Hindawi Publishing Corporation
Modelling and Simulation in Engineering
Volume 2011, Article ID 676428, 13 pages
doi:10.1155/2011/676428

*Research Article*

# Electrical Modification of Combustion and the Affect of Electrode Geometry on the Field Produced

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Received 11 March 2011; Accepted 26 May 2011

Academic Editor: Zeki Ayag



There has been extensive work to show how electric fields can influence combustion. However, many different set ups are used. This work shows how different set ups produce different field strengths and that the field is not always uniformly distributed. The field strength is modelled using Ansys Maxwell. The type of material used is discussed and the set up of apparatus. It is recommended to use parallel plates for experimentation. Parallel plates produce the most uniform field this allow's it's influence to be directly investigated and related to the field strength.

## 1. Introduction

Ions are created as part of hydrocarbon combustion [1]. These ions can be moved and excited when subjected to an external electric field [2]. The effects of this can be used to extinguish flames [3–6], to increase the flammability limits [5–15], to reduce the pollutants emitted [8, 9, 16–28], effect the temperature (by entraining air) [9, 17, 29], modify the burning velocity [7, 13, 30], or to increase/decrease the heating to surfaces surrounding a flame. The effects have been well documented; however, the results are sometimes contradictory. For example, it is unclear whether an electric field can be used to change the burning velocity. Jaggers and Von Engel found that this was possible [7] but this is contradictory to other reports by Bowser and Weinberg [31] and also Jaggers et al. [32]. One of the reasons for this could be that the experimental set-up was not the same. Different electrode geometries will produce different electric fields.

Although the exact affect of an electric field has not been quantified, it is clear that it does have an effect (see all of the above references). This effect is related to the field strength.

In other areas of research the affect of electrode geometry has been studied; see Christopoulos for an overview [33]. Programs have been developed to model the electric field produced by different electrode geometries, for example, Maxwell [34] and FEMM [35]. The aim of this report is to use these programs to model the affect of electrode geometry on the field produced. This report also aims to recommend an electrode geometry that produces a uniform field, so that the combustion modifications can be directly related to a field strength. The results of this study can also be used to identify electrode geometries where the field is intensified around a flame so that the voltage required to modify the flame is less; however, this is beyond the scope of the present study. Physical measurement of the field is also problematic as the measuring probe distorts the field [36].

It is also not currently possible to model the electric field with the flame present. This is because the flame is conductive of electricity (see Lawton and Weinberg [37]) and will modify the field. However, the field is also having an effect on the flame and changing its shape. This coupling of the flame and field requires combination of a computational fluid dynamics (CFD) program, a chemical kinetic mechanism which includes ions and an electric field modelling program. There has been some work to couple chemical kinetics with CFD (see fluent [38]) but the chemical mechanisms are not complex enough to cope with the introduction of ionic species. There is not even a full chemical kinetic mechanism that includes ions for modelling in programs such as CHEMKIN [39, 40]. There has been some work to develop one (see [41–44]) but is not currently good enough to predict the exact concentrations of ions and where they are formed in the flame.

Current work to predict what the electric field looks like and how the electrode geometry changes the type of field produced is contained in [37]P480, [45] P508, and [46, 47]. However, this work was conducted before the development of modern modelling programs such as Maxwell [33] and FEMM [35]which can offer a greater insight into how the field looks.

*1.1. Boundary Conditions Used to Model the Field.* The modelling program computes the static electric field arising from potential differences and charge distributions. To do this it relies on solving the first of Maxwell's equations: Gauss' law. Gauss' law can be stated in several ways but it is the differential form that the modelling program uses:

$$\nabla \cdot (\varepsilon_r \varepsilon_0 \nabla \phi(x, y)) = -\rho, \quad (1)$$

where

(i) $\nabla$ is the del operator. This expresses the divergence. So the divergence of the vector $v(x, y, z) = v_x \mathbf{i} + v_y \mathbf{j} + v_z \mathbf{k}$ is div $\underline{\vec{v}} = \dfrac{\delta v_x}{\delta x} + \dfrac{\delta v_y}{\delta y} + \dfrac{\delta v_z}{\delta z} = \nabla \cdot v$,

(ii) $\phi(x, y)$ is the electric potential and $\varepsilon_r$ is the relative permittivity. This is set in the modelling process,

(iii) $\varepsilon_0$ is the permittivity of free space, $8.854 \times 10^{-12}$ $\text{Fm}^{-1}$ (Farads per metre),

(iv) $\rho$ is the charge density.

The program solves (1) for the potential ($\phi(x, y)$) of the finite element mesh. It then automatically computes the electric field and flux density using the equations. As part of the iteration process, the mesh in areas of high error is refined (in this case by 15%).

The following settings will be used to try to make the results comparable to each other. All the electrodes are a distance of 60 mm apart and have a potential of +10 kV facing 0 V (ground). Unless stated the upper electrode is the one at high voltage (also known as EHT for Extremely High Tension). This is not the voltage used by many of the researchers. The main reason for conducting this modelling was to compare the types of field produced by different geometries to identify the best type for this study's application. To include the different voltages and distances would make the results very difficult to compare; so as far a possible the voltages and distances between electrodes have been kept the same.

Virtually all the models have been created using a rotational symmetry and the results mirrored (using a graphical processor, not the modelling program) to show a cross-section through the centre of the field. This was considered to give the best visual representation of the model. There have been a few instances where rotational symmetry was not suitable to use (set-up numbers 9 and 11 in Table 1).

Some of the researchers have used a metal mesh as one of the electrodes rather than a solid plate. It is not possible to model this in 2D and to produce a 3D model overcomplicates the problem. Meshes have therefore been modelled as a solid brass plate.

The voltages were applied to the electrodes using a sheet source applied to the outside of the conductor (either 0 V or 10,000 V). It was chosen to apply the boundary in this manner so that the voltages did not interfere with the rotational symmetry boundary condition (or the outer boundary) when they overlapped. It is also a good representation of the theory that the modelling program is based on. This requires that the model is in equilibrium. Gauss' law states that the charge in a combustor rests on the surface when in equilibrium so that it can be as far apart as possible. It also states that because charge is free to move in a conductor, then if the conductor is in equilibrium, then there cannot be a field in the conductor and the flux entering/leaving a conductor must be at 90° or the charge would experience an unbalanced force and move (meaning it is not in equilibrium).

