Monitoring Flame Position and Stability in Combustion Cans Using ECT

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Abstract *- It is well known that flames are rich in charged particles, ions and free electrons and such electrical activity will modify the permittivity and conductivity of the reaction zone. Work at UMIST over the past decade has led to the development of sensitive circuitry to detect such electrical changes within an enclosed volume. A commercially available electrical capacitance tomography (ECT) system, based on a switched capacitor circuit, was used in the investigations reported in this paper. Although nominally a capacitance measuring circuit, e.g. monitoring changes in permittivity, the ECT system also responds to changes in conductivity. In flames, the latter is normally the dominant effect.*

The ECT system has been connected to six electrodes inside a sealed combustion chamber, and used to monitor laminar methane/air flame propagation. The results were encouraging but inferior in spatial and temporal resolution to those obtained using high-speed Schlieren photography. A new (open) combustion can has been built, which has 12 electrodes, thus giving better spatial resolution. The new model is aimed at jet engine combustion studies. Here two factors are of particular importance:

1. Is the flame centrally located?
and 2. Is the flame stable?

The sensitivity of the ECT system increases rapidly as the flame approaches the electrodes and can thus be expected to highlight the two factors noted above.

Keywords: Electrical Capacitance Tomography, Combustion

1. INTRODUCTION

Traditionally, combustion processes have been monitored by optical means, using such techniques as Schlieren, shadow, interferometric, holographic and LIF. For flame visualisation, high quality optical access to the area of interest is required and combustion laboratories round the world have shown great ingenuity to obtain this access.

When fuel is burnt, a large number of charged particles, ions and free electrons are generated. These will modify both the permittivity and conductivity of the reaction zone; in general the latter effect dominating. The commercially available ECT system is nominally a design for measuring changes in capacitance, linked to permittivity. However, inspection of the front-end circuitry reveals that the circuit will also respond to changes in conductivity. In practice, the ECT system has yielded encouraging results when used in combustion studies.

The ECT system has the major advantage of not requiring optical access and uses passive, non-invasive electrodes. The sensor can be incorporated into the combustion chamber in such a way that it could be developed for routine commercial use.

2. EARLIER WORK

Analysis of the charge/discharge circuitry, used in the standard ECT system, show that it responds, not only to the change in capacitance but also the change in conductivity. Thus, when applied to flames, the system will produce an output dependent on the modulus of the impedance of the volume of interest. The situation is further complicated by the fact that the flame is not in direct contact with both electrodes used in the measurement. Typically, the flame will be spaced away from both electrodes. Thus there is a complex relationship between the measured impedance and the actual impedance of the flame [1].

One of the first experiments undertaken was to burn a gas flame between two capacitor plates connected to ECT electronics. Measurement of the gas flow and the 'capacitance' reading indicated a linear relationship between the two [2]. Thus the evidence from practical experiments was that an ECT system would produce data from which a flame image could be reconstructed.

Initial experiments were carried out in an open metal cylinder with six short electrodes mounted below the rim at one end. The cylinder was approximately the size of a cylinder in the engine of a family car [3] . Measurements between the electrodes allowed a coarse image of a Bunsen-burner flame to be tracked as it was moved around the cylinder or from side to side. If the flame touched the electrode, enabling direct electrical contact to be made, then the reconstructed image was seen to flare and cover a larger area than viewed by direct eye-observation.

Subsequently a closed metal cylinder, once again with six electrodes, was constructed. This cylinder had a gas-injection port, pressure transducer, spark electrode and optical windows at either end. The volume was filled with a methane/air mixture and ignited by a spark. The laminar flame development was monitored by the pressure transducer, the ECT system and a Schlieren optical system, with a high-speed drum camera.

The ECT system was able to observe the initial spark, (but not resolve its location) and to monitor, via crude images, the flame development and subsequent decay. With only six electrodes to interrogate, 15 independent measurements can be taken for each frame. The maximum frame rate was approximately 300 per second.

The Schlieren optical system yielded high quality images of the developing flame, although it missed the initialising spark. Frame rates of up to 10000 frames per second are routinely available from the high-speed ciné camera [4].

The initial trials were aimed at applying ECT to the study of internal combustion engines. However, more traditional techniques, such as Schlieren optics recorded on high-speed ciné film have a clear advantage in terms of spatial and temporal resolution. Nevertheless, ECT, because of its robust non-invasive electrodes, holds potential for future developments.

3. RECENT DEVELOPMENTS

Jet engines are fewer in number than internal combustion engines, but higher in cost. Interest from the manufacturers has prompted an investigation into applying ECT to the combustion can. Several factors need to be monitored in respect of the flame:

1. size
2. location
3. stability

One can envisage ECT electrodes fitted inside a combustion can and monitoring these factors permanently. ECT has the potential for performing the above measurement conveniently, and on a long-term basis.

To further the investigation, an open ended steel cylinder was fitted with twelve electrodes, as shown in figure 1. The cylinder is 150 mm in diameter and 200 mm high. The electrodes are 100 mm long and are located centrally along the cylinder. The electrodes are made from brass, which is electrically insulated from the cylinder wall with a thin sheet of PTFE. The electrodes are separated by 6.5 mm and in this gap a 3 mm $\times$ 3 mm steel guard is fitted, in an attempt to reduce the standing capacitance between adjacent electrodes. Such radial guards should reduce the tendency for the signal to flare, as noticed during the earlier trials, when the flame touches the electrodes.

