is applied to the ring electrode surrounding the burner, as mentioned previously in the manner illustrated by the configuration of FIG. 7. Thus, an electric field is applied to the flame. The maximal temperature increased by approximately 100 degrees to 731° C (which appeared to be the equilibrium) compared to that of FIG. 8A within 40 seconds. In these conditions there is the occurrence of slight sparking between the electrodes.

To verify if the sparks are responsible for this increase in temperature, the conditions of FIG. 8C and 8D were tested. FIG. 8C illustrates a scenario in which no electric field is applied, as in FIG. 8A. FIG. 8D illustrates the scenario in which a voltage of 9 kV at 100 Hz (a voltage at which no sparking occurred) is applied to the ring electrode surrounding the burner. The temperature still increased by 50 degrees compared to that of FIG. 8C in approximately 40 seconds.

Thus, it should be appreciated from FIGs. 8A-8D and the data illustrated therein that according to one or more embodiments a flame may be concentrated over a smaller area when an electric field is applied.

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According to another non-limiting embodiment, a flame may be stabilized by the application of a time-varying electric field, and in some instances a time-varying gradient electric field, thereto. The flame may be stabilized in that its ability to remain in existence when it otherwise would be extinguished may be increased. A non-limiting example of a configuration resulting in stabilization of a flame is that illustrated in FIG. 7. Application of the electric field to the flame as illustrated may allow the flame to exist at higher fuel flow rates than would be possible absent the electric field. The electric field may have any suitable strength and frequency to accomplish this result.

According to another non-limiting embodiment, an electric field may be used to suppress a flame. The electric field may, for example, be configured to create a boundary between a fuel source and a flame, such that the fuel source does not ignite. A non-limiting example is illustrated in FIG. 9.

As shown, a flame 902 may be positioned near a fuel source (e.g., a burner) 904. The fuel 906 emitted by the fuel source 904 may initially propagate toward the flame 902. However, application of a time-varying gradient electric field, in the manner described previously herein, from an electrode 908 (as a result of application of an applied signal 910) may prevent the flame from igniting the fuel source, thus suppressing the flame. The electric field may create an outflow from the flame (in the direction of the arrows) which may divert the fuel from the flame. This, however, is a non-limiting example.

According to another non-limiting embodiment, a time-varying electric field may be used to increase the flow and nebulization of a fluid. A non-limiting configuration is illustrated in FIG. 10. As shown, container 1002 may include a fuel 1004 and a plume 1006. Application of a time-varying gradient electric field thereto in the manner previously described herein, using an electrode 1008 may increase the plume.

According to another non-limiting embodiment, a Davy Lamp configuration is used to manipulate a flame. In some such embodiments, a flame arrestor grid may be used as one electrode. A combination of thermal quenching and electric fields may be used to extinguish the flame. FIG. 12 illustrates a non-limiting embodiment.

As shown in FIG. 12, the apparatus 1200 may include a first electrode 1202 and a second electrode 1204. A power supply 1206 may apply a voltage difference between the electrodes 1202 and 1204.

The electrode 1202 may be a metal mesh structure having a mesh size sufficient to allow a fuel source to pass through. In some non-limiting embodiments, the electrode 1202 may be considered a flame arrestor grid, as will be further appreciated from the discussion below. The mesh size should be such that liquid can rapidly pass through, but not so large that the flame is not quenched (as described below). Non-limiting examples for suitable mesh sizes are between 1 mm and 1cm.

The electrode 1204 may be any suitable electrode formed of any suitable material.

The power supply 1206 may apply a direct current (DC) or AC signal to the electrodes 1202 and 1204. Non-limiting examples of suitable voltages for AC signals include greater than 5 kV at a frequency greater than 1 Hz (e.g., between 1 Hz and 1 kHz, or even greater). Non-limiting examples of suitable DC signals include -5 kV, between 5 kV and 50 kV, 50 kV, greater than 50 kV, or any other suitable voltages.

If fuel on the electrode 1202 catches fire 1208, a suitable electric potential may be applied to the electrode 1202 by the power supply 1206. The fire may be extinguished, for instance because contact with the electrode 1202 may thermally quench the fire 1208 resulting in extinguished fuel 1210 passing through the mesh of electrode 1202 to the electrode 1204. The thermal quenching may separate the flame from the liquid fuel and allow the liquid fuel to pass through the mesh. The electric field from the electrode 1202 may also facilitate extinguishing the flame, in addition to the thermal quenching. For instance, the flame may be extinguished in approximately 1/3 the time as would occur without the field (e.g., in approximately 4 seconds compared to 12 seconds which may be required without the electric field). Applying the electric field may also stabilize the flame.

The electrodes 1202 and 1204 may take any suitable configuration with respect to each other. For example, they may be separated by between 1 mm and 1 meter, greater than 1 m, or any other suitable distance. The electrode 1204 may be below the electrode 1202 or above it, as the relative orientation is not limiting.

The configuration of FIG. 12 may be used in various products. For example, a floor or flooring system may be constructed in the configuration illustrated. Other applications are also possible.

