Electrical currents and breakdown voltages as a diagnostic tool for fires a uragnostic tool for fires Raúl Ochoterena, Michael Försth (SP),Mattias Elfsberg (FOI)







Fire Technology

Electrical currents and breakdown voltages as a diagnostic tool for fires

Raúl Ochoterena, Michael Försth (SP), Mattias Elfsberg (FOI)

Abstract

Electrical currents and breakdown voltages as a diagnostic tool for fires

Two types of electrical measurements have been investigated in order to perform diagnostics of the fire dynamics in the ISO 5660 cone calorimeter. The rationale of the study is to take advantage of the pilot ignition electrodes that are already in place and use these to collect additional information such as emission of pyrolysis gases and time to ignition.

The first part of the project was a refinement of the method for measuring the so called ion current, which has already been investigated in a pilot study. It was found that thorough shielding and grounding gives an excellent signal to noise ratio. An expression for the correlation between measured current and conductivity was also developed and validated experimentally.

The second part of the project consisted of measuring the breakdown voltage, that is the voltage when dielectric failure occurs. It was found that this method was more sensitive to the fire dynamics before ignition, such as pyrolysis, but that the response to ignition was more ambiguous for the breakdown voltage than for the ion current.

Key words: electrical discharge, fire, ignition, cone calorimeter, Paschen's law

Sökord: elektriskt överslag, brand, antändning, konkalorimeter, Paschens lag

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Preface

The Swedish Board for Fire Research (Brandforsk) sponsored this project with reference number 605-091 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.

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Notations

Abbreviation	Quantity	Unit	Explanation/comment
A B	prefactor in expression for α	[m ⁻¹ Pa ⁻¹] [Vm ⁻¹ Pa ⁻¹]	
D	expression for α prefactor in expression for	$[\mathrm{Am}^{-2}\mathrm{K}^{-2}]$	
d	thermionic emission distance between electrodes	[m]	
E F	electric field	$[Vm^{-1}]$	
HAR	Height Above Burner	[v] [m]	
HRR	Heat Release Rate	[W]	
I	current	[• ·] [A]	
Lo	initial (no secondary	[A]	
1 _{e,0}	ionization) electron current		
	at cathode		
I.	total electrode current	[A]	
-e	at cathode		
Lion 0	initial (no secondary	[A]	
1011,0	ionization) ion current at	[A]	
	cathode		
Iion v	total ion current at cathode	[A]	
J	current density	$[Am^{-2}]$	
k _B	Boltzmann's constant	[JK ⁻¹]	$k_{\rm B} = 1.381 \cdot 10^{-23} \mathrm{JK}^{-1}$
n _e	electron density	$[m^{-3}]$	2
р	pressure	[Pa]	
PUR	polyurethane		
PMMA	poly(methyl methacrylate),		
R	resistance	[Ω]	
S	surface area of electrode	$[m^2]$	
SPR	Smoke Production Rate	$[m^2 s^{-1}]$	
t _{ignition}	time to ignition	[s]	
Т	temperature	[K]	
U	voltage	[V]	
$U_{breakdown}$	voltage required to overcome		
	the dielectric strength		
α	Townsend's coefficient	$[m^{-1}]$	
	for ionization		
γ	effective secondary	[]	
	ionization coefficient		
δ	degree of ionization	[]	
φ	work function for thermionic	[J]	
	emission from metal surface		
ρ	resistivity	[Ωm]	
σ	conductivity	$[Sm^{-1}]$ or $[\Omega^{-1}m$	-1]



Sammanfattning

Denna rapport är en fortsättningen på en förstudie där möjligheterna studerades för att använda jonströmsmätningar som diagnostisk metod inom brandteknik, främst ISO 5660 konkalorimetern. De positiva resultaten från förstudien ledde till detta fortsättningsprojekt.

Projektet bestod av två delar:

- förfinad metod att mäta jonströmmen
- mätningar av överslagspänningen

Den första delen gick ut på att mäta strömmen mellan elektroderna utan närvaro av gnista. Genom att skärma och jorda den utrustning som användes i förstudien åstadkoms en stor förbättring i signal/brus förhållandet. Trots detta var det fortfarande enbart möjligt att mäta själva antändningen. Detektion av pyrolysgaserna innan antändning var inte möjlig pga. alltför låga signalnivåer, även med relativt hög pålagd spänning (~1000 VDC). Ett uttryck för förhållandet mellan den uppmätta strömmen och konduktiviteten i elektrodgapet togs fram och validerades experimentellt. Kunskap om konduktiviteten är viktig om man vill gå vidare och göra uppskattningar om gasens tillstånd såsom temperatur, elektrontäthet och liknande.

Det andra delen av projektet initierades av oförmågan att mäta på pyrolysgaser med hjälp av strömmätningar utan elektriskt överslag. Två elektriska kretsar designades och tillverkades: En för att skapa en välkontrollerad gnista och en för att mäta överslagsspänningen hos gnistan. Det visade sig att överslagsspänningen svarade väl på förändringar i gasen ovanför provkroppen även före antändning. Dessutom gav själva antändningen ytterligare en påverkan på urladdningsspänningen, dock inte lika tydlig som påverkan på strömmen i den första delen av projektet.

Ett logiskt nästa steg är att även beakta fasförskjutningen mellan ström och spänning vilket rimligtvis ger en tydligare signal om förhållandet i elektrodgapet.