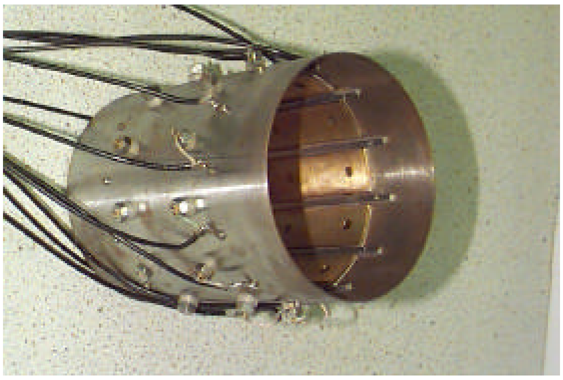

Figure 1: Model combustion can

If driven guards had been fitted above and below the sensing electrodes, then the latter could have been much shorter, giving better axial resolution. However, axial resolution is not an important factor in this investigation and the increased number of wires required when driven guards are employed was considered to outweigh the possible advantage.

4. TESTS WITH THE COMBUSTION CAN

Before the tests started, the sensor sensitivity was calibrated empty and then full of plastic beads, to provide the zero and 100% measurement points. The first test consisted of inserting the flame from a Bunsen burner inside the can. The flame was moved around inside the can and the reconstructed image displayed in pseudo-colour on a monitor. The images tracked the flame movements in real-time in a satisfactory manner. It was particularly noted that when the flame touched one or a pair of electrodes that the image did not flare out to an unrealistic size.

After the first, single burner test, six small burners were mounted on a plate, giving a flame ring diameter of approximately 65 mm. The system was unable to resolve the flames individually and the image consisted of one large flame.

Subsequently, the number of burners was reduced to three, as shown in figure 2 and the system was able to resolve the three separate flames, as shown in figure 3. An attempt was made to insulate the surface of the electrodes by painting them with sodium silicate. This was found to be unhelpful.

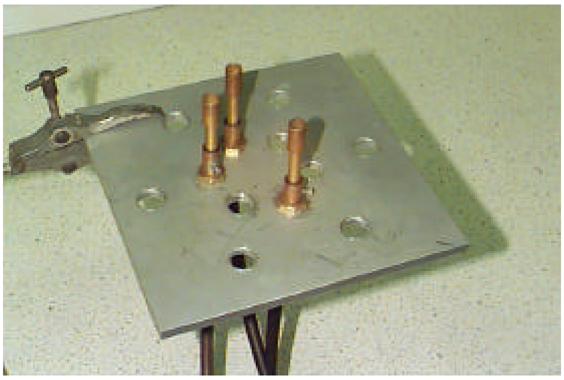

Figure 2: Three burner array

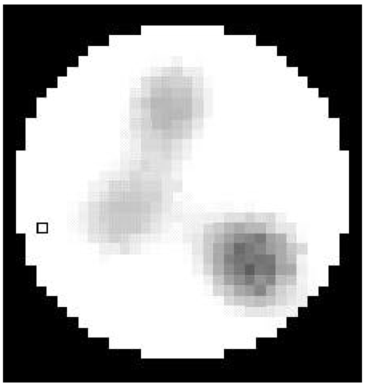

Figure 3: Three burner reconstructed image

5. COMMENT

The existing charge/discharge circuit used in the ECT system has been shown to give a good response to flames, although the contribution from the permittivity and conductivity components is unclear.

Ideally, we would wish to calibrate the sensor at zero and 100%, with no flame and full of flame. It is impractical to achieve this and so the 100% datum point is provided by filling the can with plastic beads. The software provided with the ECT system is able to use the non-ideal calibration procedure to provide good quality flame images.

Using twelve electrodes yields 66 independent measurements, more than four times that obtainable from the six electrode systems (15 measurements). More measurements gives higher resolution and clear images of three flames were obtained, compared to the earlier very coarse images. The better resolution is achieved with an accompanying loss of frame rate. As the electrodes are on the periphery of the combustion can, the system sensitivity is much higher to changes, flames in this case, near the wall. In the case of a jet combustion chamber, improved sensitivity as the flame approaches the wall is a potentially valuable feature.

6. SCOPE FOR FURTHER WORK

Currently, the link between flame temperature and ECT output has not been investigated. It is assumed that raising temperature will produce more electrical activity, thus larger signals. So far, the only observed effect has been on the increase in dielectric constant with temperature of the machineable ceramic used to support and insulate the electrodes. Monitoring and control of flame temperature is an important factor in pollution control measures.

The electrodes used in the experiments described above were bare metal, aluminium or brass. An attempt to insulate the surface via a thin protective layer did not produce beneficial results. However, the idea of electrodes coated with a thin insulating layer is thought to be advantageous. A new set of electrodes is to be prepared which will be coated with a thin layer of aluminium oxide, deposited on the metal via a plasma torch. This layer will provide insulation on the front and back of the electrode.

The current ECT system gives an output dependent on the capacitive and resistive path between the electrodes. Although in theory, these two components can be resolved in the charge/discharge circuitry, this course is not practical. However, new excitation signals, based, not on square wave switching but digitally synthesised sine waves, offers the possibility of separating the real and imaginary components. This additional information about the electrical nature of the flame will yield useful data on the combustion process being monitored.

The digitally synthesised sine wave generator, coupled with modern digital signal processing chips affords the opportunity to produce variable or multi-frequency excitation. Such techniques offer the possibility of elucidating the make-up of the flame in the form of various size ions etc.

7. CONCLUSION

The current ECT system generates images of adequate resolution for viewing the location of a jet flame within a combustion can. The electrodes and associated wiring are of sufficient ruggedness and simplicity to be built in to a practical combustion can and the time resolution of a few milliseconds is sufficient for the monitoring and control of a jet engine. Developments in hand to improve spatial and temporal resolution, plus developments to yield temperature information and concentration of various ions will make the general technique even more useful for the monitoring and control of jet engines.

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