In some embodiments, an electrode may be moved relative to a flame, for example by swiping the electrode across a flame. A non-limiting example of a suitable configuration is illustrated in FIG. 13. As shown, the apparatus 1300 includes a fuel source 1302 (e.g., gal, liquid, solid, etc.) which may create multiple flames 1304. Ten flames 1304 are shown, but the number is non-limiting, and may even include only a single flame in some embodiments. An electrode, such as the sheathed wire electrode of FIGs. 11A and 11B may be oriented as indicated at 1306 (i.e., with the electrode oriented into and out of the page) and may be moved in the direction indicated by arrow 1308 across the flames. The electrode may be connected to a current source (AC or DC) of any suitable potential (e.g., greater than 5kV in some non-limiting embodiments). Moving the electrode in the direction shown may deflect the flames and may extinguish the flames in some embodiments (e.g., with an oscillating signal of approximately 1 kHz and electric potential greater than 30 kV, as non-limiting examples). The closer the electrode is to the origin of the flames, the greater the likelihood of extinguishing the flames. For example, positioning the electrode within approximately 1 cm of the flame origin may increase the likelihood of extinguishing the flames.

From the foregoing, it should be appreciated that various types of manipulation of flames using electric fields may be achieved. In some non-limiting embodiments, the electric fields may be oscillating electric fields having a gradient in three dimensions (referred to herein as "three-dimensional gradient fields"). In some embodiments, the electric fields are generated using fewer than three electrodes. The electrode(s) may be insulated to prevent generation of an ionic wind. Thus, the manipulation described according to various embodiments may be achieved without the need for an ionic wind.

Various techniques for manipulating flames have been described. As mentioned previously, it should be appreciated that the various aspects described herein may be used individually or in any combination of two or more, unless otherwise stated.

As mentioned previously, one or more aspects of the present application may relate to manipulation of flames, and the manipulation may take one or more of various forms. Non-limiting examples of manipulation may include extinguishing a flame, suppressing a flame, bending a flame, controlling the mixing within the flame, and concentrating the flame. However, other forms of manipulation may also be possible, and the various aspects described herein are not limited to any particular form of manipulation unless otherwise stated.

Also, as mentioned previously, the aspects described herein may apply to various flame types (i.e., flames resulting from combustion of various types of fuels), unless otherwise stated. For example, ethanol, methanol, toluene, and hexane are non-limiting examples of fuel sources to which aspects of the present application may be applied. Other types of flames are also possible.

Moreover, various benefits may be realized by the application of one or more of the aspects described (though it should be appreciated that not all aspects necessarily provide each benefit). For example, one or more aspects may be used to put out a fire without the need for adding a suppressant (e.g., a chemical suppressant), which may reduce damage to items (e.g., personal and real property) as well as avoiding the need for toxic chemicals. In some embodiments, a fire may be put out from a distance. Moreover, manipulation of flames of different compositions may be achieved with the same technique of manipulation. Other aspects may provide improved combustion, e.g., more efficient combustion with the production of fewer combustion byproducts. Various other benefits, alternatively or in addition, may be realized by one or more aspects, as those listed are non-limiting examples.

One or more aspects and embodiments of the present application involving the performance of methods may utilize program instructions executable by a device (e.g., a computer, a processor, or other device) to perform, or control performance of, the methods. In this respect, various inventive concepts may be embodied as a computer readable storage medium (or multiple computer readable storage media) (e.g., a computer memory, one or more floppy discs, compact discs, optical discs, magnetic tapes, flash memories, circuit configurations in Field Programmable Gate Arrays or other semiconductor devices, or other tangible computer storage medium) encoded with one or more programs that, when executed on one or more computers or other processors, perform methods that implement one or more of the various embodiments discussed above. The computer readable medium or media can be transportable, such that the program or programs stored thereon can be loaded onto one or more different computers or other processors to implement various ones of the aspects discussed above. In some embodiments, computer readable media may be non-transitory media.

Having thus described several aspects and embodiments of the technology, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art. Such alterations, modifications, and improvements are intended to be within the spirit and scope of the technology. Accordingly, the foregoing description and drawings provide non-limiting examples only.

Also, the phraseology and terminology used herein is for the purpose of description and should not be regarded as limiting. The use of "including," "comprising," or "having," “containing,” “involving,” and variations thereof herein, is meant to encompass the items listed thereafter and equivalents thereof as well as additional items.

What is claimed is:

APPENDIX

Quantifying Flame Deflection

In order to measure the angle of deflection, the flame is filmed during the application of the electric field using a digital camera at a frame rate of 1 fps. The frames are then superimposed on one another to create a composite, grayscale image as shown below.

The angle of deflection is then measured by calculating the principle axes of "inertia" of the flame's image. First, the center of "mass" is calculated as

$$x_{cm} = \sum_i \sum_j x_j M_{ij} \text{ and } y_{cm} = \sum_i \sum_j y_i M_{ij} \tag{0.1}$$

where M_{ij} is the intensity of pixel (i,j). The inertial tensor is then calculated as

$$I = \begin{bmatrix} \sum_{i,j} (y_i - y_{cm})^2 M_{ij} & \sum_{i,j} x_i y_j M_{ij} \\ \sum_{i,j} x_i y_j M_{ij} & \sum_{i,j} (x_j - x_{cm})^2 M_{ij} \end{bmatrix} \tag{0.2}$$

The eigenvectors of the inertial tensor represent the "principle axes" of the flame; the one of interest, **v**, points along the long axis of the flame. The angle of deflection is then calculated as $\theta = \tan^{-1}(|v_x / v_y|)$.

CLAIMS

1. A method, comprising:
manipulating a flame by applying a time-varying three-dimensional gradient electric field to the flame.

2. The method of claim 1, wherein the time-varying three-dimensional gradient electric field has a magnitude given by $E \approx 1$ MV/m, a gradient between $dE/dr \approx 10^7$ V/m^2 and $dE/dr \approx 10^9$ V/m^2, and a frequency given by $f \approx 1000$ Hz.