Summary

This report is a follow up to a pilot study where the possibilities of using current measurement for fire diagnostics, primarily in the ISO 5660 cone calorimeter, was investigated. The positive results from the pilot study led to this project which consisted of two parts:

- a refined method to measure the ion current
- measurement of the breakdown voltage

In the first part of the project the current between the electrodes was measured without a spark. This means that the electrodes could not be used as a spark igniter at the same time. By thoroughly shielding and grounding the equipment from the pilot study a major improvement was obtained in the signal to noise ratio. Despite this is was still not possible to measure pyrolysis gases since the signal was too weak, even with a relatively high applied voltage (~1000 VDC). An expression for the relationship between the measured current and the conductivity in the electrode gap was developed and validated experimentally. Knowledge about the conductivity is important in estimations of gas properties such as temperature, electron density, etc.

The second part of the project was initiated from the inability to measure pyrolysis gases from current measurements without electric breakdown. Two circuits were designed and constructed: One for producing well defined high voltage pulses and one for measuring the breakdown voltage. It was found that the breakdown voltage responded clearly to changes in the gas composition above the tested sample even before ignition. When ignition occurred an additional change in the breakdown voltage could be observed, although not as distinct as the current pulses measured in the first part of the project.

A logical next step would be to also measure the phase difference between current and voltage. This is expected to give a signal which more clearly characterizes the status of the gas/plasma in the electrode gap.

1 Introduction

This project is a follow up to a pilot study regarding the use of ion current measurements as a tool for ignition detection in the ISO 5660 cone calorimeter [1, 2]. In the pilot study it was found that ignition could easily be detected by applying a DC voltage of 200 V over the pilot ignition electrodes in the cone calorimeter [3] and measuring the ion current in the ~3 mm air gap between the electrodes. It was found that the ion current was vanishingly small before ignition and that ignition could easily be detected since one or several current pulses occurred when the tested sample ignited. The pulse height was typically on the order 1-10 μ A and its length was on the order of some 10 ms. One drawback of this method was that it was not sensitive enough to detect for example the onset of pyrolysis. Another drawback was the fact that the electrodes of the cone calorimeter become assigned for the ion current measurements, using a DC voltage of 200 V, and therefore they cannot be used to create the pilot ignition spark that is prescribed in the cone calorimeter standard [3].

Current measurements as a method to monitor flame behaviour is not a new concept in the combustion sciences. Ionic flame monitoring is the measurement of ion currents due to an applied voltage between two electrodes in a flame. This is commonly used as a safety mechanism in burners [4, 5]. 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 the risk that a malfunctioning burner might fill up a space with a combustible or explosive gas mixture. More advanced versions of these so called flame rods have been presented where the ion current is characterized by its DC amplitude, AC amplitude, and flickering frequency. This gives more detailed information concerning the status of the flame and it has been proposed that these three parameters combined can give an early warning that a problem is developing in the combustor [6]. From a fire safety perspective conductivity of flames is also important in various other fields such as for example when assessing risk for electrical breakdown between power lines and earth during forest fires [7].

In recent years ion current sensors in internal combustion engines have gained considerable interest [8-10]. 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. In a recent study the relationship between ion current and temperature was explored [11].

Conductivity of flames [12] and hot air [13] has been studied for over 100 years and is an area of on-going 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. Including the ion chemistry makes the feat even more difficult. Using electric fields to control the combustion has been proposed by several authors for different applications such as gas turbine control [14, 15] and for metallurgical processes [16] for example. In a recent study [17] laser diagnostics were used to do fundamental research on the effect of electric fields on premixed methane-air flames. Direct numerical simulations [18] and experimental measurements [19] have been performed to study the ability of electric fields to stabilize flames. An exponential relation between applied DC voltage and the change in burning velocity of premixed methane/air flames has been reported [20] while another study indicated a rather linear relationship between AC voltage and velocity in a propane flame [21]. The effect of electric field on soot was studied in reference [22] and one conclusion was that the majority of soot particles were positively charged. Microwaves were used to enhance flame stability in a methane-air stagnation flame in reference [23]. Finally flame flickering induced by magnetic fields was observed in reference [24].

One rationale for exploring the possible use of the electrodes in the cone calorimeter for flame diagnostics is to obtain an objective and well defined method for detecting ignition [25, 26]. In the current standard procedure for the cone calorimeter [3] an operator visually determines when ignition occur. This will by necessity be a subjective measure. Especially for flame retarded materials the flame can be indistinct and unstable [27] and when smoke is obscuring the test object it can be very difficult to objectively determine when ignition occurs. According to the standard for the smoke chamber test method [28] 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 after this point. 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 information could be obtained. It is suggested that measurement of ion current or dielectric breakdown voltage could be the input signal for such a system.

In this report two electrical phenomena were explored:

- The ion current that flows between the electrodes under moderate voltages. This is a refinement of the previous pilot study [1, 2].
- The voltage that is required to overcome the dielectric strength of the medium between the electrodes. In other words, the voltage required to create an electric breakdown.

Section 2 of this report contains the basic physical theory for the explored phenomena. The experimental materials and methods are described in Section 3 while the results are presented and discussed in Section 4. The report ends with conclusions in Section 5 and a discussion on suggested future work in Section 6.

Since this project was a direct continuation of the pilot study presented in reference [1] some parts in the present report are overlapping with the previous report.