The experimental set-up should for practical reasons be conducted in a Faraday cage. This provides a safety feature from the high voltages and also shields the equipment from any other electrical interference. The modelling has been set-up to reflect this set-up. The boundary was set a significant distance away from the area of interest so that inconsistencies at the boundary did not affect the solution in the area of interest (between the electrodes). The affect of increasing the distance of the boundary from the electrodes can be seen in Figure 1.

Figure 1 shows that if the Faraday cage (earthed) is too close to the electrodes, then the field will be significantly altered. All the simulations in the remainder of this report show the perfect case of a boundary that is set at infinity.

To better analyse the results the field strength 0.2 mm above the bottom electrode can be plotted for all of the Faraday cage positions shown in Figure 1. The results of this are shown in Figure 2. The horizontal red line represents the balloon boundary condition where the Faraday cage is an infinite distance away.

Figure 2 shows that for practical situations the affect does not seem to be greatly altered once the Faraday cage is over 300 mm away from the electrodes. All the experiments in this report have therefore been conducted in a faraday cage that is over 300 mm away from the apparatus.

*1.2. Program Used.* There are several programs available. Both of the programs used in this report are freely available to download on the internet; so an interested reader may try modelling themselves. These are Maxwell [33] and FEMM [35]. We have an example of the field produced by parallel plates for both Maxwell and FEMM.

As you can see clearly from Figures 3 and 4 FEMM and Maxwell produce very similar results. Therefore only Maxwell will be used to produce the rest of the results in this report.

Table 1: Type of electrodes used in the literature and the field they produce.

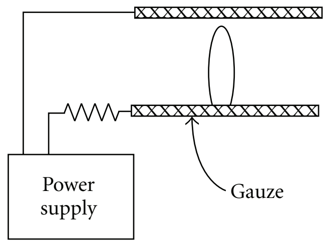
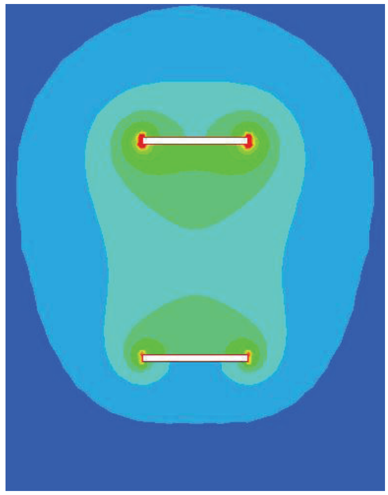
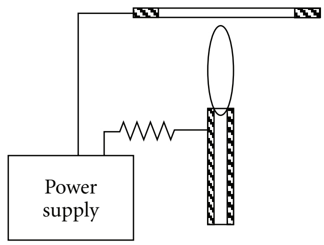
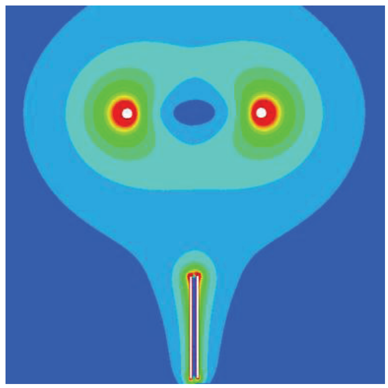
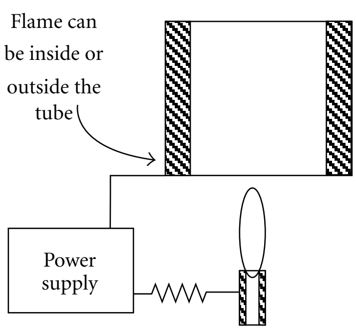
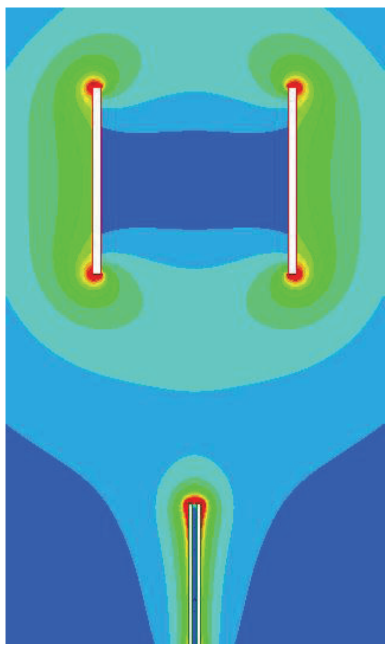
| | Type of electrode | Model | Ref. |
|---|---|---|---|
| 1 |   |  | [44] |
| 2 |   |  | [1, 4, 6, 8, 11, 12, 45, 54, 58, 59] |
| 3 |   |  | Solid Tube [30, 58, 60–62] Mesh Tube [4, 63, 64] |

Table 1: Continued.

