TRANSACTIONS OF THE INSTITUTE OF AVIATION ISSN 0509-6669
No. 4 (245), pp. 26-36, Warsaw 2016 eISSN 2300-5408
DOI: 10.5604/05096669.1226349

SELECTED APPLICATION OF ELECTRICAL CAPACITANCE TOMOGRAPHY IN MONITORING OF COMBUSTION PROCESS

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Abstract

The article describes experimental studies using Electrical Capacitance Tomography (ECT) in monitoring the combustion processes. The main goal of the study was to develop a new diagnostic method suitable for monitoring flame and the combustion process. This is motivated by the need to achieve a more precise description of the process and, ultimately, to implement efficient and reliable control and optimization methods as a key step towards the development of more efficient, flexible, reliable and clean combustion systems.

Research was carried out on different stands. For monitoring the flame, a number of burners were used, including an industrial burner WG10N. The main objective of the study was to visualize the position and structure of the flame, to determine the spatial resolution and change signal level for different flow conditions. The second part of the paper describes experimental research into combustion chamber of GTD-350 engine. On various parameters of power supply of the combustion chamber the combustion process was reconstructed. The obtained results showed that it will be a very good tool for controlling the distribution of the reaction zone, especially in the development of a new combustion chamber operated at a very high pressure, where installation of optical windows is very difficult and in many cases impossible.

Keywords: combustion process, flame, visualization, tomography.

1. INTRODUCTION

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

$$C_{ij} = \frac{1}{\phi_i - \phi_j} \int_{\Omega} \varepsilon(x,y) grad[\phi(x,y)] d\Omega \qquad (1)$$

where: C_{ij} – capacitance between the pair of electrodes i and j; $\varphi_i – \varphi_j$ – the potential difference between the source and the detecting electrode; ε(x,y) – the relative permittivity distribution in two dimensions; φ(x,y) - the potential distribution in two dimensions; Ω – a closed curve surrounding the detector electrode.

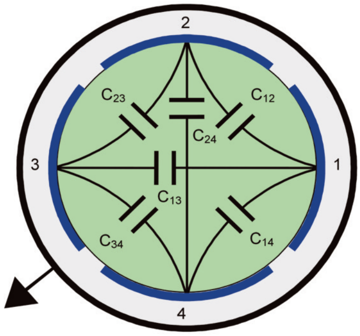

Fig. 1. Diagram of the sensor for Electrical Capacitance Tomography [Gut, 2011].

An ECT system has three main units: the sensor, sensing electronics and computer, as shown in figure 2. The sensor consists of a set of electrodes symmetrically mounted outside or inside a chamber. The sensing electronics measure the capacitances for all possible electrode combinations. The computer system has two major functions. Firstly, it controls the measurement operations performed by the sensing electronics. Secondly, it uses the measurement data to reconstruct tomographic images as well as it presents and interprets them.

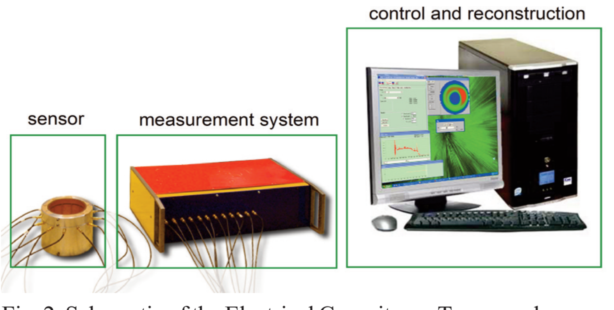

Fig. 2. Schematic of the Electrical Capacitance Tomography system [Gut, 2009].

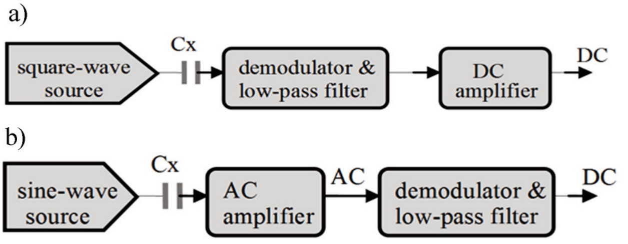

Fig. 3. Simplified block diagrams of the charge/discharge (a) and AC-based circuits (b) [Gut, 2011].