2 Theory

An electric force is exerted on electrons and ions in an electric field. Due to these forces there will be a flux of charged particles, creating a current. If two metal plates separated by air are connected to a voltage difference on the order of 10 V no visible effect will occur [29]. However, with a very sensitive ampere meter a current on the order of 10^{-15} A would be detected. The source of this current is electrons and ions created by natural radioactivity and cosmic rays. If a flame zone passes through the electrode gap the current will increase considerably. Charged species have been studied in a methane-oxygen flame [30, 31]. The most important of these species are electrons, CHO⁺, H₃O⁺, C₂H₃O⁺, CH₅O⁺, O₂⁻, OH⁻, O⁻, CHO₂⁻, CHO₃⁻, and CO₃⁻ [32]. Due to these electrons and ions, the current increases and for the electrode gap in the cone calorimeter typical currents on the order of 10^{-6} A have been observed with an applied voltage of 200 V [1, 2]. Section 2.1 presents the most important parameters affecting this current.

If the applied voltage is further increased the current between the electrodes will rise once a certain voltage is reached, $U_{breakdown}$, and a discharge will be seen. This happens when the electrons gain sufficient energy, due to the electric field, between collisions with other species. At this point, when the kinetic energy of the electrons reaches the atomic ionization potential of the involved elements, each electron will knock out one additional electron upon collision. Immediately after the collision there will therefore be two slow electrons that again will accelerate in the electric field and then knock out two more electrons, and so on. In other words there will be an electron avalanche and a self-sustained electric discharge will remain as long as the high voltage is applied. The basic theory for $U_{breakdown}$ is given in Section 2.2.

2.1 Current in electrode gaps without electric breakdown

It has previously been shown [1, 2] that when the applied voltage is below $U_{breakdown}$ the current between the cone calorimeter electrodes follows Ohm's law:

$$I = \frac{V}{R} \tag{1}$$

For a homogeneous electric field in an area A with electrode distance d the resistance R is

$$R = \frac{d}{\sigma A} \tag{2}$$

where

 σ is the conductivity in the gas between the electrodes [Sm⁻¹] (or [Ω^{-1} m⁻¹]).

The current is therefore

$$I = \frac{V\sigma A}{d} \tag{3}$$

The conductivity is due to charged particles, that is electrons, positive ions, and negative ions. Since electrons are much lighter than ions they are most easily accelerated by the electric field. Therefore it is the electron concentration the determines the conductivity, as long as the electron density is not much lower than ion concentrations. Negative ions affect the conductivity negatively since they are electron depleting [9].

Experiments have shown that for air [29]:

$$\sigma = \frac{9.6 \cdot 10^{-16} \cdot n_e}{p} \tag{4}$$

where

 n_e is the concentration of electrons [m⁻³], and p is the pressure [Pa].

Combining Equations (3) and (4) yields:

$$I = \frac{9.6 \cdot 10^{-16} \cdot n_e VA}{pd}$$
(5)

This indicates that for a given air pressure it is the electron density that mostly influences the current. Simulations have shown that for a flat laminar lean methane-oxygen flame [32] the molar fractions of electrons, the degree of ionization δ , is on the order of 10^{-9} . This information can be used in expression (5) by using the ideal gas law:

$$n = \frac{p}{k_B T} \tag{6}$$

which gives the electron density n_e as:

$$n_e = \delta n = \frac{\alpha p}{k_B T} \tag{7}$$

Expression (5) transforms into:

$$I = \frac{9.6 \cdot 10^{-16} \cdot \delta VA}{k_B T d} \tag{8}$$

Making the very bold assumption that $\delta = 10^{-9}$ is valid in the flame zone between the electrodes in the cone calorimeter and that the flame temperature is 1300 K this can be evaluated numerically (see Section 4.1.3 on the geometry of the electrodes):

$$I = \frac{9.6 \cdot 10^{-16} \cdot 10^{-9} \cdot 200 \cdot \pi \cdot 1.2 \cdot 10^{-3} \cdot 1.65 \cdot 10^{-3}}{1.38 \cdot 10^{-23} \cdot 1300 \cdot 3 \cdot 10^{-3}} = 22 \ \mu \text{A}$$
⁽⁹⁾

This is more or less in the same order of magnitude as the results of the measurements in the cone colorimeter, where the current was in the range $1 - 10 \ \mu A$ [1, 2]. The current in expression (9) is not more than an indication since the degree of ionization may vary significantly between different flames [32, 33] and the contact area between flame and electrode may be smaller than the full area of the electrode [9, 34].

Other parameters also affect the current, for instance the availability of electrons. If the electron emission from the negative electrode is dominated by thermionic emission the current density J on the surface is given by [9, 29]

$$J = CT^2 e^{-\frac{\varphi}{k_B T}} \tag{10}$$

Where

C is a constant [Am⁻²K⁻²]

 φ is the work function of the metal, that is the energy required to leave the metal surface [J]

The work function in its turn depends on the external electric field [35]. Other parameters affecting the current is gas flow [36] and gas composition [29].

2.2 Electric breakdown

If electron losses, due to for example recombination and attachment to walls, are ignored the current to the anode will equal the current of emitted electrons from the cathode, I_0 . This is valid as long as the voltage over the electrode gap is low enough that no ionization due to collisions between accelerated electrons and molecules occur. If the voltage increases further ionization will subsequently start. This is characterized by Townsend's coefficient for ionization, α [m⁻¹].

$$\alpha = Ape^{-\frac{Bp}{E}} \tag{11}$$

where

Ais a constant $[m^{-1}Pa^{-1}]$ Bis a constant $[Vm^{-1}Pa^{-1}]$ Eis the electric field $[Vm^{-1}]$

 α is the number of ionization events caused by one electron per unit length [29]. Due to the ionizations the current at the anode becomes:

$$I = I_0 e^{\alpha d} \tag{12}$$

Obviously the total current will be the same at the cathode. The current at the cathode consists of the initial electron current I_0 and an ion current which is

$$I_{ion} = I - I_0 = I_0 (e^{\alpha d} - 1)$$
⁽¹³⁾

In other words each electron in the initial electron current generates $e^{\alpha d} - 1$ ions in the electrode gap. For sufficiently high electric fields the positive ions hitting the cathode will knock out electrodes. The number of so called secondary electrons that each ion hitting the cathode knocks out is denoted γ .

