Flame Imaging Using 3-D Electrical Capacitance Tomography

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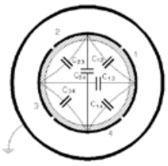
1 Introduction

Combustion processes have been traditionally monitored by optical means, using such techniques as Schlieren, shadow, interferometric, holographic or LIF ones. For flame visualization, high quality optical access to the area of interest is required. However, utilization of the above in industrial conditions is difficult. Combustion laboratories all over the world look for new techniques of visualization of flame. One of them is the Electrical Capacitance Tomography (ECT).

The basic idea of ECT is to measure changes in the electrical capacitances between all possible combinations of electrodes that occur when a dielectric material is introduced into the measurement space. These inter-electrode capacitance changes are caused by variations in the permittivity of the material inside the vessel:



$$C_{ij} = \varepsilon_0 \varepsilon_r \frac{A}{d},$$

Figure 1. Schematic of the sensor for 2-D ECT. (where: C_{ij} – the capacitance between electrodes i and j; A – the area of each plane electrode; d – the distance between the electrodes; ε_0 – the permittivity of free space; ε_r – the dielectric constant or relative permittivity of the insulator used)

An ECT system has three main units: sensor, sensing electronics and a computer.

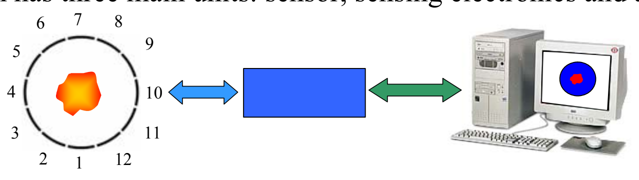


Figure 2. Schematic of Electrical Capacitance Tomography system.

The sensor consists of a set of electrodes symmetrically mounted around the measurement space. The sensing electronics measure the capacitances for all possible electrode combinations (for 12 electrodes system: 1-2, 1-3, .., 1-12, 2-3, 3-4, .., 3-12, 3-4, 3-5,.., 11-12). The computer system has two major functions. Firstly it controls the measurement operations performed by the sensing electronics, and secondly, it uses the measurement data to reconstruct tomographic images, presentation and interpretation.

2 2-D reconstruction of diffusion flame

At present, the main aim of Capacitance Tomography is to obtain the images of permittivity distribution in gas-flow flow systems, a dense pneumatic conveying system or a bubbling fluidization [1][2][3]. But experimental studies have been carried out showing that this method can be applied to visualization of some types of combustion processes, especially stationary flames [4][5].

When fuel is burnt, a large number of charged particles, ions and free electrons are generated. The above charged particles may be formed as a result of chemical reactions, which are called chemi-ionization and thermal ionization [6]. They will modify both the permittivity and conductivity of the reaction zone. So, the ECT is based on measurements of a variation of electrical properties of the flame, such as electrical permittivity and conductivity of the reaction zone. Signal level depends on the concentrations of various kinds of charged particles present during the combustions.

The method commonly used to obtain ECT images from capacitance measurements is the Linear Back-Projection (LBP) algorithm, which produces relatively low-accuracy images. For improving the accuracy of LBP images a simple iterative image computation method – ILBP (Iterative Linear Back Projection) is used [7].

Tomographic techniques have been widely accepted as a valuable tool for the process control and monitoring. The conventional tomographic approach is to reconstruct a 2D image of a process cross section. In this case, only one plane row electrodes with usually 12 or 16 electrodes is used.

The first test consisted in inserting the flame from a Bunsen burner inside the can. The flame was moved inside the can and the reconstructed image displayed in a pseudo-colour in a monitor. The images tracked the flame movements in real-time was a satisfactory manner. An image sequence of combustion process is shown on Fig. 3.

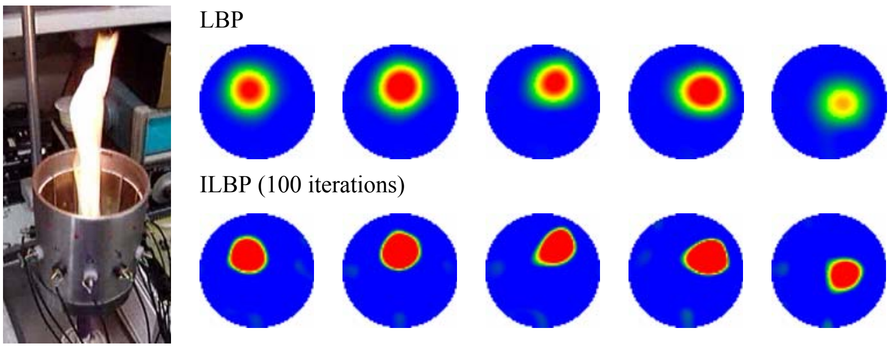


Figure 3. 2-D reconstructed images of a single flame inside the model cylinder can (12 electrodes).