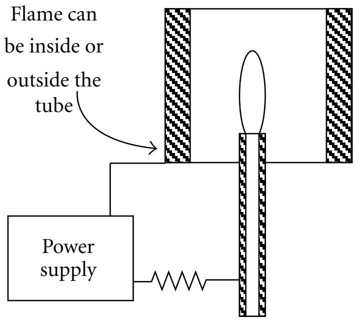
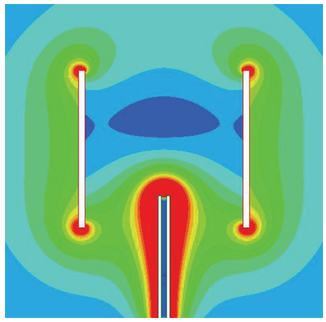
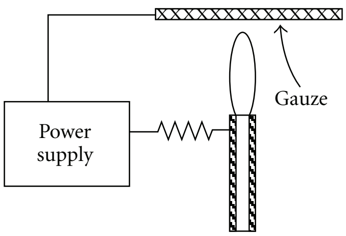
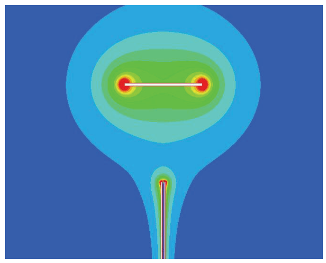
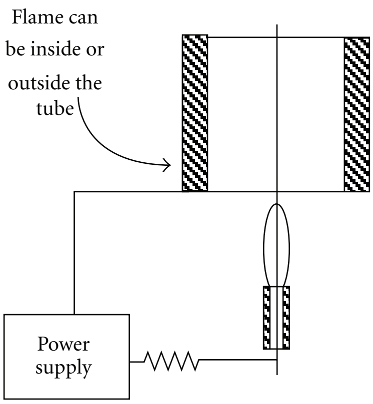
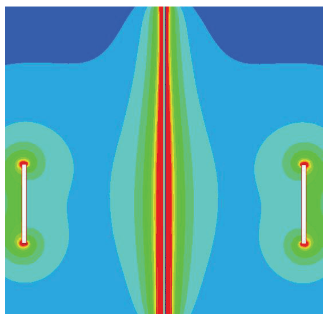
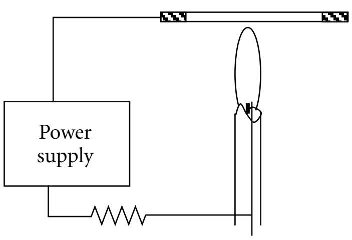
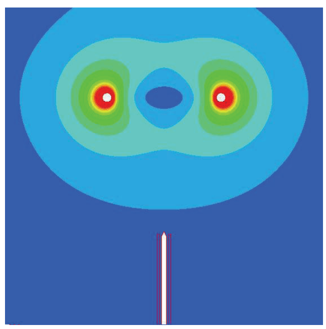
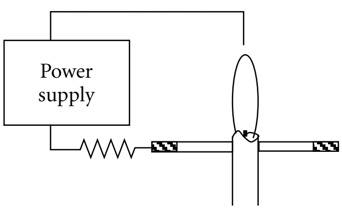
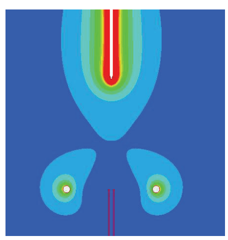
| | Type of electrode | Model | Ref. |
|---|---|---|---|
| 4 |  |  | As 3 above |
| 5 |  |  | [12, 18, 26, 58, 65, 66] |
| 6 |  |  | [16, 48, 50, 53, 67] |
| 7 |  |  | [45] |
| 8 |  |  | [45] |

Table 1: Continued.

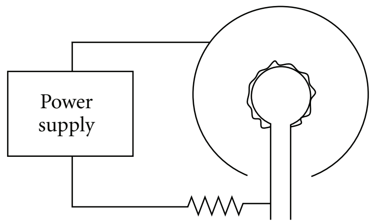
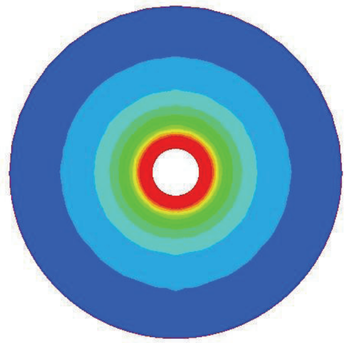
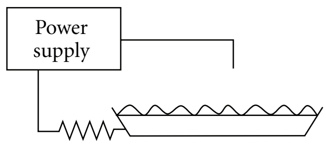
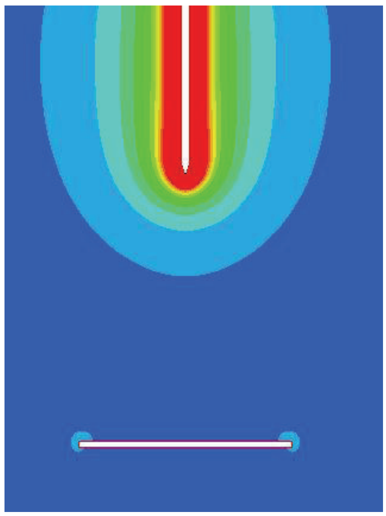
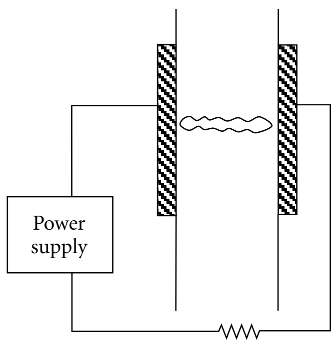
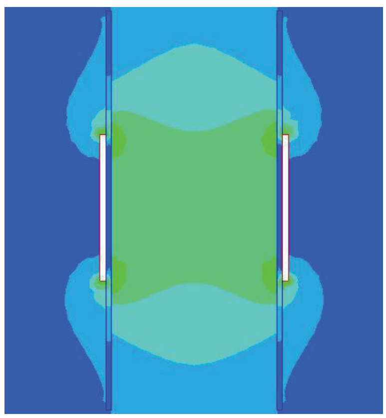
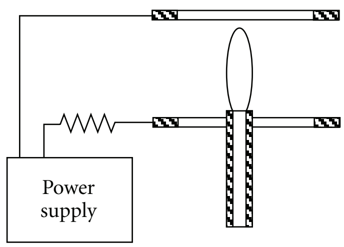
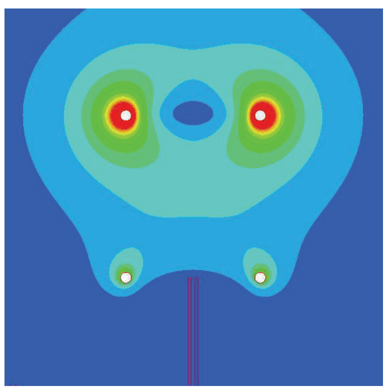
| | Type of electrode | Model | Ref. |
|---|---|---|---|
| 9 |   |  | [17, 49, 68, 69] |
| 10 |   |  | [3] |
| 11 |   |  | [7, 70] |
| 12 |   |  | [16] |

Table 1: Continued.