There are two most popular types of measurement circuits suitable for ECT. They are the charge/discharge circuit and the AC-based circuit. The main difference between those two types of circuits lies in the positions of the demodulators. In a charge/discharge circuit the demodulator precedes any of the signal amplification. For the AC-based circuit, the AC signal from the measured capacitance is amplified and thereafter demodulated [1].

Each of those methods has its advantages and disadvantages. The main advantage of the charge/discharge circuit is its simplicity and low cost, hence it is widely used for measuring small capacitance. The main disadvantage of the charge/discharge circuit is the fact that it suffers from the coupling capacitance of CMOS switches, which are usually several times larger than the change in the measured capacitance. The main advantage of the AC-based circuit is its low drift due to the use of AC amplifiers instead of DC amplifiers as well as its high signal-to-noise ratio. The disadvantage of this circuit is that it is complicated and expensive, especially for high frequency operations. In our case, a charge/discharge measuring circuit was developed. The measurement system can cooperate with 16 electrode sensors and allows for operation with a frequency at 50 frames/s.

The method normally used to obtain ECT images from capacitance measurements is the Linear Back Projection (LBP) algorithm, which produces relatively low-accuracy images. This algorithm is simple, fast and ideal for online reconstruction, especially for the fast process. An Iterative Linear Back Projection (ILBP) was used to improve the accuracy of the LBP images. The full description of the algorithms can be found in many publications [2,3].

Currently, the main aim of Capacitance Tomography is to obtain images of permittivity distribution in gas flow systems, a dense pneumatic conveying system or a bubbling fluidisation [4-6]. But experimental research has been carried out showing that this method can be applied to visualise different kinds of combustion processes [7,8]. As opposed to the classical applications of the ECT system, in the reconstruction of the combustion process the signal level depends on the concentrations of various kinds of charged particles present during the combustions. Possible carriers are electrons and both positive and negative ions. The charged particles may be formed as a result of chemical reactions, called chemi-ionisation and thermal ionisation. Creation of the various charged particles usually comprises of two phases. The first phase originates from chemi-ionisation in the reaction zone of the flame. The major ions in the first phase are CHO^+, H_3O^+ and $C3H3^+$. The second phase is related to high temperature and pressure in the burnt gas, which is due to thermal ionisation. The major ion in the second phase is NO^+.

2. RESEARCH ON FLAME RECONSTRUCTION

In the first experiment an open-ended duralumin cylinder was used, which was fitted with twelve electrodes. The cylinder was 100 mm in diameter and the electrodes were 80 mm long. The 12 electrodes were made from brass which was electrically insulated from the cylinder wall with a thin sheet of mica. Additionally, four burners, each with its own independent fuel supply system, were installed at the bottom of the experimental stand. The experimental stand is shown in figure 4.

Fig. 4. View of the experimental stand [Gut, 2012].

Initial experiments were focused on the possibility of a 2-D reconstruction of one Bunsen burner flame. The flame was moved around inside the can and the reconstructed image was displayed in pseudo-colour on a monitor. An image sequence of the combustion process is shown in figure 5.

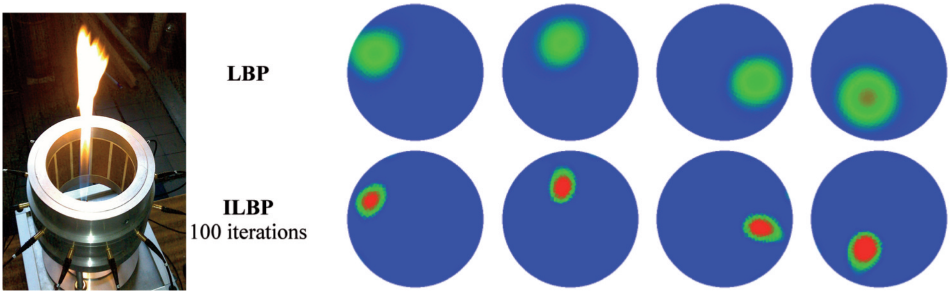

Fig. 5. Reconstructed images of a single flame inside the model cylinder can [Gut, 2012].