3. The method of claim 1, wherein the flame is generated by a liquid fuel source.

4. The method of claim 1, wherein the flame is generated by a gaseous fuel source.

5. The method of claim 1, wherein the flame is generated by a solid fuel source.

6. The method of claim 1, wherein the flame is a toluene flame.

7. A method, comprising:
extinguishing a flame by application of an oscillating three-dimensional gradient electric field to the flame.

8. The method of claim 7, wherein the oscillating three-dimensional gradient electric field has a gradient of approximately $dE/dr \approx 10^8$ V/m^2 at a center of the flame.

9. The method of claim 7, wherein extinguishing the flame by application of an oscillating three-dimensional gradient electric field comprises inducing lift off of the flame by application of the oscillating three-dimensional gradient electric field.

10. The method of claim 7, comprising using an electrode to apply the oscillating three-dimensional gradient electric field to the flame.

11. The method of claim 7, comprising applying the oscillating three-dimensional gradient electric field in a direction substantially perpendicular to a direction of flow of the flame.

12. A method, comprising:

suppressing a flame by application of an oscillating three-dimensional gradient electric field.

13. The method of claim 12, wherein the oscillating three-dimensional gradient electric field has a gradient of approximately $dE/dr \approx 10^8$ V/m^2 at a center of the flame and a magnitude of approximately 1 MV/m at the center of the flame.

14. The method of claim 12, wherein suppressing a flame comprises preventing contact between a flame and a fuel source.

15. The method of claim 14, wherein preventing contact between the flame and the fuel source comprises creating an outflow from the flame that diverts the fuel source from the flame.

16. A method, comprising:

bending a flame by application of an oscillating three-dimensional gradient electric field to the flame.

17. The method of claim 16, wherein the oscillating three-dimensional gradient electric field has a gradient of approximately $dE/dr \approx 10^8$ V/m^2 at a center of the flame and a magnitude of approximately 1 MV/m at the center of the flame.

18. A method, comprising:

controlling mixing in a flame by application of an oscillating three-dimensional gradient electric field to the flame.

19. The method of claim 18, wherein the oscillating three-dimensional gradient electric field has a gradient of approximately $dE/dr \approx 10^8$ V/m^2 at a center of the flame and a magnitude of approximately 1 MV/m at the center of the flame.

20. A method, comprising:

concentrating a flame by application of an oscillating electric field to the flame.

21. The method of claim 20, wherein the oscillating three-dimensional gradient electric field has a gradient of approximately $dE/dr \approx 10^8$ V/m^2 at a center of the flame and a magnitude of approximately 1 MV/m at the center of the flame.

22. The method of claim 20, comprising applying the oscillating gradient electric field in a direction substantially parallel to a direction of flow of the flame.

23. A method, comprising:

manipulating a flame by applying a time-varying electric field to the flame, the time-varying electric field being non-uniform in three dimensions.

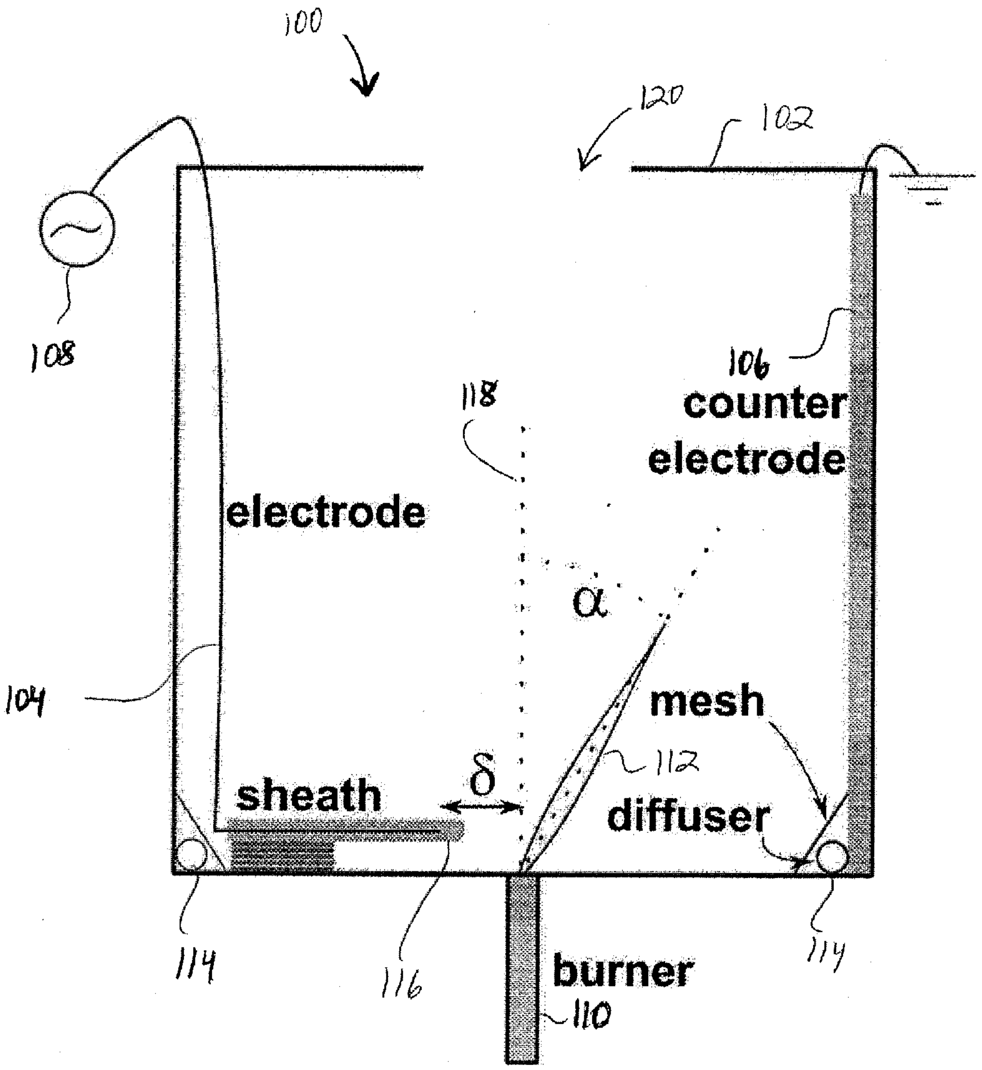
100
120
102
108
106
counter
electrode
118
electrode
α
104
mesh
112
δ
sheath
diffuser
114
116
burner
110
114