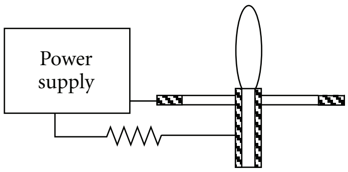
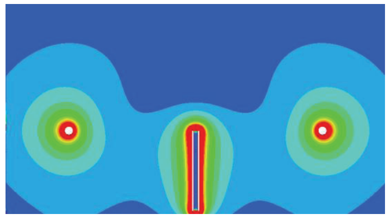
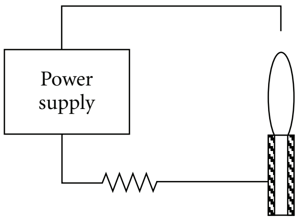
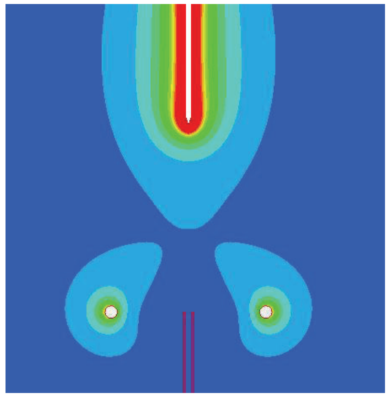
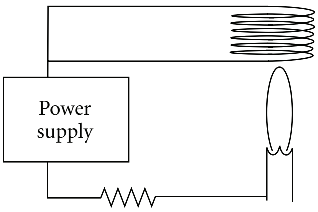
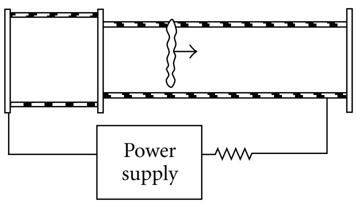
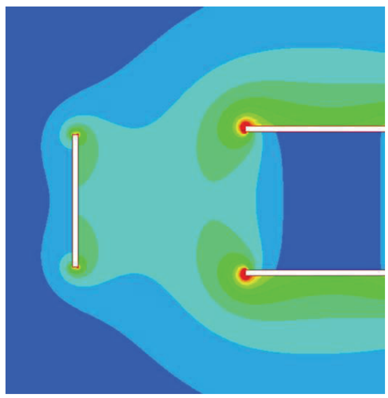
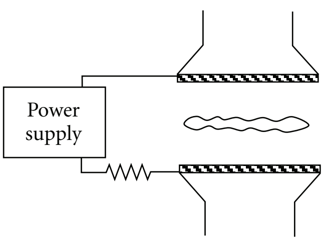
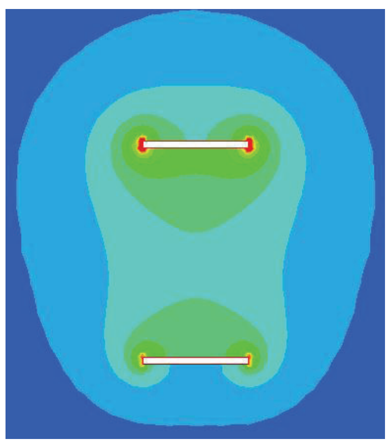
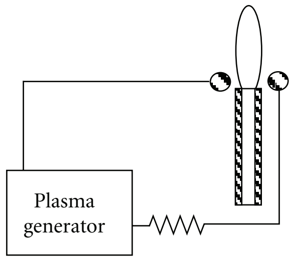
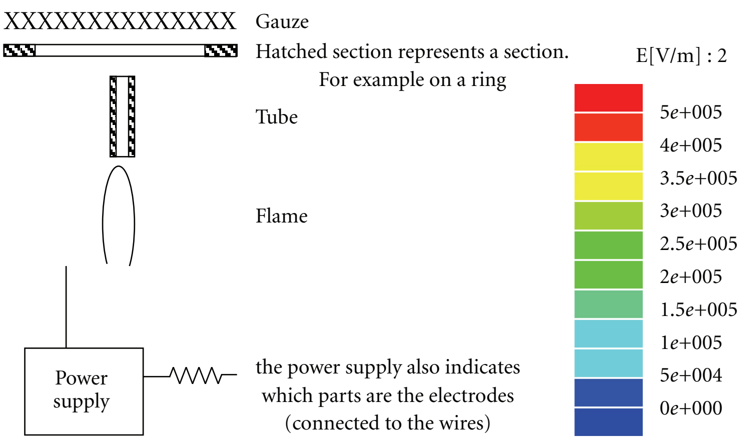
| | Type of electrode | Model | Ref. |
|---|---|---|---|
| 13 |   |  | [71] |
| 14 |   |  | [23] |
| 15 |   | Not possible to model as only 2D software is available | [13] |
| 16 |   |  | [71, 72] |
| 17 |   |  | [10, 18, 60, 65, 66, 73, 74] |

Table 1: Continued.

| | Type of electrode | Model | Ref. |
|---|---|---|---|
| 18 |   | This cannot easily be modelled as the field is created by the arc between the electrodes as well as from the electrodes themselves. The voltage is also AC, and while this can be modelled, it is not easily viewed. | [71] |

Key




## 2. Electrodes Used and the Field Produced

Many of the effects are attributed to the aerodynamic affects caused by the ionic wind [3, 5, 6, 10, 11, 13, 31, 44, 48–54]. Therefore as the ionic wind is dependant on the orientation of the electrodes, this orientation is very significant. Also, if the field is not uniform, then the ionic wind will not be produced uniformly across the field. This effect could be used to magnify the affect in certain areas once the effects are properly understood. However, the diversity of apparatus tends to make understanding this topic more difficult as the results cannot be compared.