The reconstructed images accurately show the location and distribution of the flame inside the measuring space. In this case there was only one "object" (flame), therefore, the reconstruction was not difficult. In the next stage it was necessary to check whether the system would be able to reconstruct more flames. For that purpose, the same configuration of position two, three and four burners was used in the reconstruction.

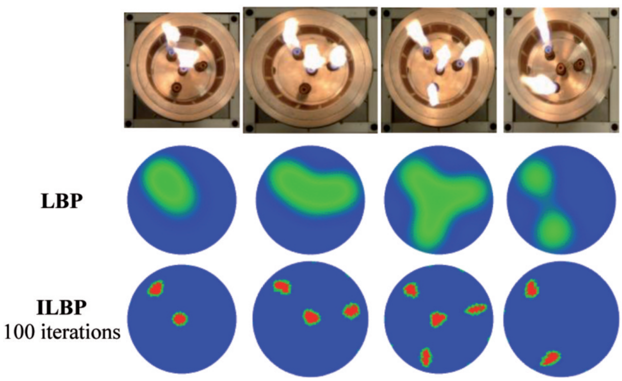

Fig. 6. Two and three burner reconstructed image [Gut, 2012].

From the description of the LBP method [6], it is clear that images produced by using this method will always be approximate. The method spreads a true image over the whole of the sensor area and consequently produces very blurred images. In this case, we do not know how many burners were used but using simple iterative techniques turned out to be helpful. Now, we can correctly define the position and the number of flames. When the ratio size of the sensor as compared to the size of the flame was considerable, the reconstruction image showed only the location and distribution of the flame. Yet, by an appropriate selection of the size of the sensor and the method of reconstruction, it was possible to obtain details of the flame structure of the premixed laminar flame. In this case, the diameter of the sensor (also the proportion length of electrodes) was reduced from 100 mm to 45 mm. In the premixed flame, three zones can be distinguished (fig. 7): zone combustion mixture, flame front and zone mixture of combustion products and air. The main zone is the reaction zone (flame front) where intense reactions of fuel oxidation take place and the intermediate and final products of combustion (including radicals) are formed. That zone is very thin and large gradients of concentration and temperature occur there. The cross section shows that the flame reaction zone is in the form of a ring.

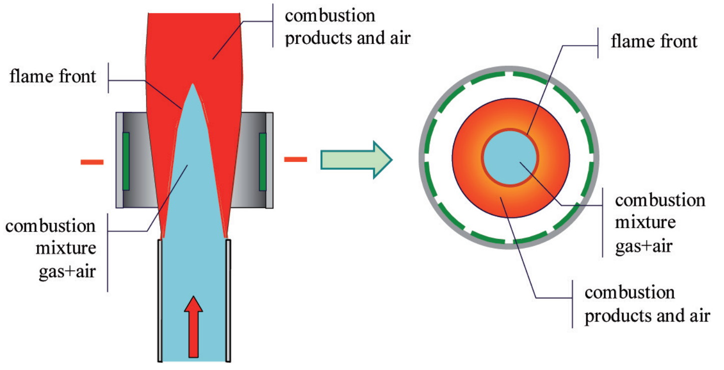

Fig. 7. Premixed laminar flame structure [Gut, 2012].

The reconstruction was divided into two stages. In the first stage, the combustion process was monitored when the flow rate of fuel (methane) was constant. After a specified period of time, the valve was closed and, as a result, the fuel gas flow decreased until the flame was extinguished. Each of those stages is illustrated in figure 8.