Figure 1.

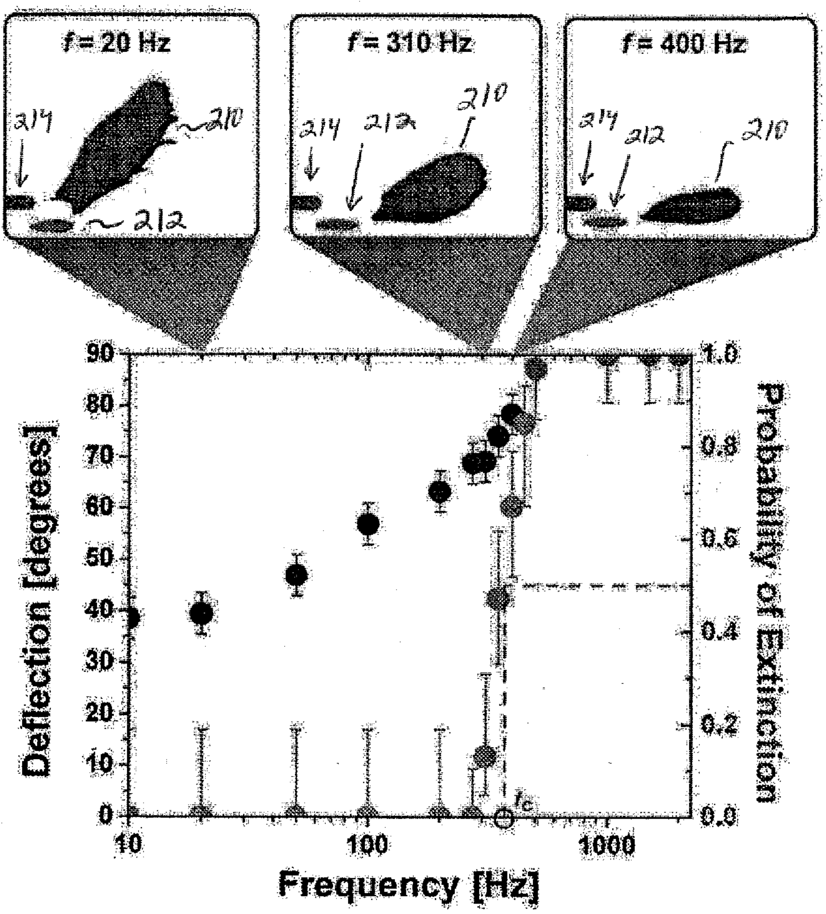
f = 20 Hz
214
210
212
f = 310 Hz
214
212
210
f = 400 Hz
214
212
210
Deflection [degrees]
0
10
20
30
40
50
60
70
80
90
Probability of Extinction
0.0
0.2
0.4
0.6
0.8
1.0
f_c
10
100
1000
Frequency [Hz]

Figure 2.

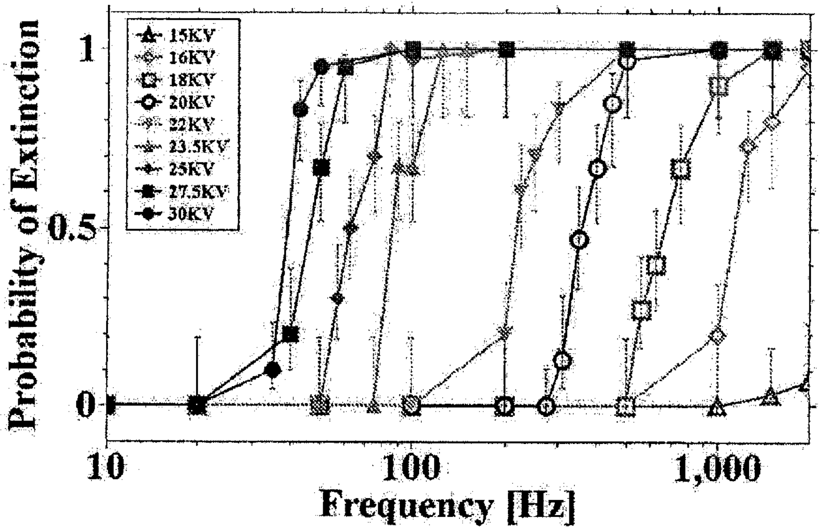
15KV
16KV
18KV
20KV
22KV
23.5KV
25KV
27.5KV
30KV
Probability of Extinction
1
0.5
0
10
100
1,000
Frequency [Hz]

Figure 3.