Currently a full schematic for ionic reactions is not currently available; however, there has been extensive work conducted to try and create a full model by Pedersen [41], Pedersen and Brown [42], Hu et al. [44, 55], Yuan et al. [17], Saito et al. [20], Jones et al. [56], and Smook et al. [57].

In some papers, particularly the older ones, the type and orientation of the electrodes is not even stated; so the conclusions drawn could be very unreliable. Here in after is a table to show the reader the scale of the problem and demonstrate the wide variety of experimental apparatus used(Table 1 ).

The results show that there are several field generation methods that provide an even field with little variation (1, 16, 17). Most notably there are several fields that do not produce a field at all in the flame region (numbers 7, 8, 10, and 14). Consequently, the results from these tests may therefore not provide reliable results.

The results can be more easily compared if the field strength is plotted against the distance from the burner exit (Figure 5). All the results are plotted along a vertical line from the burner mouth to the upper electrode at 60 mm, along the axis of symmetry. Only number 6 cannot be plotted in this way as there is a wire acting as the ground electrode along the axis of symmetry. The most uniform fields should appear as a flat horizontal line of the highest possible field strength. Large variations as mentioned previously are undesirable in this case.

The results cannot all be plotted on the same scale as the peaks for the wire and ring reach 3500 MV but the main field strengths do not generally exceed 1.8 MV (see Figure 5). Therefore only the largest peak would be seen on a graph which plots this peak and the other apparatus would not even show on the bottom of the graph. Therefore the top of the peaks has been missed off the top of the graphs to show the main area of interest not the peak field strength (Figures 5 and 6).

Clearly the most uniform fields also have the lowest maximum value of field strength (Figure 6). Numbers 1, 11, and 16 produce the most uniform fields. However the largest field strength possible is also desirable. This means that numbers 1 and 11 are better than 16. The centre line of 16 shows an even plot but the field is less uniform towards the outside of the flame region. The direction of the field is also important as this will govern the direction of the ionic wind. Number 1 produces a field that will create an ionic

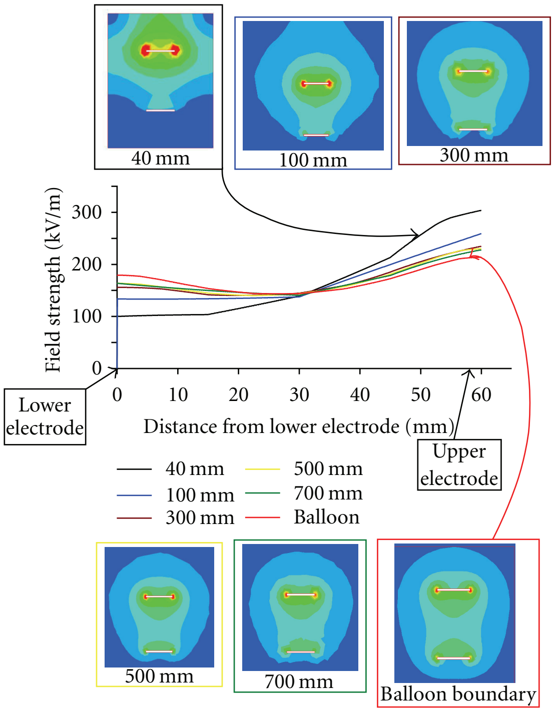



FIGURE 1: Graph to show the affect of altering the distance between the Faraday cage and the electrodes.

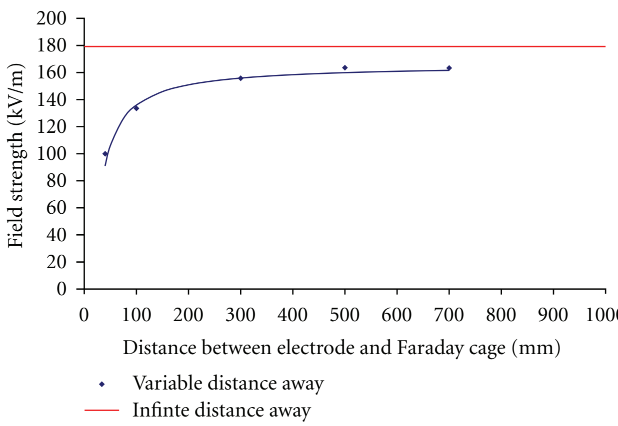



FIGURE 2: Graph to show the affect on the field strength (0.2 mm above the bottom electrode) by altering the distance between faraday cage and apparatus.

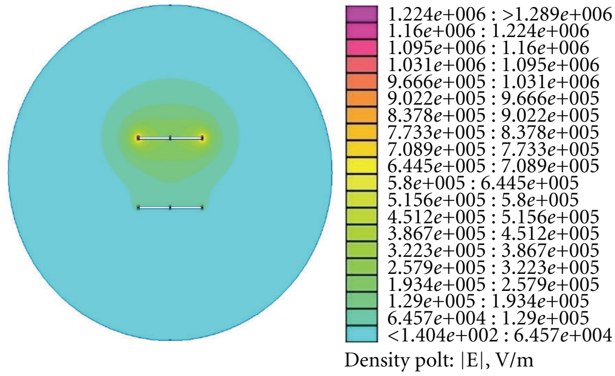



FIGURE 3: Field produced by FEMM balloon boundary.

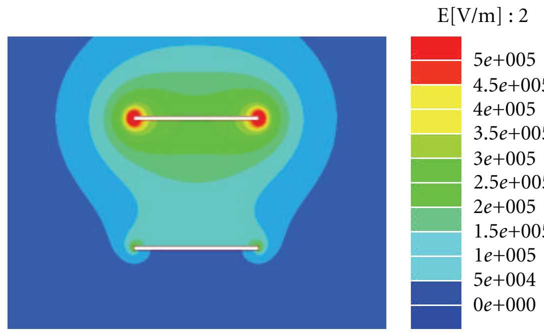



FIGURE 4: Field produced by Maxwell with a balloon boundary.

wind parallel to the flow whereas number 11 produces an ionic wind that is transverse to the flow.

