

Dynamic Combustion Tomography

Tadeusz Piotrowski PhD, Andrzej Plaskowski DSc,
Instytut Przemysłu Organicznego, 03-236 Warszawa, ul. Annopol 6, tel. 811-12-31

Prof. Maurice Beck,
University of Manchester, Institute of Science and Technology,
PO Box 88, Manchester M60 1QD, UK

Mr. Malcolm Byars
Process Tomography Ltd, 86 Water Lane, Wilmslow, Cheshire SK9 5BB, UK

Abstract - *Industrial Organic Chemistry Institute, Warsaw, Poland with collaboration with UMIST and Process Tomography Ltd, UK, started to apply a capacitance process tomography to reconstruct the image of a flame propagation in the vertical, Hartmann's type, cylindrical explosion vessel during combustion of dust-air mixtures. The tomographic images of a gas flame from laboratory burner and explosive combustion of the dust-air clouds have been presented. The background of process tomography has not been described.*

Keywords: Explosion, Combustion, Process safety, Process Tomography, Capacitance Sensors.

1. INTRODUCTION

In fact up to date a simple commonly and fully developed method for monitoring and control of the formation and combustion of dust - air clouds during the experiment in the steel not transparent explosion vessel does not exist. The use of high speed cameras and especially constructed equipment is very difficult, complicated and time consuming. Combustion tomography should help to solve that problem.

An application of the tomography technology should help to obtain a image of the flame front propagation in the explosion vessel with destination to measure its velocity, to determine easily and exactly the spraying times (electromagnetic valve opening times and dust-air cloud forming times) and optimum ignition delay times t_v for various dusts, to select the best spraying devices constructions on the base of recorded tomographic images of dust-air clouds created inside the measuring vessels of various types not only on the base of pressure or pressure rise criteria.

While determining the explosive perimeters of dust - air mixtures (lower explosive limit LEL, maximum pressure of explosion P_{max} , maximum rate of pressure rise $(dP/dt)_{max}$, K_{st} parameter) one of the most important problem is creation of the correct and repeatable dust cloud in the measuring vessel and then to ignite it in a proper moment t_v .

A weighted portion of dust m , should be uniformly sprayed in the volume V of the vessel in order that the real concentration c of a dust - air cloud was in every point of the inner vessel's

space equal to the concentration calculated from the equation (1).

$$c = m / V \text{ [g / m}^3\text{]} \quad (1)$$

As the dust cloud is a dynamic creation the problem is very difficult.

To estimate the value of air blast and ignition parameters a very complicated methods have to be used. For example the method of making a motion images of a dust spraying with a high speed film camera and analysing every frame of the film.

Method of the process combustion tomography opens quite new possibilities of application in that area.

On the basis of the recorded tomographic images showing the course of the dust-air cloud combustion (unlimited flame propagation to the whole vessels volume - for cylindrical vessels usually in the upward direction) a new chance occurs for verification of the criterion for dust's lower explosive limit, which may in some cases differ from 50 kPa and the ignition source location.

Studies of the run of dust clouds deflagration in the „open” and „half-open” spaces (industrial equipment, installations, etc.) are done in order to precise experimental determining of the value of minimum explosive (hazardous) mass for dusts. This depends on a local concentration of a dust cloud at the place (volume) of potential explosion hazard. Such a concentration is a very difficult to measure during the explosion time, because explosion space (volume) is not exactly defined. In fact it does not exist a commonly and fully accepted method to

evaluate that parameter. Combustion tomography should help a lot to solve that problem.

We are proposing to investigate the use of Electrical Capacitance Tomograph (ECT) for visualising the dust dispersal phenomena and the flame propagation process in these vessels. This would be particularly valuable in verifying the tests to a satisfactory standard are being carried out, particularly in the case of dust explosion work, where the initial dispersal of the dust is difficult and where the flame propagation can be irregular for other reasons not yet thoroughly understood.

2. INVESTIGATION PROPOSED (PURPOSE, BACKGROUND)

The development of process tomography method opens new possibilities of application to the combustion dust - air mixture problems:

- direct (on line) watching of the formation and combustion of dust - air clouds in the explosion vessel

- verification of the criterion for a correct estimation of the lower explosion limit measurement in dust - air mixture explosion research

- design of the modern research instruments for correct evaluation for the explosion hazard created in industry by combustible dust.

This project of combustion tomography should help to solve that problem.

