

On the use of ion current measurements to detect ignition in the cone calorimeter

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Abstract

Measurements of the ion current between two electrodes have been conducted in a premixed propane flame and in a cone calorimeter in order to assess whether the ion current can be used for combustion diagnostics in general and for detection of ignition in a cone calorimeter in particular.

It was seen that the ion current responds distinctly to where it is positioned in a propane flame and also to the fuel/air ratio of the flame. In the cone calorimeter the measured ion current shows clearly when ignition occurs. The ignition detected by the ion current measurement agreed with visual inspection. It was also seen that soot deposits on the electrodes do not affect the ion current in such a way the ignition detection could be jeopardized. However, short circuiting could occur if the electrodes were kept in a sooty flame long enough for the soot to completely bridge the gap between the electrodes. The latter scenario is not a problem from an ignition detection point of view since soot growth occurs after ignition has taken place.

The general conclusion from the study is that no unforeseen obstacles with the use of ion current measurements in combustion diagnostics were observed.

Key words: ignition, ion current, flame conductivity, cone calorimeter

Sökord: antändning, jonström, ledningsförmåga i flammor, konkalorimeter

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Preface

The Swedish Board for Fire Research (Brandforsk) sponsored this project with reference number 311-081 which is gratefully acknowledged. Brandforsk is owned by the Swedish government, assurance companies, local authorities and industry and has as mission to initiate, finance and follow-up different types of fire research. The project was a limited pilot study and therefore no reference group was established.

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Sammanfattning

Mätning av jonströmmen mellan två elektroder har genomförts i en propanflamma och i konkalorimetern. Syftet med studien var att se om jonströmmen kan användas för att detektera antändning i konkalorimetern. Detta skulle vara användbart eftersom det redan finns två elektroder som används för pilotantändning i konkalorimetern. Den nya metoden skulle därför kunna implenteras relativt enkelt och kostnadseffektivt. Anledningen till att det är intressant att elektroniskt detektera antändning är att detta idag utförs av en operatör genom visuell inspektion. Bestämningen av när antändning sker blir därför subjektiv och operatörsberoende.

Första delen av mätningarna gjordes i en propanflamma för att karakterisera det elektrodpar som användes. Spänningen varierades mellan 50 V och 300 V. Jonströmmen över elektrodgapet ökade linjärt med spänningen. Det observerades också att jonströmmen förändrades då elektrodernas läge i flamman förändrades och då ventilationsgraden i flamman förändrades. Detta visar att mätmetoden kan ge information om förbränningsförhållandet.

Den andra delen av mätningarna gjordes i konkalorimetern vilket också är den tilltänkta slutanvändningen för metoden. Antändning detekterades med lätthet då de två testade bränslena polyuretanskum och spånskiva användes. Försök genomfördes även vid underventilerade förhållanden, 15-18 % O₂, och detektering av antändning var fortfarande möjlig. Signalen blev dock generellt svagare för underventilerade förhållanden.

Som slutsats från studien framkom att mätning av jonström är en lovande metod för branddiagnostik i allmänhet och för antändningsdetektion i synnerhet. En mer optimerad mätapparat behöver dock utvecklas och testas innan metoden fullt ut kan ersätta dagens metod med visuell observation.

Mer avancerade tillämpningar av jonströmsmätning föreslogs slutligen, såsom detektion av pyrolys och glödbrand, och uppskattning av flamhastighet vid antändning. Dock krävs omfattande grundläggande studier innan denna typen av tillämpningar kan användas.

Summary

The ion current between two electrodes has been measured in a propane burner and in a cone calorimeter. The purpose was to investigate if the ion current can be used as a detector for ignition in the cone calorimeter. This would be advantageous since there already is an electrode pair in the cone calorimeter, used for pilot ignition. Therefore implementation of ion current measurements as a detector for ignition would be possible to do in a simple and cost-effective way. The reason why it is interesting to detect ignition electronically is that this task today is done by visual inspection by the operator, and therefore subjectively operator dependent.

The first part of the measurements were done in a propane burner in order to characterize the electrodes. The voltage was varied between 50 V to 300 V. It was seen that the current through the electrode gap increased linearly with applied voltage. It was also seen that the ion current changes with position in the flame and with air/fuel mixture in a distinct way, showing that the method is sensitive to and can give information about combustion conditions.

The second part of the measurements was done in the cone calorimeter, which is the intended end use for the application. Using two type of fuels, polyurethane foam and particle board, it was found that ignition was easily detected using ion current measurements. Experiments were also performed under vitiated conditions, with 15-18 % O_2 , and ignition could still be detected, although the signal was in general weaker than for the well ventilated case.