The total electron current I_e from the cathode therefore becomes

$$I_e = I_0 + \gamma I_{ion,\gamma} \tag{14}$$

Where $I_{ion,\gamma}$ means that it is the total ion current, that is

$$I_e = I_0 + \gamma I_{ion,\gamma} = I_0 + \gamma I_e \left(e^{\alpha d} - 1\right)$$
⁽¹⁵⁾

In expression (15) the ion current is calculated based on the total electron current I_e and not based on the initial electron current I0. This reason for this is obvious; when secondary emission is taking place I_0 should be replaced by I_e in both expressions (12) and (13). The total electron current leaving the cathode becomes

$$I_e = \frac{I_0}{1 - \gamma(e^{\alpha d} - 1)} \tag{16}$$

Finally the total current at the anode becomes, taking into account the emitted electron current from the cathode and the ionization in the electrode gap:

$$I = \frac{I_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \tag{17}$$

A transition from a non self-sustained current to a self-sustained current (that is an electric breakdown) occurs when the denominator becomes zero:

$$1 = \gamma \left(e^{\alpha d} - 1 \right) \tag{18}$$

that is

$$\alpha d = \ln\left(\frac{1}{\gamma} + 1\right) \tag{19}$$

Substituting (11) into (19), and using E=U/d gives

$$Apde^{-\frac{Bpd}{V}} = ln\left(\frac{1}{\gamma} + 1\right)$$
(20)

that is

$$V = \frac{Bpd}{\ln\left(\frac{A}{\ln\left(\frac{1}{\gamma} + 1\right)}\right) + \ln(pd)}$$
(21)

Expression (21) is known as Paschen's law [37]. Whereas reasonably well defined experimental data of the gas phase properties *A* and *B* exist in the literature, information on γ is very scattered since this is a quite complex parameter depending on, among many factors, the state of the cathode surface. Often values of $\gamma \sim 10^{-1} - 10^{-2}$ are assumed [29]. See Table 1 for a list of tabulated data from the literature.

Gas	$A [m^{-1}Pa^{-1}]$	$B [Vm^{-1}Pa^{-1}]$	γ[]	
.	[29]	[29]	1 2 10-6	5001
N_2	9	257	>1.3.10°	[29]
O ₂	7	206	$10^{-7} - 4.5 \cdot 10^{-2}$	[29]
Air	11	274	$8 \cdot 10^{-6} - 1.5 \cdot 10^{-4}$	[29]
			10 ⁻²	[38]
H ₂	4	99	$10^{-6} - 2.4 \cdot 10^{-3}$	[29]
H ₂ O	10	218		
CO ₂	15	220		

Table 1Coefficients in different gases for Townsend's coefficient for ionization (11) and for
Paschen's law (21).

As an example, the breakdown voltage for a 3 mm electrode gap (such as in the cone calorimeter) at atmospheric pressure (101 kPa) would become

$$V = \frac{274 \cdot 101 \cdot 10^3 \cdot 3 \cdot 10^{-3}}{\ln\left(\frac{11}{\ln\left(\frac{1}{10^{-2}} + 1\right)}\right) + \ln(101 \cdot 10^3 \cdot 3 \cdot 10^{-3})} = 13 \text{ kV}$$
(22)

The can be compared with typical values for the dielectric strength of air which is 3.2 kVmm^{-1} at atmospheric pressure [29].

Strictly speaking the breakdown voltage in expression (21) is rather dependent on the molecule concentration than on pressure. This means that if the pressure is constant and temperature increases the breakdown voltage will decrease.

Furthermore, in a flame environment the gas properties obviously differs from the properties of air. For example electrons and ions much more abundant in flame zones than in air. In one study [22] it was found that the flame reduced the dielectric field strength to one seventh that of air. In other words the breakdown voltage is expected to drop when ignition occurs.

The theory for breakdown voltage described here is valid for moderate products of pressure and gap distance, $pd < 300 \text{ Pa} \cdot \text{m}$ [29]. Since the experiments in this study has been performed at atmospheric pressure and with a gap distance of 3 mm this is really at the limit of the applicability of the theory. For high products of pd the breakdown is better described by the faster processes of spark discharges (streamers) [29, 39]. However, the theory above is only used for a qualitative interpretation of the experimental results so the physics of streamers will not be described.

3 Experimental methods

3.1 Electrical measurements

The majority of tests were performed with the type of electrode assembly originally used in the cone calorimeter. Figure 1 shows such an electrode, supplied by Fire Testing Technology Limited, East Grinstead, UK.



Figure 1. Original equipment electrode assembly for the cone calorimeter.

3.1.1 DC measurements of ion currents without electric breakdown

The basic schematics of the circuit for the DC measurements, see Figure 2, were similar to the circuit used in a previous study [1, 40]. The main difference is that the new circuit was more thoroughly grounded, see Figure 3, and sealed, see Figure 3 and Figure 4. The ion current was measured using an oscilloscope (Tektronix TDS 1002B, 60 MHz bandwidth) that measured the voltage over a 100 k Ω shunt resistance. For some tests, in order to increase the signal to noise ratio, the shunt resistance was removed, forcing the current to pass through the 1 M Ω resistance of the oscilloscope.