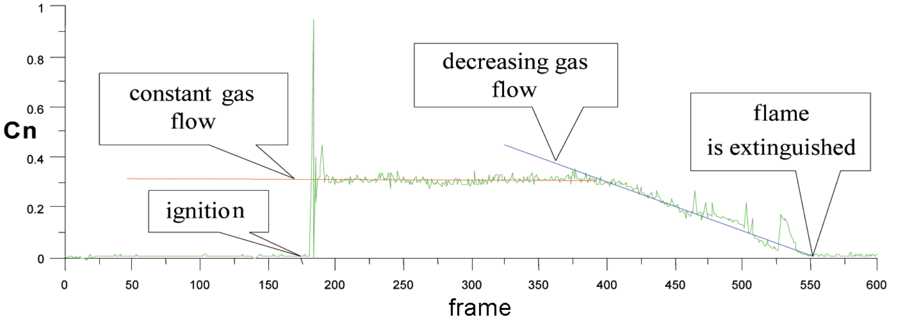

Fig. 8. Changes of mean normalised capacitance for different flame intensity [Gut, 2012].

A reconstruction of a combustion process on the basis of the collected data was reconstructed. For a few selected frames the reconstructed image is shown in figure 9.

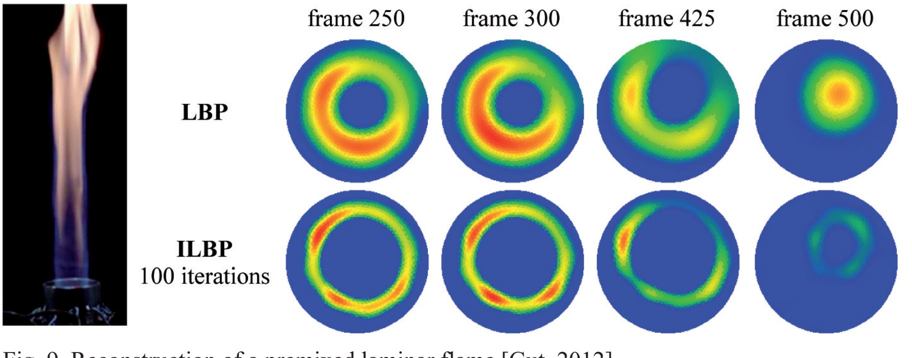

Fig. 9. Reconstruction of a premixed laminar flame [Gut, 2012].

In the 2-D image of the premixed laminar flame cross section, it can be seen that the combustion process occurred in the form of a ring. This is consistent with the previously presented diagram of the diffusion flame. Because the measurement is taken from a cross section depending on the length of the electrodes, the picture is of an average value. Obviously, a better resolution of the reaction front is imaged by the ILBP method. The spatial resolution of a tomography imaging system depends on the number of independent measurements and the fineness of sensitivity focus for each measurement. Therefore, more electrodes of a smaller size would result in a better imaging reconstruction. However, the measurement sensitivity of a capacitance is proportional to the electrode profile. As the electrode size is reduced, the signal-to-noise ratio (SNR) of the system decreases. In order to improve the SNR of the measurement, the size of the electrode can be increased, and it is limited only by installation restrictions and cost consideration. As a consequence, the electrode size must be increased and the total number of electrodes decreases. The selection of electrode dimensions is a matter of balancing between the spatial imaging resolution and SNR.

In the next stage of the research a gas burner with a variable power 12.5 - 50 kW − Weishaupt WG10N was used. Burners of this type are equipped with digital burner management which is used for setting, controlling and monitoring all burner functions. Figure 10 shows a photograph of an industrial burner and an electrode system.

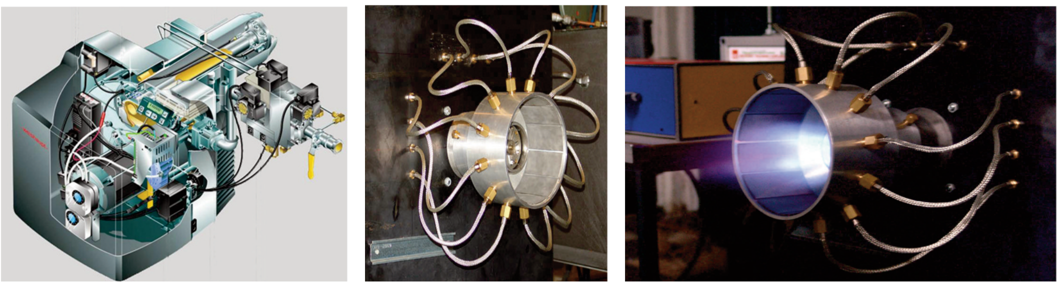

Fig. 10. View experimental stand [Gut, 2013].