The subject of the study is the combustion process of dust cloud in the specialised vessel with constant volume. The combustion has a deflagrative nature, with the time depending on kind and concentration of dust and usually the time of action is limited between 50-500 ms. The effect of the combustion is the sudden increase of the pressure in the chamber. The measuring parameter is the pressure / time history, which describe the speed of combustion process. The rate of pressure rise dp/dt , which describe the rapidity of combustion process and severity of its consequences is very important too.

There are the following steps of experiment:

- creation of the dust cloud of theoretical concentration c (1) in the chamber of constant volume V , formation of the defined quantity of dust (mass m) by the stream of air under the pressure (p , $t=const$) through the special construction of the spray device,

- ignition of the dust cloud by the special ignition source of energy E , when it is assumed that after the time t_v the cloud is uniform.

- measurement of the pressure P (temperature T) and of the rate of pressure rise dP/dt during the combustion process.

The problem concerns the cylindrical vessel (Hartmann type) of $V= 6-10 \text{ dm}^3$ and spherical chamber $V= 20\text{dm}^3$ with different kind of spray device construction-

- it is not possible to control the correctness of dust cloud creation inside the chamber and uniformity of density distribution

- it is not possible to control and verify every time the ignition time delay and value of turbulence index in the dust cloud - and it is very important to obtain true value of P and dP/dt

- it is not possible to observe the combustion front wave disperse. There is essential to define the deflagration low limit - so far it is used so call "pressure criterion" which is defined as the value of 50 kPa.

The process tomography application could give the possibility to obtain the spatial distribution of dust cloud image (shape, density, turbulence during the pressure measurement), dispersion of the combustion front image and may be the possibility to measure the speed of the front.. It give the possibility to define correct time of spray (valve control, cloud shaping etc.) and to optimise the ignition time delay. Above information's could help to design the best spray systems on the base of the images of the move of the dust cloud what is impossible from the pressure measure only. On the base of information from process tomography it should be possible to verify the combustion low limit, which can be below 50 kPa and to define it for each experiment separately.

The outcome of this work could be the use of ECT for developing improved test procedures at the Organic Industry Institute Laboratories and also for recommendations for test equipment that could be regularly installed in user - industry laboratories and on hazardous processes.

Process Tomography problems to be solved:

- **Sensing electrodes.** This is a challenging area which will involve transient pressure and temperature effects, requirements for internal electrodes and (ultimately) multi-plane electrodes for measuring 3-D combustion effects and to obtain velocity profile information. Some work has been done by UMIST and PTL, but it is not yet well documented. It is very important to gather up suitable information and to engage the services of suitable technical staff to do the detailed design and construction of electrode systems.

- **Electronics.** Specific aspects for the combustion tomography projects are time synchronisation, high imaging speed (possibly variable imaging speed), multi-plane tomography (but two-planes with guards would be acceptable to begin with). For a proper understanding of the combustion

process, it may be necessary to measure both real and complex permittivity. PTL has already done this on a single channel pulse charging system, but the engineering design of a tomography system incorporating these features would be quite a substantial task, which needs to be critically considered. It is expected that the next generation capacitance circuits being developed at UMIST may be intrinsically capable of measuring both real and complex permittivity.

- **Computation.** Present program of pressure transient measuring system for the explosion work was adapted from the BBC micro computer into 'windows' format. The electronics work mentioned above also has software implications. A particular aspect of the explosion risk tomography could be to carry out post-processing to reduce computational needs, it is thought that this should present little difficulty. More complex would be to incorporate iterative reconstruction algorithms within this post-processing package and we need to decide if this is within the scope of the project.

We started the realisation of the project with the design an equipment for tomographic research of dust/air mixture. We have worked on the definition of the research problems including technical conditions to research equipment and process tomography system (sensors, reconstruction algorithm, electronics system).

Next we started to realisation of the research equipment and to combustion tomographic research of selected dust /air mixture. In this case we need to prepare research procedure, to select the dust, to test the equipment and to make some modification if necessary, to choice the spray conditions, define the experiment's parameters - spray delay, parse of blast, kind of spray device, delay of ignition etc. At the end of this stage the analysis of results, tomographic system and program verification and proposition of the research standard combustion process tomography procedure should be done. Same of this results we will show on the Congress.

The obtained results should give us the base to do the research of the selected model aerodispersion mixtures and to work out tomographic research standard. In this stage we will receive the standard images of the selected mixtures. On the base of these research we will start to prepare the album of the standard images of the selected mixtures. The complex research instruction, including hardware and software instruction will be done.