Figure 2. Schematics for the DC-measurements circuit.



Figure 3. Careful grounding and shielding of the leads was necessary for reduction of electric noise.



Figure 4.

The shunt resistance and connections were enclosed in a steel box.

In addition to reducing the noise, actions were also taken to increase the ion current. For this purpose the applied voltage was, for some tests, increased from 200 VDC to 1000 VDC. Also, in order to increase the ion current, tests were made with larger electrodes, see Figure 5.



Figure 5. Modified electrodes with enhanced surface area.

3.1.2 Measurements of breakdown voltage

The circuit creates a fast increase in the electrical potential between the electrodes at a given frequency. The increase in the electrical potential leads into an electrical discharge once the potential between the electrodes is high enough to break the dielectric capacity of the medium contained in the measuring volume, i.e. the gap between electrodes.

The circuit basically consists of a transformer with its primary winding connected to a direct current source that is switched on and off by a power transistor (T2); meanwhile its secondary winding is directly connected to the electrodes, see Figure 6 and Table 2. The transformer is of the step-up type with an iron core and a relation of turns between the secondary and the primary windings close to 100:1 (X1). The inductance of the primary and secondary windings of X1 are 9.9 mH and 44 mH, respectively.

The power transistor is configured to act as a fast switch, closing the circuit when it receives a square pulse from the control unit and opening the circuit when the pulse ceases. The frequency and duration of this pulse can be controlled on demand. When the transistor closes the circuit, the primary coil of the transformer is energised and its magnetic field commences to rise without reaching saturation. When the transistor opens the circuit, the coil faces a rapid change in the current flowing through it and the magnetic field, which was stored in it, is transformed into a large electrical potential between its terminals.

The circuit was supplied with direct current with a potential and current flowing through it of 10 V and 0.55 A, respectively. The high voltage pulse was produced with a repetition rate of 50 Hz.

The rising time of the pulse could be controlled by means of modifying the capacitance of the capacitor (C3) which is connected in parallel to the switching transistor. A component with higher capacitance leads to a slower rising time and a component with lower capacitance to a faster rising time. A schematic of the electronics used to create the high voltage to the electrodes is shown in Figure 6.





Table 2Component list for the electronics used to create the high voltage pulse to the electrodes.
See Figure 6.

Symbol	Value/Type
R1 & R2	250 Ω
R3 & R8	10 kΩ
R4	1-10 kΩ
R5 & R6	100 Ω
R7	10 Ω
C1	4700 μF
C2	1 µF
C3	8.2 nF
T1	BC337NPN
T2	IRF740
D1	L-7104GD
D2	L-7104YD
D3 & D4	1N4005
X1	B 0221119027

The potential across the electrodes was measured using a resistive voltage divider and commercial Tektronix P6015A. The resistive voltage divider consisted of two resistors, one of 1G Ω and other of 1M Ω which were connected in series across the electrodes. The latter resistor and the oscilloscope (1 M Ω) were connected in parallel. A schematic of the voltage divider is shown in Figure 7.





The reason to build a simple voltage divider is that it is a cost effective solution and furthermore the plastic details of the commercial Tektronix probe were not compatible with the high heat fluxes near the cone calorimeter. When measuring the breakdown voltage, the voltage divider measures a higher voltage compared with the Tektronix probe. One explanation could be that the inductance of the voltage divider is high for signals with fairly fast rise times but that the Tektronix is better designed for dynamic measurement. This is of minor importance in this study since the goal is to see if for example pyrolysis and ignition affects the breakdown voltage are difficult to measure, even with commercial probes, for fast processes such as those studied in this report. All results presented in this report are obtained using the low cost voltage divider.



Figure 8

The cone heater and burning sample with different leads indicated. a) leads to the high voltage coil, b) leads to the voltage measurement circuit, c) leads to the original electrode pair of the equipment, not used here.



Figure 9. High voltage pulse from the circuit shown in Figure 6.

An example of a typical pulse, generated by the above described circuit, is shown in Figure 9 where the potential between the electrodes is plotted as a function of time. It can be observed that the potential between the electrodes rises until an electrical discharge occurs between them. Hereafter the potential falls as a consequence of the ionisation of the gases in the measuring volume.

The average of sixty-four pulses, each of them sampled at a rate of 100 MS/s, was recorded and stored by the acquisition system. Thereafter, the maximum voltage between electrodes was measured digitally for each set of data, thus obtaining the breakdown voltage against time. This data was filtered using a low-pass filter.

3.2 Fire sources

3.2.1 Propane burner

In the first part of the measurements of breakdown voltage a well controlled 1 kW propane burner was used, as shown in Figure 10. The burner comply with the IEC 60695-11-2:2003 standard [41]. Well ventilated combustion conditions were used with 650 ± 30 ml/min propane and 10 ± 0.5 l/min air fed to the burner, corresponding to an equivalence ratio of 1.6, resulting in a blue flame.



Figure 10 The propane burner used in the measurements of breakdown voltage.

3.2.2 Cone calorimeter

The cone calorimeter [3] was used for most of the measurements, schematically illustrated in Figure 11. 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 levels used in this study were 25 and 50 kW/m².