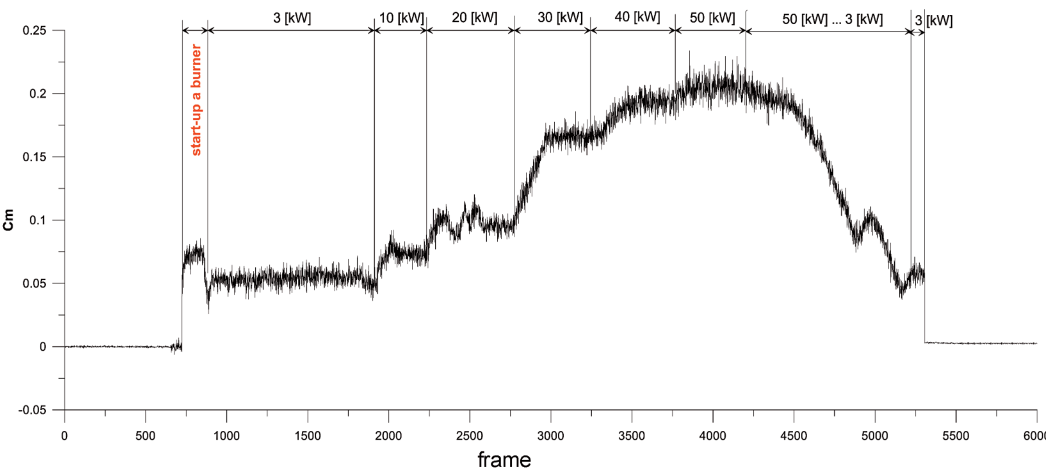

Fig. 11. Variations of mean normalized capacitance for different flame intensity [Gut, 2013].

In real operating conditions, the burner is mounted in a heat exchanger or a boiler. However, for research purposes a special clamping system of burners was designed and built. In this way, the burner was equipped with a steel plate and a mounting system to the platform. Additionally, for the burner was made a special sleeve that forms the structural base for mounting the electrodes. Due to high temperatures occurring in the space between the electrodes, a difficult problem to solve was to find appropriate cables connecting the electrodes to the measuring system. The ideal solution was to use a special heat-resistant silicone braided wire metal whose resistance temperature reaches 400°C.

In order to determine a possible system of Electrical Capacitance Tomography for a few selected power burner reconstruction of the combustion process was carried out. The tomography system registered 25 measurement frames per second; each frame consisted of 66 measurements. On the basis of the measurement data from individual pairs of electrodes a reconstruction of the combustion process was carried out. Variations of mean normalized capacitance for different flame intensity and a few selected frames the reconstructed image is shown in figure 11 and figure 12.

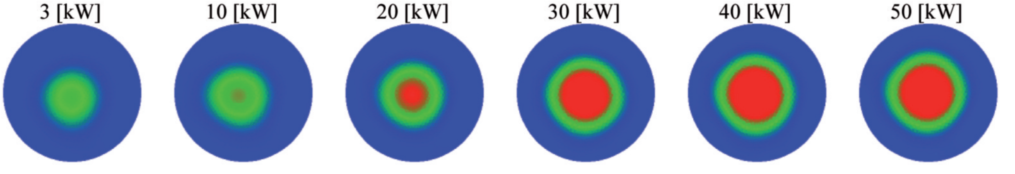

Fig. 12. Images reconstruction for different power of burner [Gut, 2013].