The figures above also indicate how the choice of geometry can increase the maximum field strength by over 6 orders of magnitude from the estimated average field strength (shown approximately by numbers 1, 11, and 16). This maximum in the flame region could create a much greater ionic wind affect. The problem is that this ionic wind will significantly move the flame and may pull it out of the region where the affect is greatest. The results are very useful for those using AC or pulsed fields where the ionic wind is not significant. The affects observed in these fields could be greatly multiplied by choosing an electrode that concentrates the field into the flame region. This can be considered to be the first 30 mm from the burner mouth for the majority experiments in the literature.

Figure 8 shows that it is very difficult to increase the field strength over the entire flame region. The only significant enhancement on the parallel plates (vertical 1 or transverse 11) is those experiments conducted in a microgravity environment (number 9). This apparatus, however, is very expensive to use and not easily available. It is also not suitable for standard combustion systems.

The ring and burner apparatus (number 2) also gives much higher field strengths for the first 10 mm but then drops below the more uniform fields and even reaches 0 at 25 mm above the burner. The presence of the flame may however increase this region.

*2.1. Affect of the Upper Electrode.* There was some speculation in the literature [6, 11] as to whether the geometry of the upper electrode made much difference to the field setup. It was found experimentally that it did not cause any measurable difference to the flame modifications caused. The models of the two cases are shown in Figure 9.

The results show similar trends near to the burner mouth but the plate produces a more uniform field at the top. This change near to the upper electrode is unlikely to affect the experimental results significantly as the flame would tend to be positioned below this area. With the plate the maximum field strength is lower ($4.58 \times 10^6$ with plate and $7.89 \times 10^6$ with a ring).

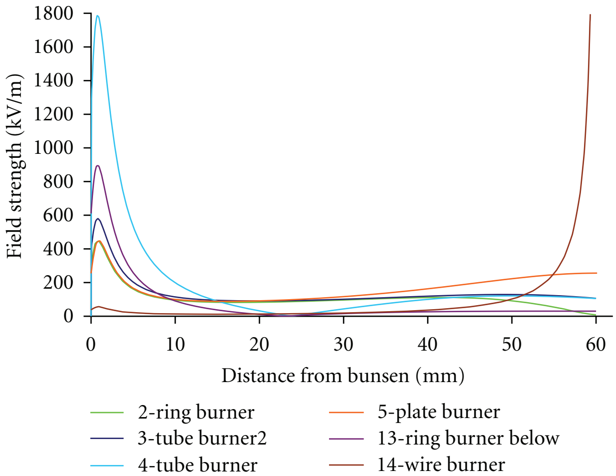



Figure 5: Field strength versus distance from the burner for medium field strengths.

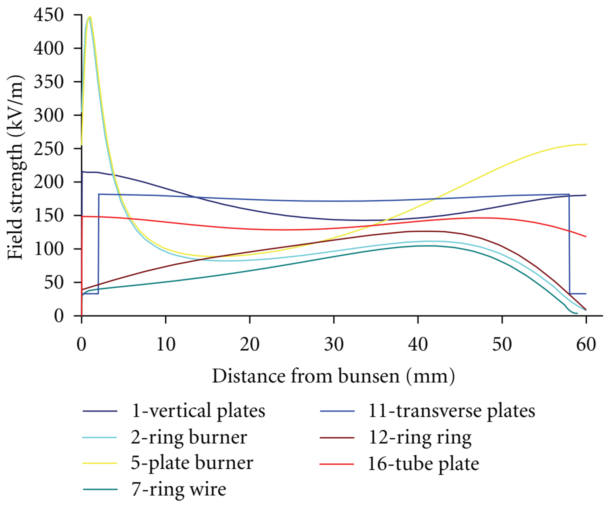



Figure 6: Field strength versus distance from the burner for small field strengths.

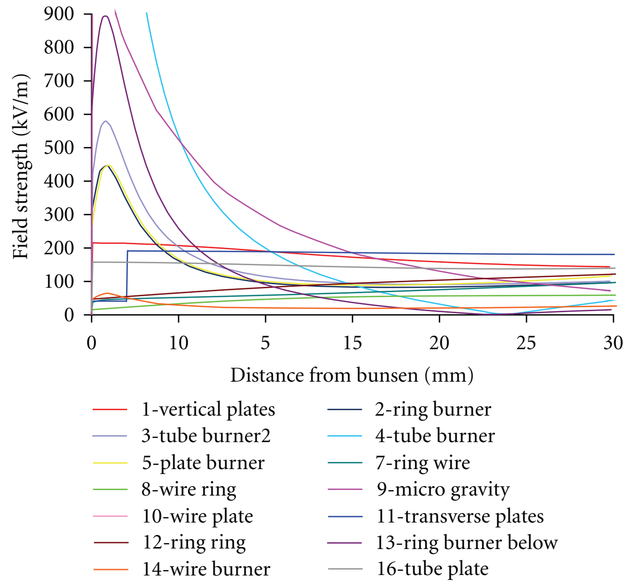



Figure 7: Enlargement of flame region.

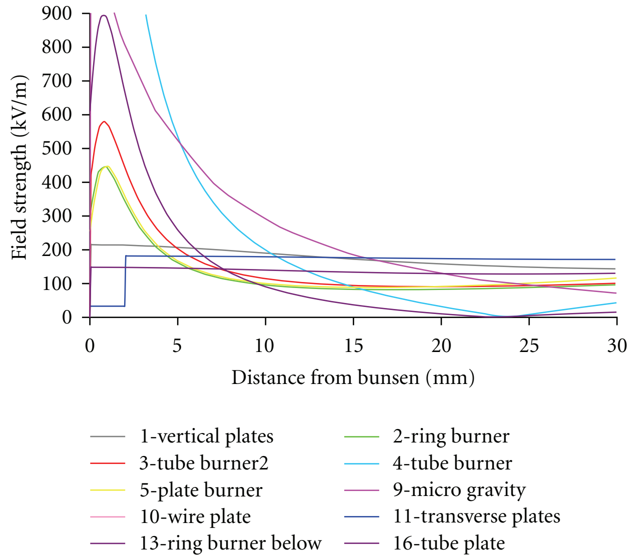



Figure 8: Enlargement of flame region with selected data removed.