The cone calorimeter can be used to measure time to ignition, HRR (Heat Release Rate), SPR (Smoke Production Rate), and MLR (Mass Loss Rate) of the tested object. It is also possible to sample the exhaust gases to an FTIR spectrometer or other external analysers to measure for example unburned hydrocarbons and toxic gases such as NO, HCl, and HCN for example. No external gas characterisation measurements were performed in this study.



Figure 11 Schematic picture of the cone calorimeter.

Normal operation of the cone calorimeter requires pilot ignition of the pyrolysis gases. This is achieved by a spark igniter actually consisting of the same spark gap as that shown in Figure 1. For the measurements of breakdown voltage in Section 4.2.2 the test electrodes simply acted as the pilot. For the measurement of ion current in Section 4.1.1, without electrical breakdown, no pilot was used.

3.2.2.1 Fuels used in cone calorimeter

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

- Polyurethane foam with a density of 21 ± 1 kg/m3. 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.
- Black PMMA, poly(methyl methacrylate), with a density of 1180±50 kg/m3. The area of the specimens where 100 mm x 100 mm and the thickness was 10 mm.

The fuels are shown in Figure 12 to Figure 14.



Figure 12 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 13 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.



Figure 14 Black PMMA used in the experiments. The specimens have dimensions 100 mm x 100 mm x 10 mm and a density of 1180±50 kg/m3.

3.2.3 Smouldering combustion

An attempt was made to detect changes in the breakdown voltage during smouldering combustion. For this purpose EN 1021-1 was used [42]. Figure 15 shows the setup including an upholstered furniture mock-up, cigarettes, and the measurement equipment for breakdown voltage. The upholstered furniture mock-up consisted of standard PUR-foam, see Figure 12 clad with blue cotton textile.



Figure 15 The test setup for smouldering combustion according to EN 1021-1.

4 **Results and discussions**

4.1 DC measurements of ion currents without electric breakdown

The purpose of these tests were twofold. Firstly, to investigate whether the signal to noise ratio could be improved as compared to the previous, unshielded circuit. Secondly, to determine whether the new circuit, with increased applied voltage, could be used to detect pyrolysis gases. In the previous study it was found to be a straightforward task to detect flames with a DC-circuit but no attempts were made to study pyrolysis gases or a smouldering fire. Finally the relation between the ion current and the conductivity in the electrode gap was calculated and the calculations could be validated by experiment.

4.1.1 Improved signal and signal to noise ratio

In order to assess the new circuit a representative result obtained with the previous, unshielded, circuit is shown in Figure 16 [1].



Figure 16. Ion current measured at the ignition of a particle board subjected to 50 kWm-2 irradation [1]. The measurement circuit was unshielded. The applied voltage was 200V and the shunt resistance was 100 k Ω .

Figure 17 shows the ion current measured with the new circuit. It is clear that the signal to noise ratio has improved considerably.



Figure 17. Ion current measured with the new shielded circuit, see Figure 3 and Figure 4. The applied voltage was 200V and the shunt resistance was 100 kΩ.

Tests were also performed with the $100 \text{ k}\Omega$ shunt resistance removed. This forces all the current to pass through the $1 \text{ M}\Omega$ resistance of the oscilloscope, and thereby increasing the voltage signal in the oscilloscope. A representative result is shown in Figure 18. There is no significant evidence that removing the shunt resistance increases the signal to noise ratio.



Figure 18. Ion current measured with the new shielded circuit. The applied voltage was 200V and there was no external shunt resistance, meaning that all current passed the 1 MΩ resistance of the oscilloscope.

In order to increase the ion current the applied voltage was increased to 1000 V. A representative result is shown in Figure 19. The ion current clearly increased as can be seen by comparing with the typical result using 200 V, shown in Figure 17. Although only selected, albeit fairly representative, results are shown here they describe the general behaviour of the system. A rough estimate of the minimum resistance in the electrode gap is $10^8 \Omega$. This is obtained using Ohm's law, R=U/I, and approximating the result in Figure 17 with $R = 200 \text{ V} / 2 \times 10^{-6} \text{ A}$, or approximating the result in Figure 19 with $R = 1000 \text{ V} / 10 \times 10^{-6} \text{ A}$. It has previously been shown that the ion current follows Ohm's law [1, 40].



Figure 19. Ion current measured with the new shielded circuit. The applied voltage was 1000V and the shunt resistance was 100 kΩ.

One proposal for increasing the ion current, thereby making the method more sensitive, has been to increase the surface size of the electrodes. Tests were therefore performed with the large electrode surfaces shown in Figure 5. A result is shown in Figure 20. The ion current is relatively high but not significantly different from the current in, for example, Figure 19.



Figure 20. Ion current measured with the large electrodes, see Figure 5, and the new shielded circuit. The applied voltage was 1000V and there was no external shunt resistance, meaning that all current passed the 1 MΩ resistance of the oscilloscope.

Using such large electrodes will introduce some problems. Due to the large size of the electrodes the irradiation from the resistively heated spiral will not reach certain areas of the tested sample, see Figure 21. Since the shadowed (the non-darkened) area is significant this might affect, for example, the HRR, which is an unwelcome effect. Furthermore, the flames might be quenched when they enter the gap between the electrodes, which could explain the absence of ion current increase using these electrodes. Therefore this approach was not found to be interesting for further development.



Figure 21. Shadow effect on the exposed sample due to the large electrodes in Figure 5.