4. RESEARCH ON FLAME RECONSTRUCTION IN COMBUSTION CHAMBER

A possibility of real time imaging of turbulent flames was tested in more complex system. For this case, an adopted combustion chamber of GTD-350 gas turbine engine was used. Inside the combustion chamber twelve electrodes were installed. All electrodes were connected to the measurement unit. The shape and size of the electrodes were designed in such a way that they did not disturb the flow in the chamber. Tests were carried out at atmospheric pressure, so the original air system supply (from the high pressure centrifugal compressor) was replaced with a radial fan. Because the air supply system was changed also the fuel injection system was modified. All tests were performed by using liquid fuel (JET-A1). Figure 13 shows photographs of the test stand.

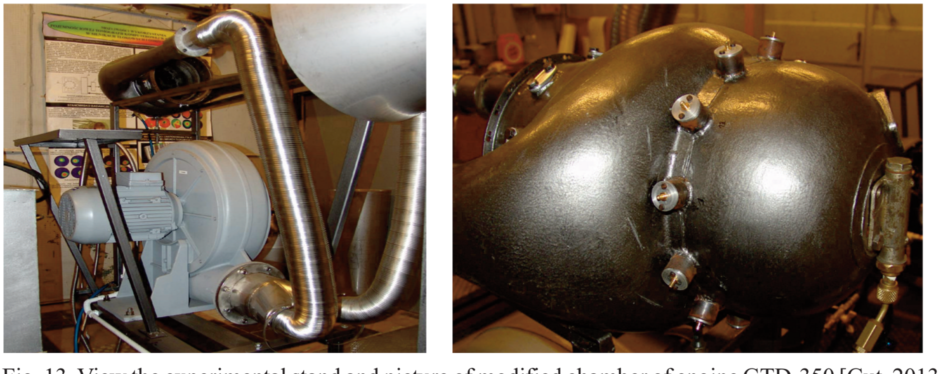

Fig. 13. View the experimental stand and picture of modified chamber of engine GTD-350 [Gut, 2013].

The first experiment was carried out to reconstruct the cross-sectional image of the turbulent combustion process inside the chamber for a "normal condition". The research was carried out for different modes of engine operation, controlling an injection dose and at a constant flow rate of air Q_{air}=0.23[kg/s]. Variations of mean normalized capacitance and reconstructed images of turbulent flames are presented in figure 14 and figure 15.

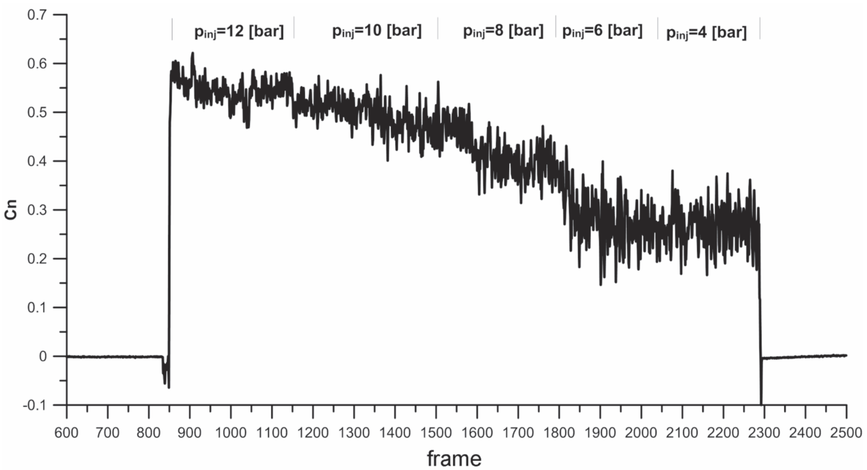

Fig. 14. Variations of mean normalized capacitance for different supply pressure of fuel [Gut, 2013].