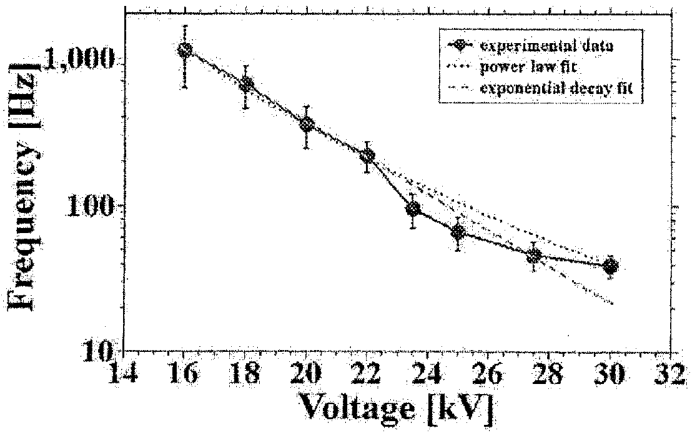
experimental data
power law fit
exponential decay fit
Frequency [Hz]
1,000
100
10
14
16
18
20
22
24
26
28
30
32
Voltage [kV]

Figure 4.

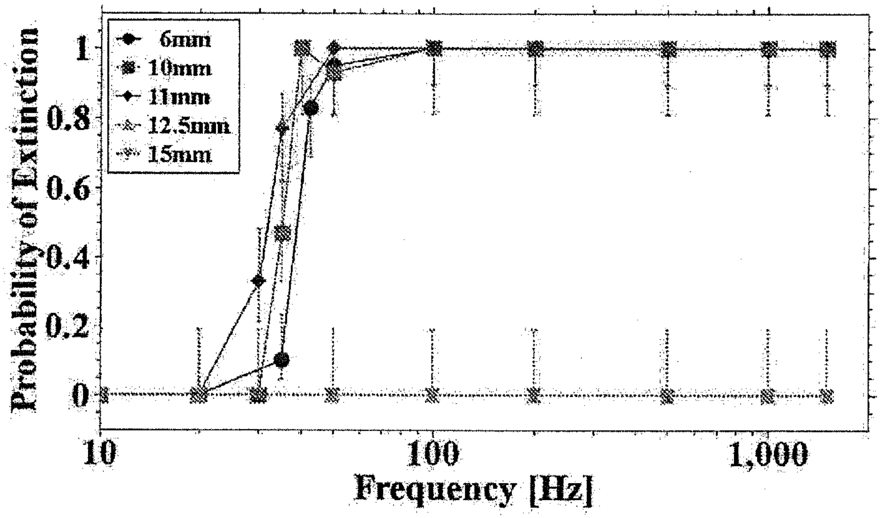
6mm
10mm
11mm
12.5mm
15mm
Probability of Extinction
1
0.8
0.6
0.4
0.2
0
10
100
1,000
Frequency [Hz]

Figure 5.

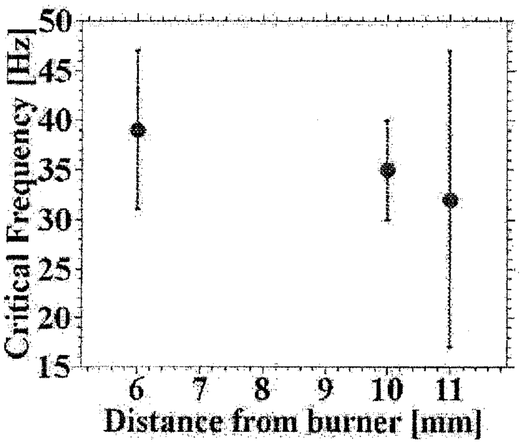
Critical Frequency [Hz]
50
45
40
35
30
25
20
15
6
7
8
9
10
11
Distance from burner [mm]

Figure 6.