4.1.2 Measurements on pyrolysis gases

Despite several attempts it was not possible to measure a current due to pyrolysis gases. The applied voltage was increased to 1000 VDC and the large electrodes in Figure 5 were tested but no signal above the noise level could be detected. A plausible explanation is that the increase in electron density, or ion density, is simply not large enough to give a measurable change in the conductivity of the pyrolysis gases.

For this reason another approach was investigated in order to measure pyrolysis gases, i.e. measurement of the breakdown voltage. As will be seen below this method can be used both for measuring the onset of pyrolysis as well as for detecting ignition.

4.1.3 Ion current vs. conductivity

When measurements are performed the result is a current. This is not a direct property of the gas between the electrodes. Rather, in order to characterize the gas in the gap the conductivity is the physical property of choice. Therefore the relation between current and conductivity is investigated here.

The resistivity is given by

$$\rho = R \frac{A}{d} \tag{23}$$

Where

R is the resistance $[\Omega]$

A the cross sectional area of the electrode gap $[m^2]$, and

d the separation between the electrodes [m]

and the conductivity is simply the inverse of the resistivity

$$\sigma = \frac{d}{AR} \tag{24}$$

The geometrical details of the electrode pair are given in the upper part of Figure 22. The distanced between the electrode surfaces is 3 mm and the two radii required to calculated the exposed electrode area in the gap are $r_1 = 2.4/2=1.2$ mm and $r_2=3.3/2=1.65$ mm. The area is, therefore

$$A = \pi r_1 r_2 \tag{25}$$



Figure 22 Details of the electrode pair and the measurement of conductivity.

The resistance is simply calculated using Ohm's law, R=U/I, yielding a conductivity of

$$\sigma = \frac{I}{U} \cdot \frac{d}{A} = \frac{I}{U} \cdot \frac{d}{\pi r_1 r_2} \cong 482 \text{m}^{-1} \cdot \frac{I}{U}$$
⁽²⁶⁾

In Figure 16, Figure 17, Figure 18, and in most figures in reference [1] the applied voltage was 200 V. Therefore

$$\sigma \simeq 482 \frac{I}{U} = 482 \text{m}^{-1} \frac{I}{200V} = 2.41 \text{m}^{-1} \text{V}^{-1} \cdot I$$
⁽²⁷⁾

The ion current in these figures can therefore simply be transformed to conductivity [Sm⁻¹] by multiplying the ion current [A] by a factor 2.41.

Expression (26) was validated by a calibration in a saline solution with known conductivity σ =1.390 Sm⁻¹. The applied voltage was 13 V and the current 35 mA. Therefore

$$\sigma \simeq 482 \cdot \frac{35 \cdot 10^{-3}}{13} = 1.3 \,\mathrm{Sm}^{-1} \tag{28}$$

This is within 7% of the true conductivity of the salinity which is acceptable given the measurement uncertainties.

Expression (26) will not be used further in this report but is an important reference for theoretical attempt to explain the ion current results. Due to effects of the sharp edges of the electrodes, the expression is probably not valid for measurements of voltage and current at electrical breakdown.

Finally, if a significant part of the current is due to thermionic emission of electrons from the cathode the current will depend on the cathode temperature, see Eq. (10).

4.2 Measurement results of breakdown voltage

Results from the measurements conducted using the intermittent spark dispositive described in Section 3.1.2 are presented in the following sections. Measurements presented below were conducted using the cone calorimeter and a well characterised burner. The latter was employed to improve the understanding of the behaviour and limitations of the measuring system before it was applied to the cone calorimeter.

4.2.1 Measurements in a 1 kW propane flame

Measurements of the breakdown potential done along the symmetry axis, and across the standardised propane flame at two heights, are shown in Figure 23. The measurement setup is shown Figure 10. It is possible to observe that, at the bottom of the flame end just before the mixing zone, the breakdown voltage is high and decreases as a function of height above the burner. It is also observed that around 180 mm HAB (Height Above Burner), the breakdown voltage increases due to the fact that the measurements are then conducted outside the reaction borders of the flame but measure in hot gases.



Figure 23. Breakdown voltage for a propane flame. U_{breakdown} is showed for several height above the burner in the flame center, and for several off-center radii (distance to the flame center) for the heights 55 mm and 105 mm.

4.2.2 Measurements in the cone calorimeter

A fixed protocol was followed in all measurements:

t = 0 s	data acquisition started
t = 10 s	the sample was introduced under the cone heater but the radiation shield protected the sample from direct irradiation
t = 20 s	the radiation shield was removed and the specimen was exposed to the set irradiation level; 25 kWm^{-2} or 50 kWm^{-2} .

The time to ignition was observed visually in addition to the drop in $U_{breakdown}$ observed in the results below.

4.2.2.1 Particle board

4.2.2.1.1 Ubreakdown vs. HRR

Figure 24 show the breakdown voltage and HRR for a measurement on a particle board with 50 kWm⁻² irradiation level. It is clearly seen that $U_{breakdown}$ drops significantly when ignition occurs at 50 s. Figure 25 shows a close-up of the dynamics around the time of ignition. The measurements continued for approximately 1000 s, for the case 50 kWm⁻² on particle board. For other measurements the typical sampling time was around 200 s.



Figure 24. Particle board. 50 kWm⁻². *t_{ignition}*=50 s.



Figure 25. Particle board. 50 kWm⁻². t_{ignition}=50 s. Close-up around ignition.

In Figure 26 and Figure 27 the results for an irradiation level of 25 kWm⁻² are shown, with different scales on the time-axis. $t_{ignition}$ is now 144 s and a distinct drop in $U_{breakdown}$ is seen when ignition takes place.