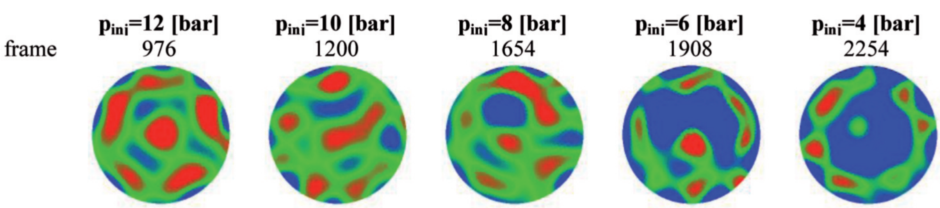

Fig. 15. Images reconstruction for different supply pressure of fuel [Gut, 2013].

One of the parameters difficult to control is the distribution of temperature inside the combustion chamber. Currently, such a system which allows for monitoring the combustion process inside the chamber does not exist. Temperature measurements of exhaust gases provide only partial information about the performance of the combustion chamber. In some conditions uncontrolled reactions may lead to fuel decomposition, which ultimately leads to carbonaceous deposit formation on the surfaces of the combustion chamber. Carbon deposits on the engine components can negatively affect the engine performance and can also block cooling holes or prompt burnout of the liner structure. It may cause a disturbance of the air supply and consequently change the distribution of temperature inside the combustion chamber. For a simulation of a non-uniform air flow to the combustion chamber, in one arm was blocked 80% of the air flow. Figure 16 shows a photograph of the modified chamber of engine GTD-350.

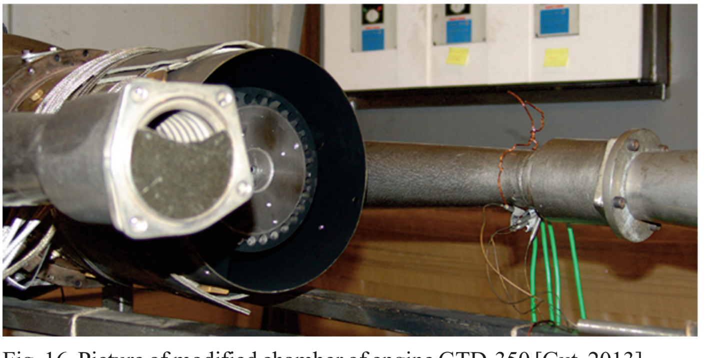

Fig. 16. Picture of modified chamber of engine GTD-350 [Gut, 2013].

In this case, the research was carried out for a different flow rate of air and at constant an injection pressure of fuel p_{inj}=10 bar. Variations of mean normalized capacitance and reconstructed images of turbulent flames for different flow rate of air are presented in figure 17 and figure 18.

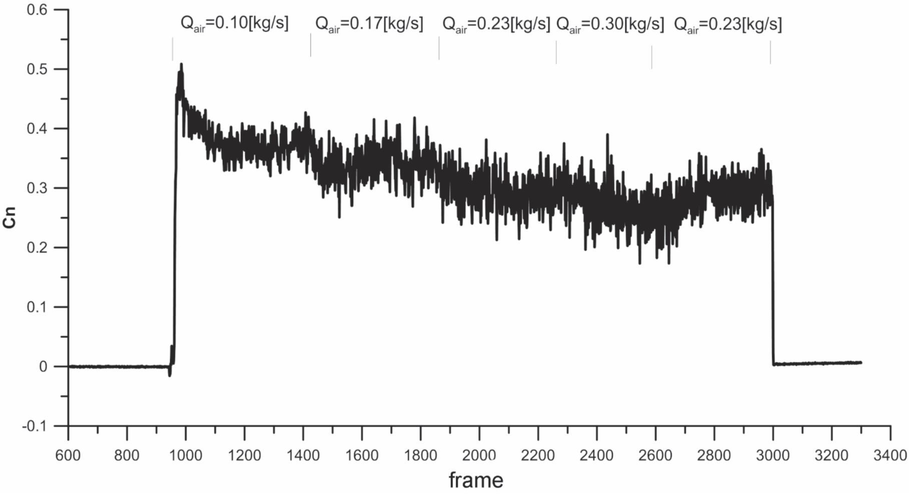

Fig. 17. Variations of mean normalized capacitance for different flow rate of air [Gut, 2013].