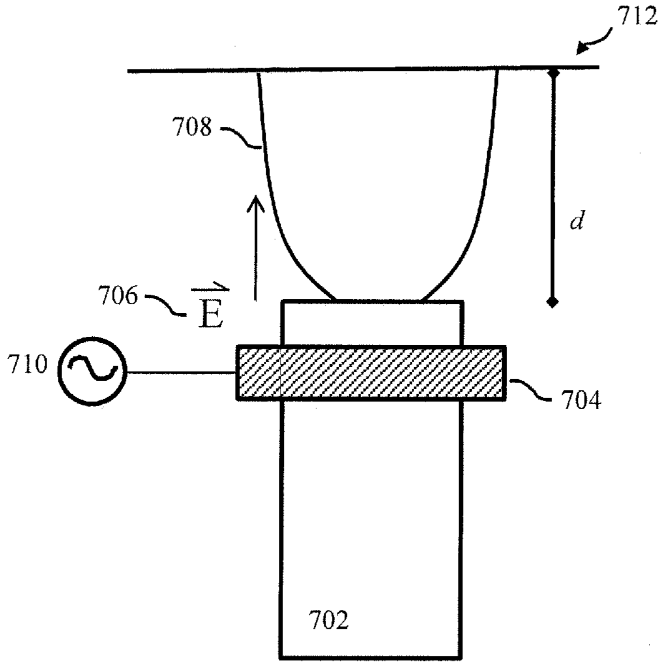

FIG. 7

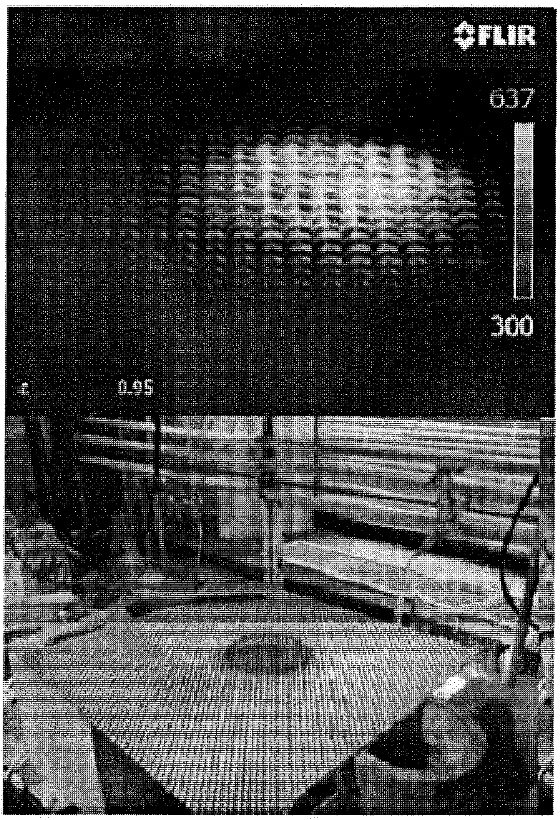

FIG. 8A

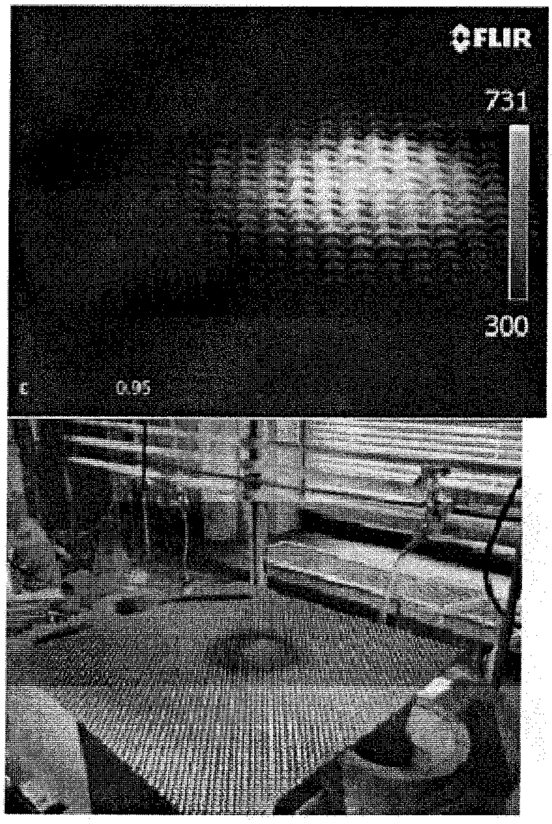

FIG. 8B

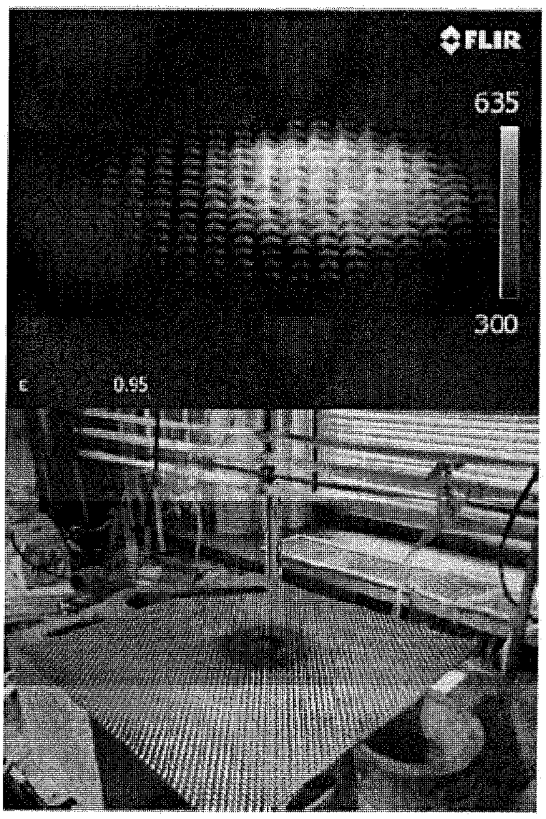