Appropriate selection of electrodes geometry and reconstruction method help to obtain detailed structure of scanned flame – „ring like" structure of diffusion flame.

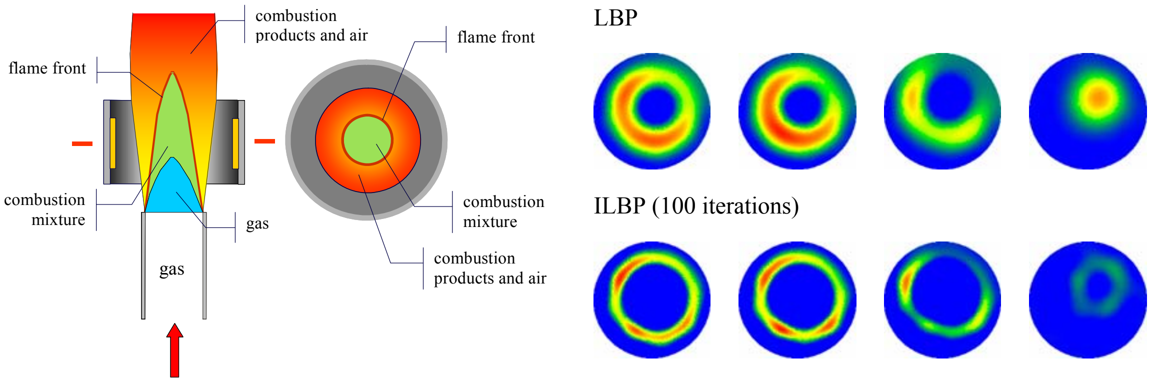


Figure 4. 2-D reconstruction of stationary diffusion flame

3 3-D reconstruction of diffusion flame.

In the case of 3D capacitance tomography, the basic structure of the sensors and the measurement concept are the same as in 2D tomography. The difference lies in their layout. In 2D capacitance tomography, with its planar layout of electrodes, some inhomogeneities (i.e. objects) cannot be distinguished and properly located in 3D space. In the case of 2D or 2.5D capacitance tomography, the measurements are made only for one or some cross sections. In the 3D capacitance tomography approach, the measurements are also performed between electrodes from different layers and therefore any inhomogeneity will certainly affect the measurement values and will be distinguished in the final image.

To demonstrate true 3D image reconstruction, three-plane ECT sensors with 18 electrodes (6 electrodes in each plane and 3 rows of electrodes) were designed and made, as shown in Figure 5.

Figure 5. The cylinders with the 3D ECT sensors (18 electrodes)

The preliminary research of reconstruction of the diffusion flame images were carried out inside the cylindrical vessel. Different flames (gaseous flames of different combustion intensity) we recorded and reconstructed using 18 electrodes sensor. In Fig. 6. direct flame pictures are compared with the reconstructed images of flames. The flames were reconstructed using both LBP and ILBP (with 100 iterations). In the pictures, it is clearly seen that the reconstructed images (especially for ILBP) property approximate real flames, especially their location and size.

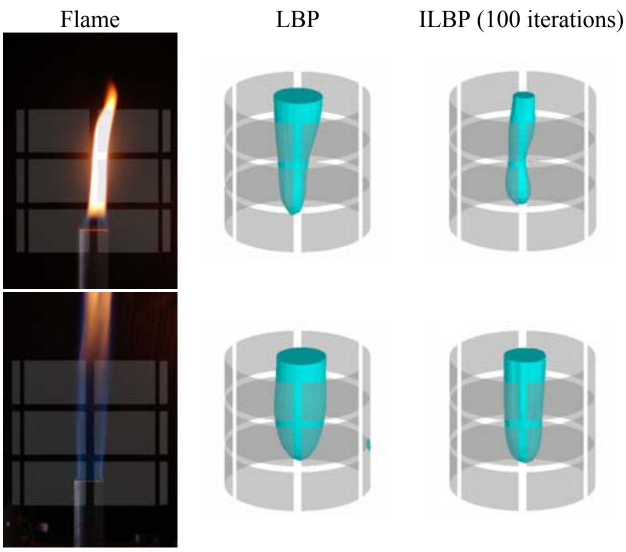


Figure 6. Reconstructed images of some flames, using 18 electrodes sensor.