It was concluded that ion current measurements show great promise as a tool for fire diagnostics in general and for ignition detection in particular. However, a more optimized prototype needs to be designed and manufactured, and carefully tested, before it is sufficient reliable to replace today's detection system with visual inspection.

More advanced applications of ion current measurements were suggested, such as detection of pyrolysis and smouldering fire, and estimation of flame speed at ignition. Still, much basic research remains before this can eventually be accomplished.



1 Background

The purpose of this pilot study was to demonstrate a proof-of-concept for using measurements of ion current between two electrodes as a means for flame diagnostics in fire testing. If this concept is successful there are a plentiful of applications where measurements of the ion current can be useful. Examples of these applications are in increasing order of complexity: ignition detection, diagnostics of pyrolysis gases, and diagnostics of the combustion process after ignition. In the pilot study the goal was to show that ion current measurements is a feasible way for an objective way of detecting ignition.

Time to ignition, that is, the time from the onset of heat transfer to an object until the time when the object ignites, is a very important fire property. Materials with long ignition times delay fire spread as compared to materials with shorter time to ignition. In order to study time to ignition a cone calorimeter [1] is often used, especially for well ventilated conditions. Using the current standard procedure for testing an operator visually determines when ignition occur, and make a note of it. This will by necessity be a subjective measure. Especially for flame retarded materials the flame can be indistinct and unstable [2] and when smoke is obscuring the test object it can be very difficult to settle when ignition occurs. According to the standard for the smoke chamber test method [3] it is required that the inspection window, used be the operator to observe the test, is closed when a certain smoke density is reached. This obviously makes it impossible to detect ignition visually. Thus the detection of ignition can be a weak link in the study of the fire properties of a material. By introducing an automatic and objective ignition detection system more accurate knowledge would be gained for many materials

In addition the dependence of time to ignition on the irradiation level is used for determining the ignition temperature and thermal inertia of materials [4]. These parameters are often used in CFD-modelling (Computational Fluid Dynamics) and therefore play an important role in fire research and construction projecting.

2 Introduction

Conductivity of flames [5] and hot air [6] has been studied for over 100 years and is an area of ongoing research. It is easy to understand the complexity of the subject given the fact that the chemistry of combustion, not including ions, is still far from well known for most fuels and combustion conditions. It is out of the scope for this pilot study to discuss possible mechanisms for the conductivity of flames.

Ion currents due to an applied voltage between two electrodes in a flame is commonly used as a safety mechanism in burners [7]. The function is to close the gas supply to the burner if the ion current disappears, that is, if the flame is extinguished. The objective is to avoid a malfunctioning burner to fill up a space with a combustible or explosive gas mixture. In recent years ion current sensors in internal combustion engines has gained considerable interest [8, 9]. Measurement of the ion current over the gap of the spark plug is a cost effective alternative to more expensive pressure sensors used for on board engine diagnostics.

Using electric fields to control the combustion has been proposed by several authors for different applications such as gas turbine control [10, 11] and for metallurgical processes [12] for example.

Conductivity of flames is also important when assessing risk for electrical breakdown between power lines and earth during forest fires [13].

3 Materials and methods

3.1 Electrodes and measurement circuit

The ion current was measured in the gap between two symmetric electrodes. The electrode pair consisted of an electrode assembly supplied by Fire Testing Technology Limited, East Grinstead, United Kingdom, see Figure 1 below. This is the same electrode assembly that normally is used as spark ignitor in the cone calorimeter, in order to induce piloted ignition [1].

In Figure 8 it is clearly seen that the method is intrusive in the sense that the flame is affected by the electrodes. This has no importance for ignition detection in the cone calorimeter since the existence of the electrodes is imposed by the standard [1].



Figure 1 Electrode assembly used for all tests in this report.

The measurement circuit is illustrated in Figure 2. The oscilloscope records the voltage drop over a 100 k Ω resistor and the ion current over the electrode gap is derived from the measured voltage. Typical time scales in these experiments were ~10 ms. The oscilloscope used was a Tektronix TDS 1002B and the DC power supply an Innotech LAB3K6. The trigger level was set between 100 mV and 200 mV in the experiments.

For the measurements in the propane burner different voltage values were applied to the electrode gap. For the measurements in the cone calorimeter the output voltage from the power supply was 200V.



Figure 2 The electric circuit used for the measurement.