The results for a comparison between a tube and a plate as the upper electrodes show similar results to the previous comparison (see Figure 10).

As before the lower section near the burner is very similar. However, in the vicinity of the upper electrode the field between the two sets of apparatus is very different. The results from this do show a slight expansion of the higher field strength region close to the burner mouth. These results can be plotted on a graph to show the field strength along the centre line of the model (Figure 11).

The experimental data tested a ring (number 2) and a mesh (number 5) as the upper electrodes. The modelling results (Figure 11) show that these two experimental apparatus produce almost identical fields.

The large peak of number 14 has been ignored for this discussion as a corona will be formed in this region. The experimental data also did not include the affect of coronas [6, 11].

The largest peak (number 4) was not also included in the experimental data. Although Figure 11 shows that the peak voltage varies by an order of magnitude, this is only in the first 5 to 10 mm. The presence of the flame will also change; this meaning that there is no way to plot this as the flame covers a significant part of the plotted axis.

In conclusion, the modelling correlates with the experimental results. The field in the combustion region is not significantly affected by different types of upper electrode but mainly by the lower electrode. This is logical as the major factor in the local production of a field is the geometry of the electrode nearest to it. In the case of a metal burner being used as an electrode, the field in the vicinity of the flame will be mainly governed by the burner geometry not the upper electrode, as long as no corona is formed. This does not,

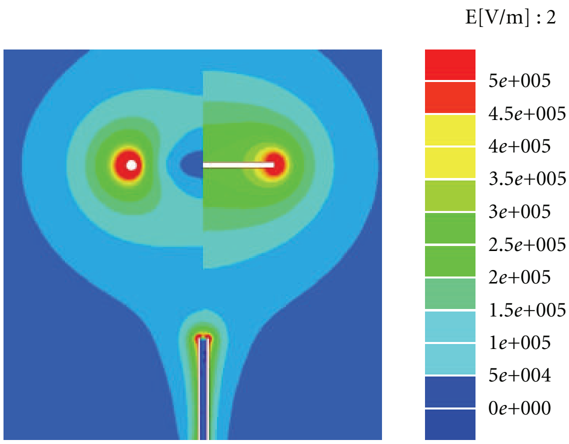



Figure 9: Comparison of plate and ring.

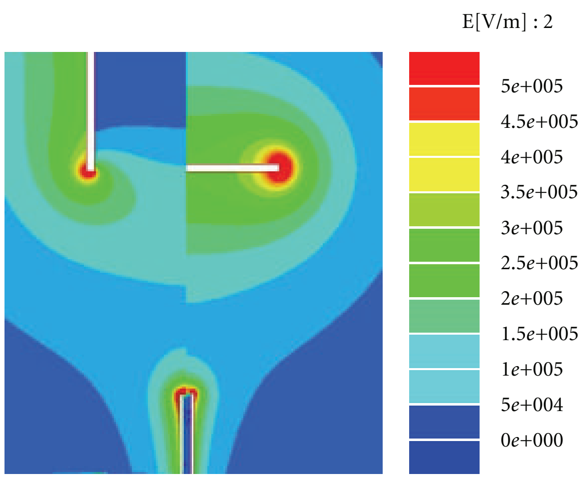



Figure 10: Comparison of tube and plate.

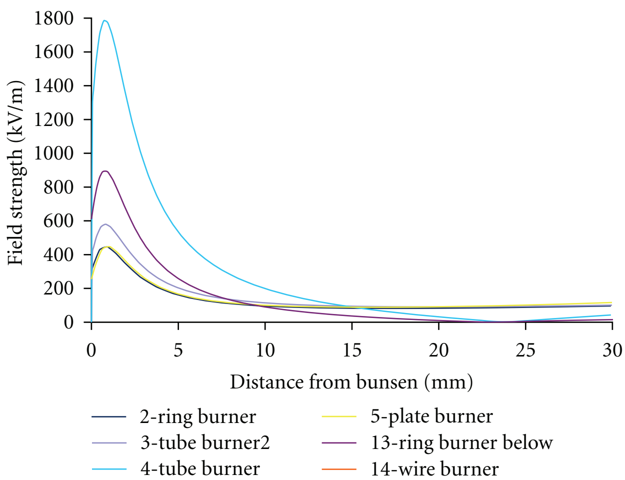



Figure 11: Affect of variations to the upper electrode.

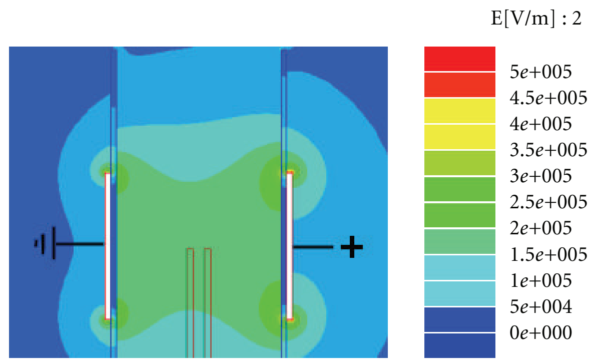



Figure 12: Ceramic burner.

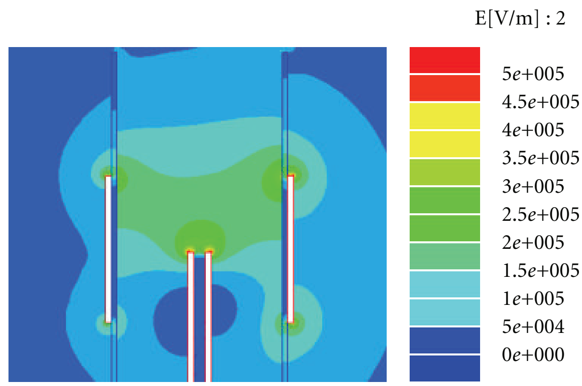



Figure 13: Metal burner.

however, mean that it is suitable to use any type of geometry as any imperfections in the burner mouth could lead to local changes in the field. It is far better to try and achieve a more uniform field that is easier to reproduce between researchers.