FIG. 8C

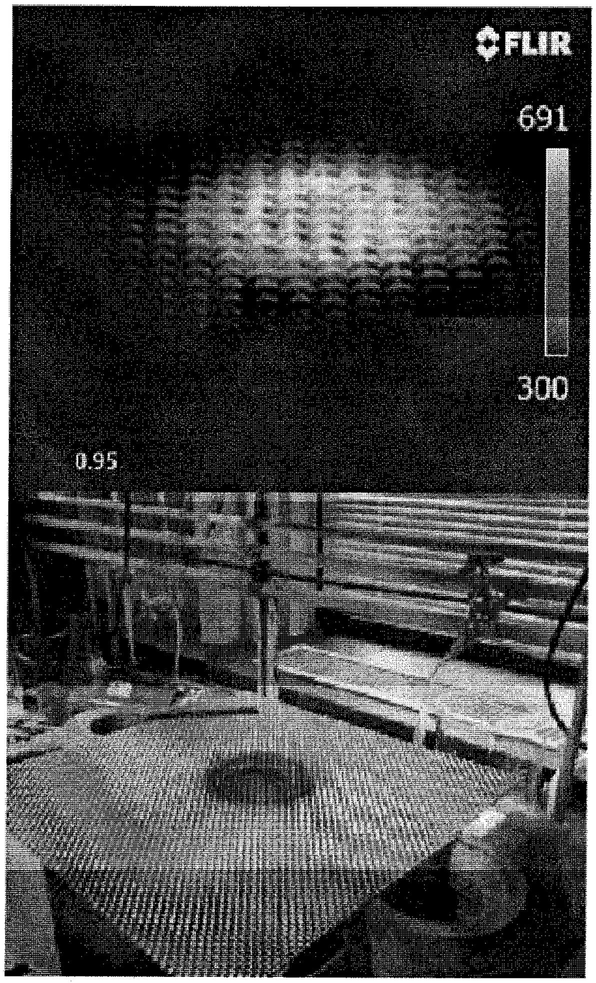

FIG. 8D

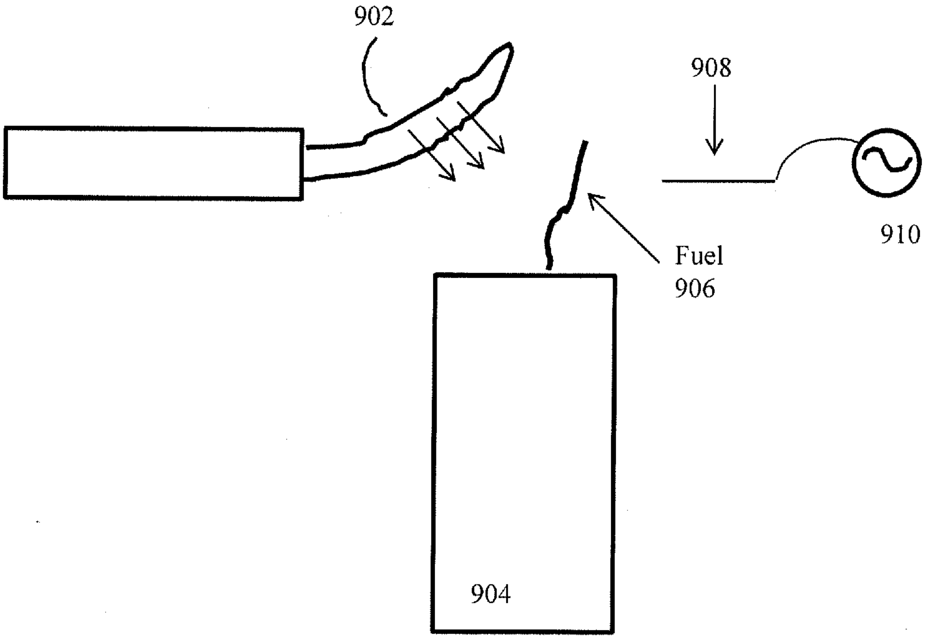

FIG. 9

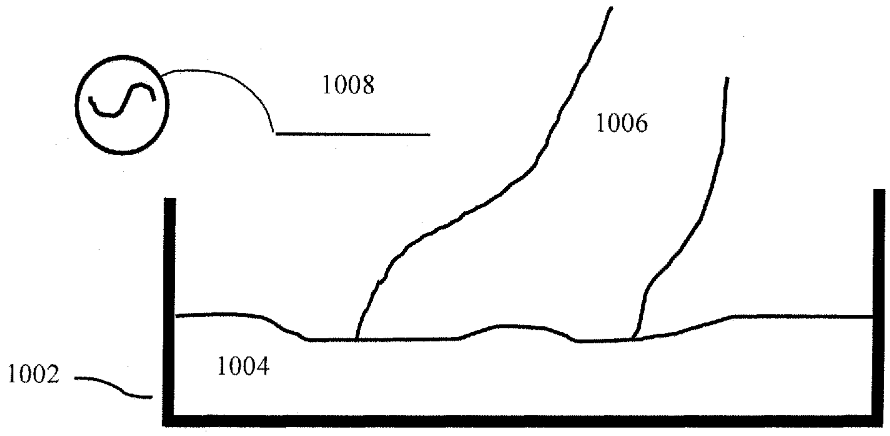

FIG. 10