3.2 Propane burner

In the first part of the experiments a well controlled 1 kW propane burner was used as shown in Figure 3. The burner comply with the IEC 60695-11-2:2003 standard [14]. Two combustion conditions were used: well ventilated and vitiated. For the well ventilated combustion 650 ± 30 ml/min propane and 10 ± 0.5 l/min air was fed to the burner, corresponding to an equivalence ratio of 1.6, resulting in a blue flame. For the vitiated combustion 650 ± 30 ml/min propane was mixed with 8.7 ± 0.5 l/min air, corresponding to an equivalence ratio of 1.9, resulting in a sooty yellow flame.



Figure 3 The propane burner used in the first part of the experiments.

3.3 Cone calorimeter

In the second part of the experiments the cone calorimeter [1] was used, schematically illustrated in Figure 4. This is a test where a 0.01 m² specimen, horizontally positioned, is subjected to irradiation from an electrically heated conical spiral above the tested material. The irradiation level used in this study was 50 kW/m².

The cone calorimeter can be used to measure time to ignition, HRR (Heat Release Rate), SPR (Smoke Production Rate), as well as mass loss of the tested object. It is also possible to sample the exhaust gases and measure for example unburned hydrocarbons and toxic gases such as NO, HCl, and HCN for example.



Figure 4 Schematic picture of the cone calorimeter.

In this project the ion current characteristics in well ventilated as well as in vitiated conditions were studied. The normal setup of the cone calorimeter, such as depicted in Figure 4, does not allow for vitiated combustion conditions. Therefore the conical spiral heater and the test object was placed in a box where the oxygen level could be reduced by adding nitrogen to the box air inlet. The setup used is shown in Figure 5.



Figure 5 The box used to perform tests with under ventilated conditions.

Normal operation of the cone calorimeter requires pilot ignition of the pyrolysis gases. This is achieved by a spark ignitor actually consisting of the same spark gap as that shown in Figure 1. However, since the measurement circuit did not include an electronic control system, the spark ignitor was not used since it would have triggered the measurements. Therefore no pilot ignition was used in this study. This is however not a critical problem for a future implementation of ion current measurements in the cone calorimeter since the construction and implementation of such control system is straightforward.

3.3.1 Fuels used in cone calorimeter

Two fuel type were used in the tests with the cone calorimeter. These were:

- Polyurethane foam with a density of $21\pm1 \text{ kg/m}^3$. The area of the specimens where 100 mm x 100 mm and the thickness about 35 mm.
- Particle board with a density of 680±50 kg/m³. The area of the specimens where 100 mm x 100 mm and the thickness was 12 mm.

The fuels are shown in Figure 6 and Figure 7.



Figure 6 Polyurethane foam used in the experiments. The specimen in the picture has dimensions 100 mm x 100 mm x 35 mm and a density of 21±1 kg/m³.



Figure 7 Particle board used in the experiments. The specimens have dimensions 100 mm x 100 mm x 12 mm and a density of 680±50 kg/m³.

4 **Experimental results**

Measurements were conducted both in a premixed propane flame and in the cone calorimeter.

4.1 Characterization of electrodes

The first experiments consisted in investigating how the ion current over the electrode gap responded to different applied voltage, height above the burner, and gas/air mixtures. This measurements were conducted in a premixed propane flame. Figure 8 below shows measurement of ion current at 53 mm and at 13 mm height above the burner. The results are summarized in Figure 9.



Figure 8 Measurements at 53 mm and 13 mm height above the burner with well ventilated combustion. Notice that the electrodes glow red, and therefore are hotter, when positioned 53 mm above the burner.



Figure 9 Average current measured for different applied voltage and for different heights and combustion conditions. The error bars gives an estimate of the variation in measured average current. Average current means that the current was averaged on the oscilloscope during 0.5 s.

4.2 Influence of soot deposits on electrodes

Next step was to see if soot deposits on the electrodes could adversely affect the measurement of ion current. Figure 10 below shows the electrodes without and with soot deposits.



Figure 10 Electrodes without (left) and with (right) soot deposits. The soot was deposited using a candle.

Three typical samples of ion currents in a premixed well ventilated propane flame using electrodes without soot is shown in Figure 11. Measurements with soot deposits on the electrodes are presented in Figure 12. The electrodes were protected from the flame by a promatect board between the measurements in order to avoid that the soot was oxidized.



Protection with the promatect board was also used for the measurements without soot in order to obtain comparable conditions.

Figure 11 Three samples of ion current measurments using electrodes without soot. The applied voltage was 100 V.



Figure 12 Three samples of ion current measurements using electrodes with soot. The applied voltage was 100 V.