3. EXPERIMENTS

We try to reach the target step by step. Visualisation of the combustion run at the real time using the gas burner placed between the set of the ECT electrodes was the preliminary research. We used 8 and 12 electrodes (127 mm diameter) placed around the flame. Electrodes used had the length of 30, 50 and 100 mm. Two types of the burners were used: typical laboratory burner and jewellers burner with dimension and intensity control combustion zone. The ECT was calibrated by air (low permittivity) and by high pressure polyethylene (high permittivity).

The accuracy of the image reconstruction depends on the sensors geometry, dimensions, switching frequency and reconstruction algorithms.

The reconstructions of the selected frames are given on the fig.1. It can be seen the flame displacement to the left bottom direction as well as its intensity. We can get the important information concerning the changes of the state of the flame at the time – so we can consider its control impelentation.

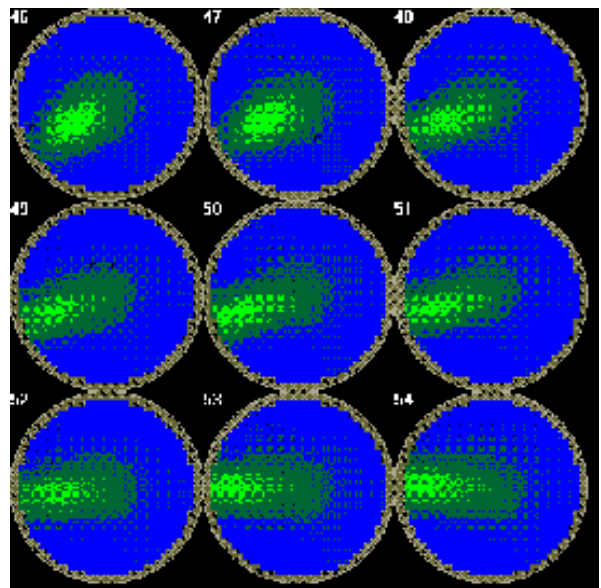


Figure 1: The reconstruction of the selected frames (46-54) of a gas flame from a laboratory burner. Lighter area - moving flame.

Much more information can be obtained by processing of the image digital presentation (bits map) and by the use of the data isolines. This kind of the frame shows even the flame structure (temperature ?) – fig.2.

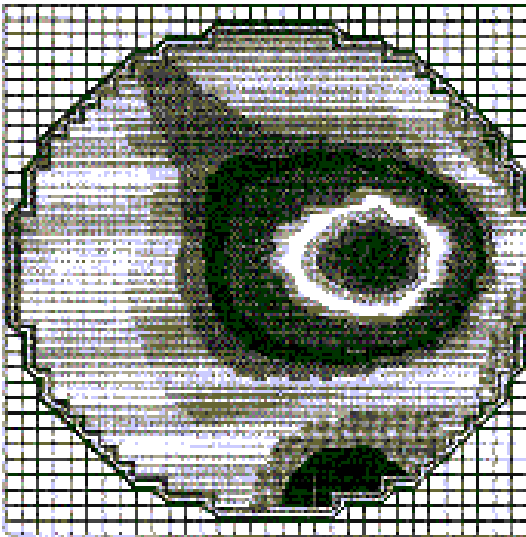


Figure 2: Image presentation as the data isolines.

Positive results of the preliminary experiments allowed us to start the next experiments on the dust/air mixture combustion.

The experiments were done on the two stages

- first on the smaller scale using horizontal inflamator,
- second on the bigger scale using vertical glass vessel Hartmann.

Inflamator (fig.3). Dust cloud is created by pressured air blowing into dust portion placed in the head of the inflamator. Created dust cloud is ignited by the spiral wire heated up to 1000°C. Next the flame of the explosive combustion of the dust aerodispersion run through the measurement space – 12 electrodes, 100 mm length. Selected frames are given on the fig.4. The time of the cloud creation and combustion is about 0.2 – 0.3 sec.