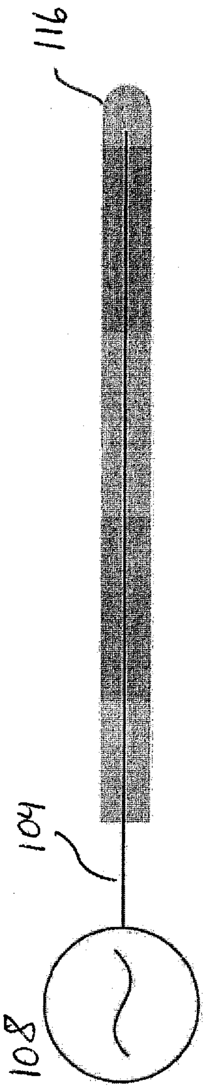

FIG. 11A

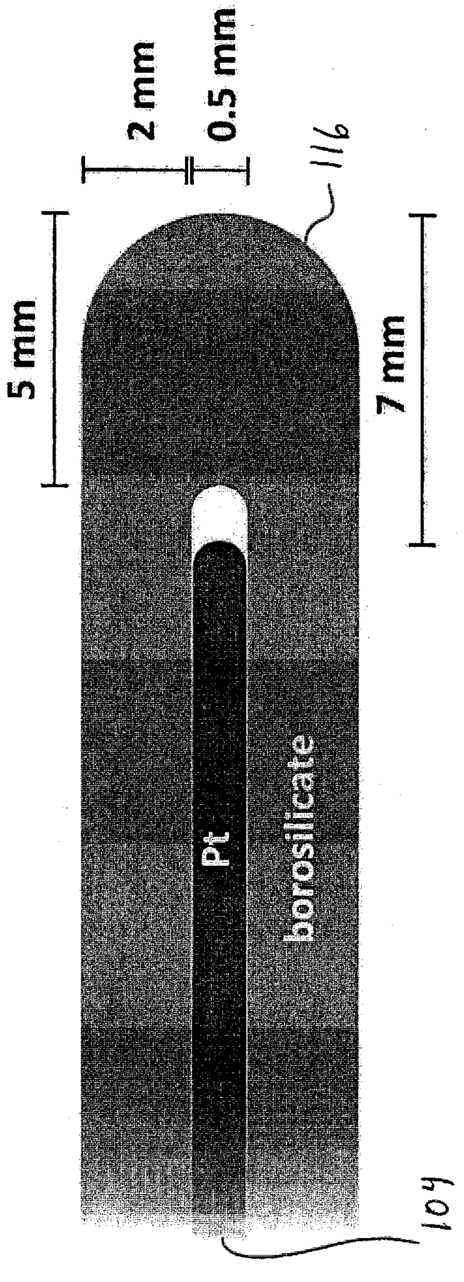

FIG. 11B

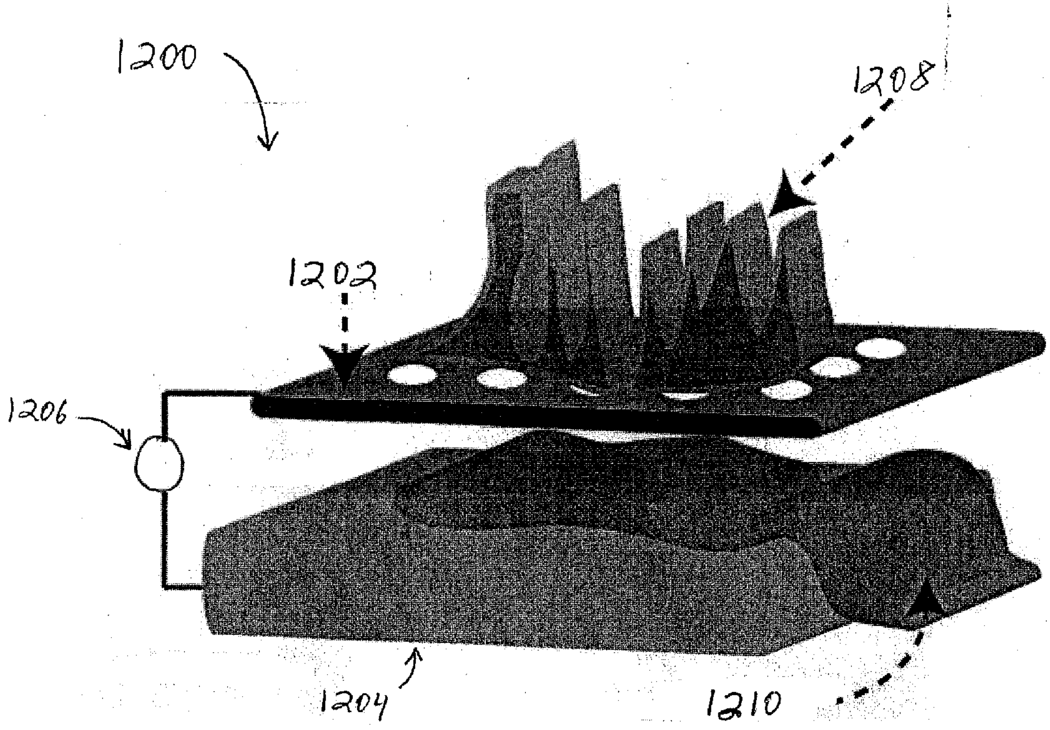

FIG. 12

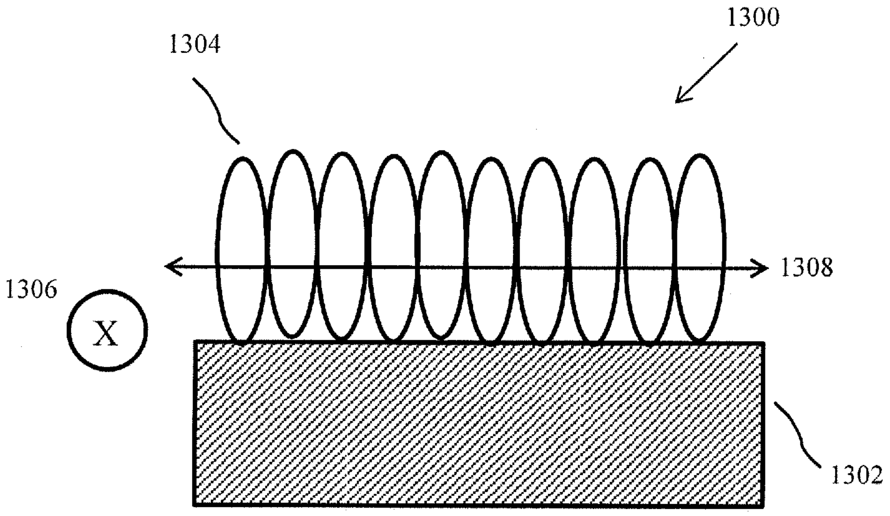

FIG. 13