4.3 Measurements in the cone calorimeter

For each fuel (polyurethane foam and particle board) and for each operating condition (well ventilated and vitiated) three typical examples of ion current measurements are presented. The applied voltage was 200 V in all measurements. In the Figures below the time scale is only relative. Whether the first pulse comes at 5 ms, 20 ms or any other time has no importance since this is only reflects where the time origin was set on the oscilloscope screen.

4.3.1 Ignition of polyurethane foam in well-ventilated conditions

In these experiments the door to the box was open, see Figure 5. The first peak, trigging the oscilloscope, always coincided with the ignition. Three examples of ion current measurements following ignition are shown below.



Figure 13 First example of ion current measurement with well ventilated ignition of polyurethane foam. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen.

The ignition creates a clearly detectable signal. Figure 14 shows the measured signal before any ignition has taken place. Comparing Figure 13 and Figure 14 it is clear that the signal to noise ratio is high for the measurements.



Figure 14 Reference graph showing the measured signal when no ignition occurs.



Figure 15 Second example of ion current measurement with well ventilated ignition of polyurethane foam. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen.



Figure 16 Third example of ion current measurement with well ventilated ignition of polyurethane foam. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen.

4.3.2 Ignition of polyurethane foam in vitiated conditions

The oxygen level in the box was 18% during the test with vitiated ignition of polyurethane foam. In order to dilute the atmosphere with N_2 the door in Figure 5 was closed. Three examples of ion current measurements following ignition are shown below.



Figure 17 First example of ion current measurement with vitiated ignition (18% O₂) of polyurethane foam. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen. The negative values on the current gives an indication of the noise and measurement uncertainty.



Figure 18 Second example of ion current measurement with vitiated ignition (18% O₂) of polyurethane foam. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen. The negative values on the current gives an indication of the noise and measurement uncertainty.



Figure 19 Third example of ion current measurement with vitiated ignition (18% O₂) of polyurethane foam. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen.

4.3.3 Particle board in well ventilated conditions

In these experiments the door to the box was open, see Figure 5. The first peak, trigging the oscilloscope, always coincided with ignition. Three examples of ion current measurements following ignition are shown below.



Figure 20 First example of ion current measurement with well ventilated ignition of particel board. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen.



Figure 21 Second example of ion current measurement with well ventilated ignition of particle board. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen.



Figure 22 Third example of ion current measurement with well ventilated ignition of particle board. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen.

4.3.4 Particle board in vitiated conditions

The oxygen level in the box was 15% during the test with vitiated ignition of particle board. In order to dilute the atmosphere with N_2 the door in Figure 5 was closed. Three examples of ion current measurements following ignition are shown below.



Figure 23 First example of ion current measurement with vitiated ignition (15% O₂) of particle board. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen. The negative values on the current gives an indication of the noise and measurement uncertainty.



Figure 24 Second example of ion current measurement with vitiated ignition (15% O₂) of particle board. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen. The negative values on the current gives an indication of the noise and measurement uncertainty.

In general the ion current signal was lower and more difficult to detect using only 15% O₂. Figure 25 below shows one of the rare events with a very low ion current signal.



Figure 25 Third example of ion current measurement with vitiated ignition (15% O₂) of particle board. The irradiation level was 50 kW/m². The ion current started simultaneously as the ignition of the specimen. The negative values on the current gives an indication of the noise and measurement uncertainty.

4.4 Short circuiting due to soot deposit

If the electrodes are kept in the flames during combustion soot may eventually deposit on them depending on the combustion conditions and fuel. If the soot grows over the entire electrode gap a short circuit will occur since soot is electrically conducting due to its graphite like structure. Such an event is shown in Figure 26 below which shows ion current measurement during an experiment with ignition of polyurethane foam under well ventilated conditions. The measurement saturates at 4 μ A; thus the true short-circuit current is not measured.





Short circuiting is not a problem from an ignition detection point-of-view since it occurs a certain time after ignition. However, it is important that the electrode gap is not already short-circuited, due to soot from previous tests, before a test.

No soot depositing can be allowed during the pyrolysis phase since this could cause a short circuit before ignition, and thereby compromising the ignition detection. No soot depositing was observed during the pyrolysis phase.

4.5 Polarity effects

It was noticed that the soot had a tendency to deposit preferentially on the negative electrode, see Figure 27 below. This effect was seen irrespective how the electrodes were positioned in the flames. The phenomenon was not studied further.



Figure 27 The soot deposited preferentially on the negative electrode.

5 Discussion

In this chapter the results are discussed and analyzed. The discussion is held in the context of assessing if it is worthwhile to pursue the development of this method, or not.

5.1 Characterization of electrodes in a premixed propane flame

Figure 9 shows that the ion current obeys Ohm's law. It is also seen that the ion current responds distinctly to parameters such as position in the flame and fuel/air ratio of the premixed flame. Another observation is that the ion current signal is higher for the lower position in the flame despite the fact that the flame is cooler there.