*2.2. Burner Material.* In preliminary experiments with fields perpendicular to the flame, it was found that a metal burner body could shield a flame from some of the affects that would otherwise be observed. Figure 12 is a model of a transverse field with a nonmetallic burner. In Figures 13 and 14 the significant change to the field can be observed with a metal burner instead of a ceramic one.

The metal burner created a high field strength spike from the sharp corners. It also shields the incoming gasses from the field around the burner mouth. This seems consistent with the experimental data. It was attempted to extinguish the flame but extinction was not possible (even at very high field strengths) as the flame decreased in size until it was only present at the very tip of the burner. At this point the burner shielded the flame from the field, as shown previously.

*2.3. Cutting a Hole in the Plate.* It would be expected that geometries that are smoother will produce a more uniform field. In the literature the most recommended set-up to produce a uniform field is parallel plates (see number 1). The field only varies by 10–20%, which is small compared to many of the other fields that vary by 100% over the flame

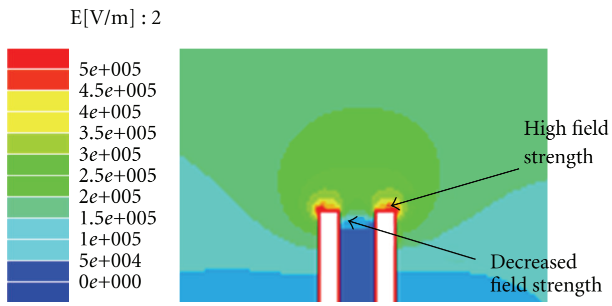



Figure 14: Enlargement of Figure 13.

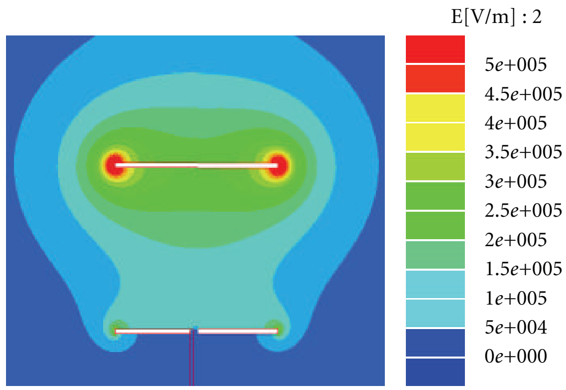



Figure 15: Comparison of bottom plates with (right) and without (left) a hole cut in.

area. However, this set up could not be used practically as there is no hole for the burner to protrude through. A mesh could be used with the burner below it but it was found experimentally that this disturbed the flow, often causing the flame to split into 2 or even 3 smaller flames as it passed through the mesh. This effect was amplified when a field was applied. There were even occasions when the flame jumped off the burner and settled on the mesh. While this provided a stable flame it was considered undesirable as the equivalence ratio could not be calculated as extra air was entrained into the flame from under the mesh.

Figure 15 shows the effect of cutting a hole in the bottom plate to allow the burner to fit through. The results show that the affect on the field is not significant. This was considered the best experimental set-up for analysis for the analysis of how an electric field influences a flame.

The field strength along the centre line of the plot can be shown for both results. This can be seen in Figure 16.

The results from Figures 16 and 17 show that the affect on the field strength is only significant in the first 1-2 mm above the burner. Therefore cutting a hole in the bottom plate to allow the burner to protrude does not significantly alter the field characteristics.

Aerodynamically the bottom plate being made of a solid sheet will have an affect as additional air cannot be entrained from directly below. However, this affect should be small. The greater affect is from the electrode above the flame. If this was made from a solid sheet, the flow would be significantly

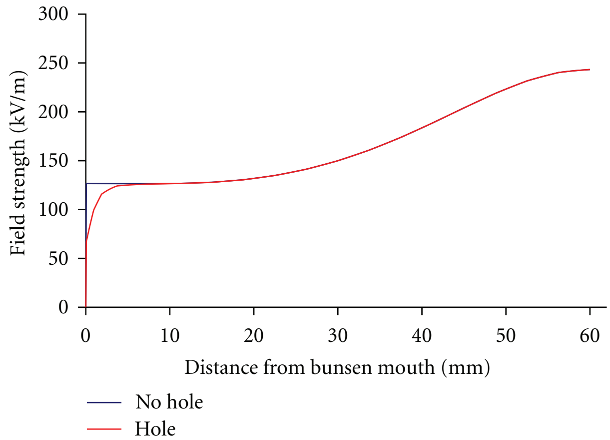



Figure 16: Comparison of the field strength with and without a hole in the bottom plate.

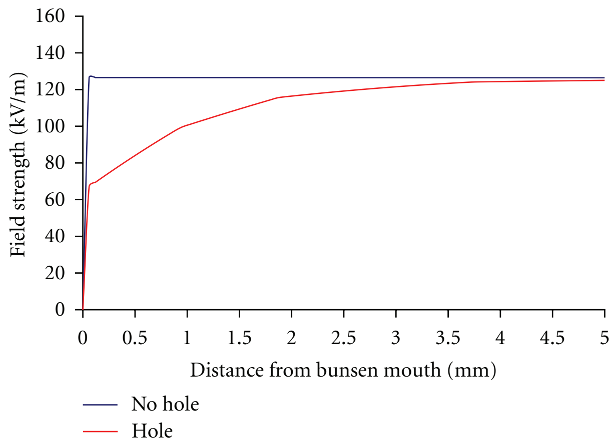



Figure 17: Enlargement of Figure 16.

altered. The best option was to use a mesh to avoid this aerodynamic disturbance (as well as heat being reflected back into the flame region).

## 3. Conclusions

In conclusion, results from many of the experiments in the literature cannot be compared as the field they have used is very different. Parallel plates produce the most uniform field.

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