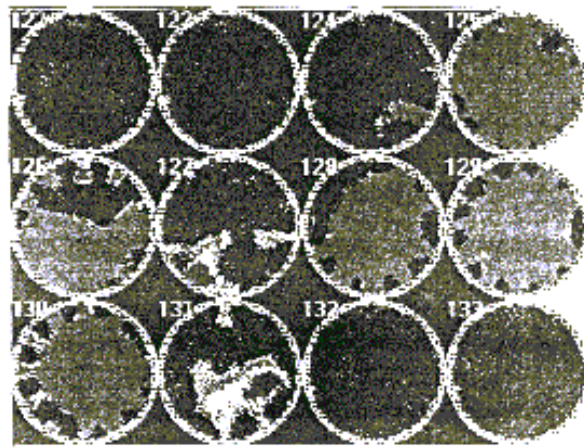


Figure 4: Selected frames (122-133) obtained in the experiment in the horizontal glass inflamator. Lighter area - combustion zone.

Hartmann type explosive vessel (fig.5). Vessel volume is about 5.5 dm³ and is ten times bigger as the inflamator's volume. The dust/air cloud is created by blowing the air through the special pressure nozzle into the portion of the dust put in the small container placed in the central part of the bottom part of the vessel.

The ignition is done by the pyrotechnic source of ignition placed at the centre in the middle of the high of the vessel. The top part of the vessel is made of polyethylene foil, and is destroyed during the experiment. The concentration of the dust cloud is about 500 g/m³. Selected frames obtained in the experiment are shown on the fig.6.

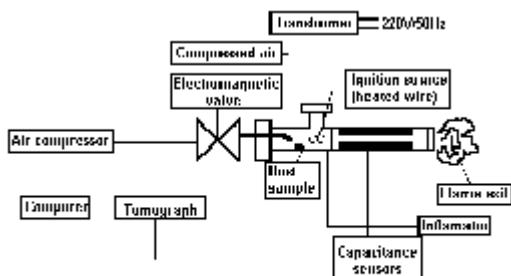


Figure 3: Experimental stand with horizontal inflamator.

4. CONCLUSION

The results of all the experiments (preliminary – quasi static and explosive combustion of the dust aerodispesion – dynamic) confirm the assumption of the possibility of the application of the ECT to the dynamic problems such as explosive combustion of the air/dust mixtures. On this base we will continue the experiments in the laboratory and industrial scale.

For the future the main problem is how to increase the accuracy of the image and obtain more information about the development and structure of the flame.

As the end of this research we see design of the specialised instrument for explosion/fire hazard monitoring and control of the industrial equipment.

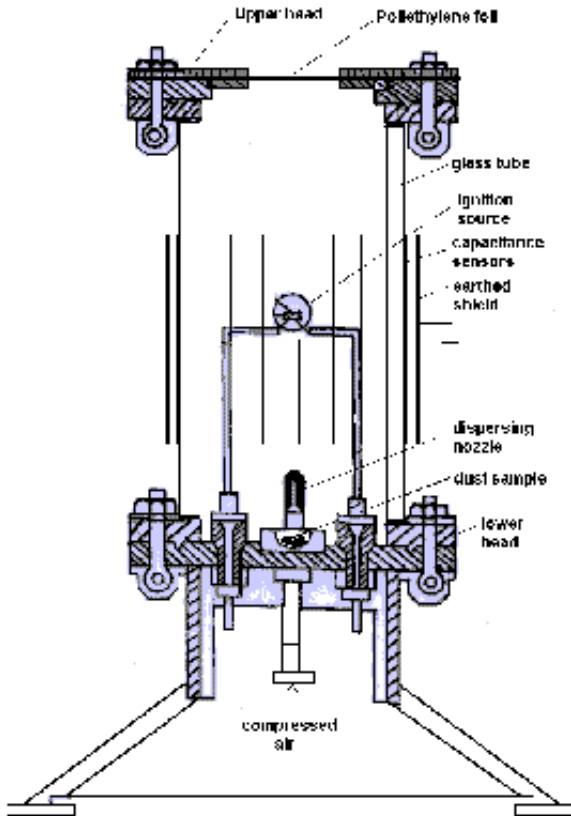


Figure 5: Explosive glass vessel Hartmann Type 5,5 dm³.