5.1.1 Influence of soot deposits on electrodes

In order to in detail evaluate the impact of soot deposits on the electrodes it would be necessary with a large number of measurements and a rigid statistical analysis of the ion currents. This was not done here but the results are rather presented in a visual way in Figure 11 and Figure 12 where it is clear that the behaviour is not significantly affected by the soot. This means that soot, at least in moderate quantities, is not in conflict with the use of ion current measurement as an indicator for ignition. Large amount of soot may however cause a short circuit. This is not a problem from an ignition point-of-view since the soot growth starts after ignition. No soot growth was observed under the pyrolysis phase.

5.2 Measurements in the cone calorimeter

The oscilloscope always trigged at the same time as the visual observation of ignition was determined. A few exceptions occurred when triggering occurred due to too much electronic noise in the lab. The most important contributor to this electronic noise was the exhaust fan of the cone calorimeter. Some actions were taken to decrease the sensitivity

to noise but this process was by no means completed. Carefully, from an EMC-perspective, designed measurement system will work in the noisy environment. The fact that it was very easy to detect ignition and record the ion current means that the pilot study was a success. This opens up many opportunities for diagnostics using the ion current and suitable electronics.

A general trend is that the ion current signal becomes weaker in vitiated conditions. No attempts to interpret the curves in Figure 13 to Figure 25 are made in this limited pilot study.

5.3 Moving forward

This study has indicated that it is feasible to construct an automatic ignition detector for the cone calorimeter. The next step would be to design and construct a prototype measurement apparatus that is incorporated in the spark ignitor circuit used for pilot ignition. This prototype should then be characterized for an application range as large as possible when it comes to fuels, irradiation levels and ventilation degrees. Before such an apparatus could come to professional use it must be showed that it is sufficiently reliable to replace today's detection system with visual inspection

Other interesting ways forward would be to do studies similar to the one presented here but applied to the smoke box method [3], for example.

Reducing the sensitivity to electromagnetic noise is of high priority when it comes to improving the performance of this measurement method and to developing a prototype. This can be done by common EMC-practice, such as shortening and shielding connecting cables, and enclose components in metallic boxes.

Except for ignition detection the ion current also presents possibilities for studying other fire related phenomena. One field would be pyrolysis and smouldering fires. In this case the ion current would be measured not in a conducting flame but in an atmosphere that has been altered by the pyrolysis process or by the emission from the smouldering fire. It is unclear what the magnitude of the ion current will be but it will be lower than the currents measured here, in flames. Therefore the reduced sensitivity to electric noise is again a prerequisite for pursuing this path. In the present study the voltage never exceeded 300 V. Using the existing DC power supply it is however possible to increase the voltage to 3.6 kV. This makes it reasonable to assume that the sensitivity to changes in the atmosphere around the electrodes can be improved. However, to study pyrolysis and smouldering fires, it might be advantageous to use AC voltage instead of DC.

Finally combustion diagnostics is an interesting field. By designing the electrodes in an intelligent way, or by using several electrode pairs, it could be possible to indicate the flame speed at ignition. This would give information about the conditions in the atmosphere above the tested sample at ignition. Some additional information could eventually be extracted from the actual shape and magnitude of the ion current signal but much basic research is needed in order to perform such an advanced analysis successfully.

6 Conclusions

This pilot study has shown that measurements of ion current between two electrodes show great promise as a tool for detecting ignition in the cone calorimeter. The method might also be used for other test methods such as the smoke box for example.

It was seen that the ion current responds distinctly to position in relation to the flame front and to the fuel/air ratio of a premixed propane flame. In the cone calorimeter the measured ion current shows clearly when ignition occurs. The ignition detected by the ion current measurement agrees with visual inspection. It was also seen that soot deposits on the electrodes do not affect the ion in such a way that the ignition detection could be jeopardized. However, short circuiting could occur if the electrodes were kept in a sooty flame long enough for the soot to completely bridge the gap between the electrodes. The latter scenario is not a problem from an ignition detection point of view since soot growth occurs after ignition has taken place.

The general conclusion from the pilot study was that no unforeseen obstacles with the use of ion current measurements in combustion diagnostics were observed. This makes the method attractive for further applications such as diagnostics of pyrolysis, smouldering fire, and flame speed at ignition for example. An important part of next step would be to make the measurement electronics less sensitive to electronic noise. This would increase the signal to noise ratio and therefore be advantageous for applications where the ion current is expected to be lower than in flames.

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