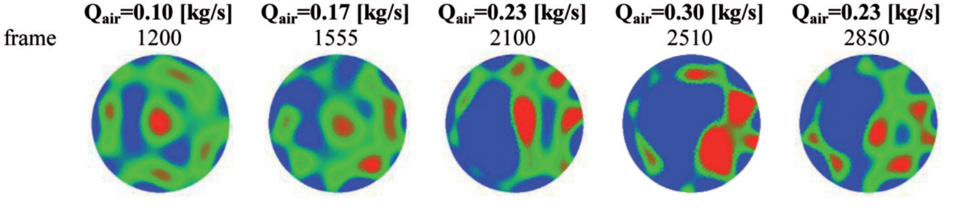

Fig. 18. Images reconstruction for different flow rate of air [Gut, 2013].

The reconstructed images show that for a low flow rate of air, the chamber modification did not have any influence on the distribution of the combustion process. For a higher flow rate we can see that combustion mainly takes place in the opposite side of the chamber.

5. SUMMARY AND CONCLUSIONS

A significant progress has been made in the last few years in ECT research at the Institute of Heat Engineering of the Warsaw University of Technology. Most research centres have focused on the use of ECT to monitor two-phase flows, whereas our main purpose has been to use the capacitance tomography system to monitor combustion processes.

The main disadvantage of this technique is its lower spatial resolution as compared to other tomographic imaging techniques or optical systems but, despite this drawback, it is a very good tool that can be used in research and diagnostics of combustion systems. This system is especially useful for monitoring the combustion process and has a major advantage over optical visualisation systems since it does not require optical access and uses passive, non-invasive electrodes. Obviously, there are many parameters affecting the concentrations of ions, e.g. temperature has a strong influence on the density of ionisation, but currently the link between flame temperature and ECT output has not been investigated.

It seems that in the future it will be possible to monitor the basic flame structure inside the turbojet combustion chamber or industrial burners. By continuously monitoring combustion, it will not only be possible to increase safety, but the system may also allow to control the combustion processes and to improve the efficiency of heating systems. It will also be a very good tool for research and in the development of new combustion chambers operated at very high pressure where the installation of optical windows is very difficult and in many cases even impossible.

Acknowledgements

This work was supported by the National Science Center, Republic of Poland: project no. UMO-2013/09/B/ST8/01735.

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WYBRANE ZASTOSOWANIA POJEMNOŚCIOWEJ TOMOGRAFII KOMPUTEROWEJ W MONITOROWANIU PROCESÓW SPALANIA

Streszczenie

W artykule opisano badania eksperymentalne z wykorzystaniem pojemnościowej tomografii komputerowej (ang. Electrical Capacitance Tomography-ECT) w monitorowaniu procesów spalania. Głównym celem badań było opracowanie nowej metody diagnostycznej odpowiedniej do monitorowania płomieni oraz procesów spalania. Jest to motywowane potrzebą uzyskania bardziej dokładnego opis samego procesu, a ostatecznie wdrożenia niezawodnych metod kontroli i optymalizacji. Jest to kluczowy krok w kierunku rozwoju bardziej wydajnych, elastycznych, niezawodnych i czystych systemów spalania.

Badania zostały przeprowadzone na różnych stoiskach badawczych. Do monitorowania płomienia zostało użytych kilka palników, w tym palnik przemysłowy WG10N. Głównym celem tych badań było zobrazowanie pozycji i struktury płomienia, określenia przestrzennej rozdzielczości i obserwacji zmian poziomu sygnału dla różnych warunków przepływu. Druga część artykułu opisuje badania doświadczalne przeprowadzone w komorze spalania silnika GTD-350. Dla różnych parametrów zasilania komory spalania zrekonstruowano przebieg procesu spalania. Uzyskane wyniki wskazują, że metoda ta będzie bardzo dobrym narzędziem do kontroli rozkładu stref reakcji w rozwoju nowych komór spalania, które pracują pod wysokim ciśnieniem, gdzie instalacja wzierników jest bardzo trudna.
Słowa kluczowe: spalanie, płomień, wizualizacja, tomografia.