The next test consisted in inserting the flame from a Bunsen burner inside the sensor. The flame was moved around inside the can and the reconstructed image was displayed as iso-surface in a monitor. An image sequence of combustion process is showing on Figure 7.

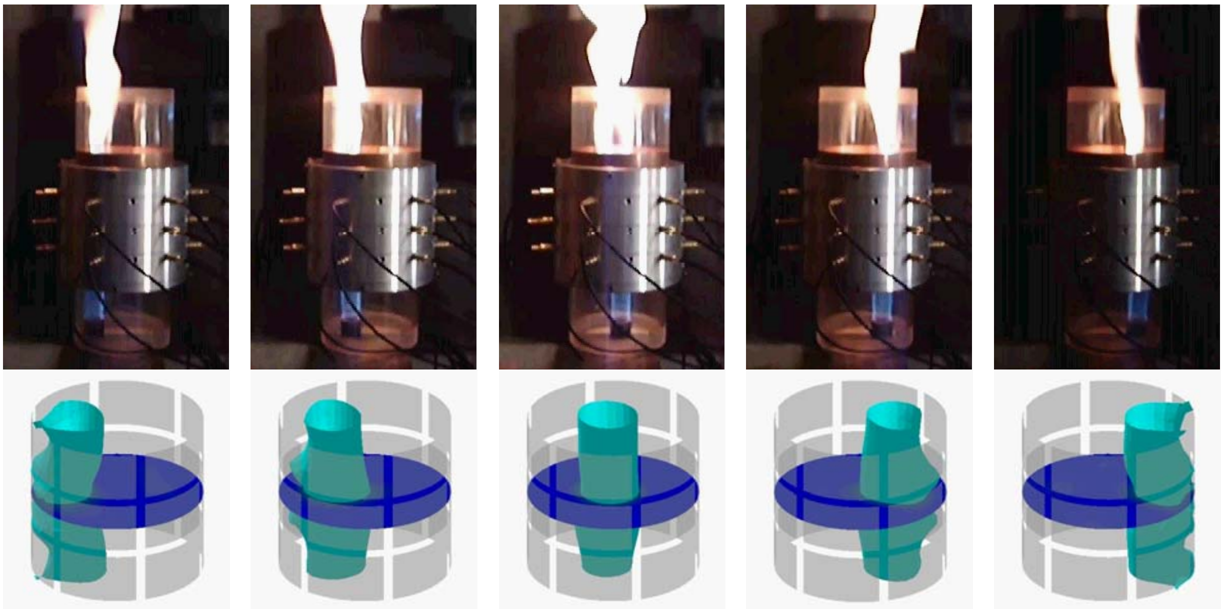


Figure 6. 3-D reconstructed images of diffusion flame, using 18 electrodes sensor.

4 Summary

Research into application of the Electrical Capacitance Tomography carried out up to now in the Laboratory of Aircraft's Engines Division of Warsaw University of Technology shows that the method is applicable to recognition of different flames. The above results can be very useful to study dynamics of flame development and could be used in a process of optimization of combustion chambers of jet engines. In contrast to the conventional visualization techniques, there is no need to apply special and very expensive optical windows. Because of low costs and simplicity, this method is very suitable for an application in real conditions as the non-invasive flame reconstruction method.

In the present study, the hardware system and software of the electrical capacitance tomography for 3D reconstruction in cylindrical chamber and section of annular chamber we developed. The flame reconstruction pictures obtained from initial experiments prove feasibility of such application in visualizing of details of flame structure inside the combustion chamber. Several cases were tested by the present system and it was found that the present system successfully determine the cross sectional images of premixed and diffusion flames.

The conducted research allows to assume that Electrical Capacitance Tomography is an excellent solution as a new method of flame diagnostics and of combustion research in real systems. The obtained results will be a good basic for an application of ECT to optimize combustion chambers of turbine engines. This will allow continuous monitoring of combustion processes in engines and verify work of the fuel supply system and combustion.

At present time, the main research was focused on proving the feasibility of the 3D system the applications for flame reconstruction. However, there is necessity to develop techniques of image reconstruction in annular chamber and to test the 3D ECT system in real engine conditions. The research will be focused on possibility of upgrading the already developed laboratory system of flame visualization to a real engine.

References

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