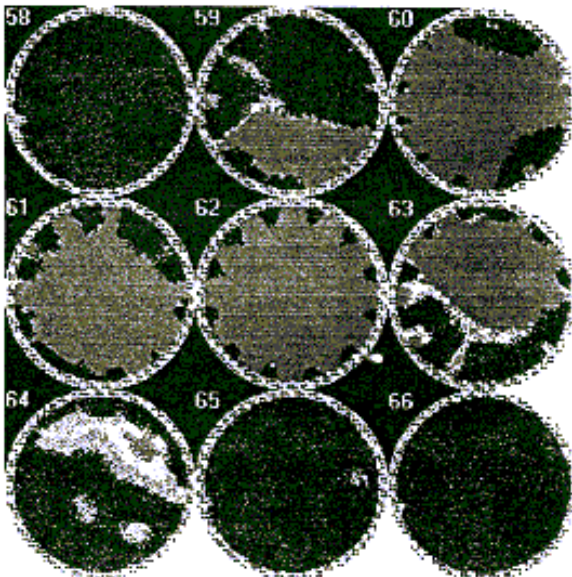


Figure 6: Selected frames (58-66) obtained in the experiment in Hartmann explosive vessel using calcium stearate as a testing dust. Lighter area - combustion zone.

REFERENCES

- [1] Imaging Industrial Flows - Application Of Electrical Process Tomography - A.PI skowski, M.S.Beck, R.Thorn, T.Dyakowski - Wydawca: IOP Bristol, Philadelphia 1995 stron 214
- [2] Cross Correlation Flowmeters - Their Design and Application - M.S.Beck, A.PI skowski, Wydawca: A.Hilger Publisher, Bristol 1987 stron 240
- [3] Beck M.S. and Williams R.A. - Sensor Design and Selection in Frontiers of Industrial Process Tomography , (New York Engineering Foundation) 1995
- [4] Beck M.S., Williams R.A. , Hoyl B.S. Morris M.A. Waterfall R.C. (eds) - Process Tomography ' 95 Implementation for Industrial Process (Manchester UMIST) 1995
- [5] Huang S.M. - Impedence Sensors - Dielectric Systems, Process Tomography - Principles, Techniques and Applications ed. R.A. Williams and M.S.Beck (Oxford:Butterworth - Heineman) 1995 pp.49-62
- [6] Process tomography: a European innovation and its applications - M.S. Beck and R.A.Williams, MEASUREMENT SCIENCE AND TECHNOLOGY - Institute of Physic Publishing- Special issue: Process Tomography March 1996, pp 215-224

- [7] Hardware design of electrical capacitance tomography systems - W.Q. Yang, MEASUREMENT SCIENCE AND TECHNOLOGY - Institute of Physics Publishing- Special issue: Process Tomography March 1996, pp.225-232
- [8] Recent developments and industrial/research applications of capacitance tomography - N. Reinecke and D.Mewes, MEASUREMENT SCIENCE AND TECHNOLOGY - Institute of Physics Publishing- Special issue: Process Tomography March 1996, pp.233-246
- [9] Yang W Q, Stott A L, Xie C G and Beck M S, Development of capacitance tomographic imaging systems for oil pipeline Measurements, *Rev.Sci.Instrum* **66(8)**, 1995, pp 4326-4332
- [10] Isaksen O , A review of reconstruction techniques for capacitance tomography, *Measurement Science and Technology*, **7(3)**, 1996, pp 325-337
- [11] Hoyle B S, Baily N J and Nooralahiyan A Y, Performance of neural network in capacitance-based tomographic process measurement system, *Measurement and Control*, **28**, 1995, pp 109-112
- [12] Tomkiewicz K. Pi skowski A. : Metody tomografii procesowej w diagnozowaniu silników rakietowych, Konferencja Automation'98, Warszawa marzec 1998
- [13] Pi skowski A., Piotrowski T : Zasady działania tomografii i perspektywy przemysłowych zastosowań, Konferencja Naukowo – Techniczna – Diagnostyka Jakości Spalania w Energetyce, Ustro – Zawodzie , marzec 1998
- [14] Waterfall R., He R., Beck C. : Visualising combustion using electrical impedance tomography, *Chemical Engineering*, Vol. 52, No. 13 pp.2129– 2138, 1997
- [15] He R., Waterfall R., Gut Z., Wola ski P.: Combustion visualisation using electrical tomography and Schlieren image techniques. Conference: Frontiers in Industrial Tomography II, Delf April 1997, pp.43 – 46
- [16] He R, Xie C G, Waterfall R C, Beck M S, Beck C M, Engine flame imaging using electrical capacitance tomography, *Electronics Letter*, **30(7)**, 1994 pp 559-560
- [17] J.Lawton, F.J.Weinburg, Electrical Aspects of Combustion, Clarendon Press, Chapter 6, Oxford 1969