Figure 26. Particle board. 25 kWm⁻². t_{ignition}=144 s.



Figure 27. Particle board. 25 kWm⁻². t_{ignition}=144 s. Close-up around ignition.

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The initial $U_{breakdown}$ is some kV lower when the irradiation level is 25 kW compared to when it is 50 kW. This is easily seen by comparing Figure 25 with Figure 27. The reason for this is unclear since in fact the opposite trend could be expected. Higher temperature means lower molecule concentrations, which typically would lead to a lower breakdown voltage, see Eq. (12) and the subsequent discussion. The trend towards a lower breakdown voltage for lower radiation level can also be seen by comparing Figure 33 with Figure 35 (PUR-foam) or comparing Figure 40 with Figure 42 (black PMMA).

4.2.2.1.2 Ubreakdown vs. SPR

Figure 28 shows the same $U_{breakdown}$ as in Figure 24 but this time compared to the SPR on the right ordinate. Figure 29 shows a close-up around $t_{ignition}$.



Figure 28. Particle board. 50 kWm⁻². t_{ignition}=50 s.



Figure 29. Particle board. 50 kWm⁻². t_{ignition}=50 s. Close-up around ignition.



Figure 30. Particle board. 25 kWm⁻². t_{ignition}=144 s.

When studying results like those shown in Figure 30 it should be observed that the SPR is completely spatially averaged since all smoke from the sample is collected in the exhaust hood, mixed, and measured in the smoke optical density measurement system, see Figure 11. By comparison, the measurement of $U_{breakdown}$ is an in-situ measurement well localized to the electrode gap, although in the presented figures there is a temporal averaging of 64 samples, corresponding to 1.2 s. This could explain the dip in $U_{breakdown}$ that is observed at 80 - 110 s, which has no clear corresponding peak in the SPR curve.



Figure 31. Particle board. 25 kWm⁻². t_{ignition}=144 s. Close-up around ignition.

4.2.2.2 PUR-foam

The results for PUR-foam are shown in Figure 32 to Figure 39. The major difference as compared to the particle board is that ignition takes place much faster, just one or a few seconds after removal of the radiation shield at t = 20 s.



Figure 32. PUR-foam. 50 kWm⁻². t_{ignition}=21 s.

It is interesting to observe that $U_{breakdown}$ stays at a relatively low level in Figure 32 for t > 100 s although the HRR drops. The same phenomena is observed when a comparison is made with the SPR, see Figure 36. The major influence on $U_{breakdown}$ is rather a decrease in the noise amplitude.



Figure 33. PUR-foam. 50 kWm⁻². t_{ignition}=21 s. Close-up around ignition.

In Figure 34 the irradiation level was 25 kWm⁻² and $t_{ignition} = 24$ s. This is also reflected in the drop in $U_{breakdown}$, especially in Figure 35.



Figure 34. PUR-foam. 25 kWm⁻². $t_{ignition}$ =24 s.



Figure 35. PUR-foam. 25 kWm⁻². *t_{ignition}*=24 s. Close-up around ignition.

4.2.2.2.2 Ubreakdown vs. SPR

The same $U_{breakdown}$ as in Figure 32 to Figure 35 is shown in Figure 36 to Figure 39 below, but this time compared to the SPR.



Figure 36. PUR-foam. 50 kWm⁻². t_{ignition}=24 s.



Figure 37. PUR-foam. 50 kWm⁻². t_{ignition}=24 s. Close-up around ignition.



Figure 38. PUR-foam. 25 kWm⁻². t_{ignition}=24 s.



Figure 39. PUR-foam. 25 kWm⁻². t_{ignition}=24 s. Close-up around ignition.

4.2.2.3 Black PMMA

4.2.2.3.1 Ubreakdown vs. HRR

Finally results for black PMMA are shown. In Figure 40 there is a drop in $U_{breakdown}$ when ignition occurs at t = 51, although this drop is not so distinct.



Figure 40. Black PMMA. 50 kWm⁻². t_{ignition}=51 s.



Figure 41. Black PMMA. 50 kWm⁻². *t_{ignition}*=51 s. Close-up around ignition.



In Figure 42, where the irradiation level was 25 kWm⁻² and $t_{ignition} = 151$ s, the correlation between ignition and a distinct drop in U_{breakdown} is very good.

Figure 42. Black PMMA. 25 kWm⁻². t_{ignition}=151 s.



Figure 43. Black PMMA. 25 kWm⁻². t_{ignition}=151 s. Close-up around ignition.

4.2.2.3.2 Ubreakdown vs. SPR

The correlation between $U_{breakdown}$ and SPR is relatively good, especially for the 25 kWm⁻² case, see Figure 47.



Figure 44. Black PMMA. 50 kWm⁻². *t_{ignition}*=51 s.



Figure 45. Black PMMA. 50 kWm⁻². t_{ignition}=51 s. Close-up around ignition.



Figure 46. Black PMMA. 25 kWm⁻². t_{ignition}=151 s.

Figure 47. Black PMMA. 25 kWm⁻². t_{ignition}=151 s. Close-up around ignition.

4.2.3 Attempt to measure smouldering fires

Finally an attempt was made to measure a change in the breakdown voltage when the electrodes were positioned above a smouldering cigarette in an upholstered furniture mock-up, see Section 3.2.3. No significant change in $U_{breakdown}$ could be measured.

There is one major difference between the measurement of smouldering fire, Figure 15, and the measurements in the propane flame and the cone calorimeter, Figure 10 and Figure 8 respectively. The temperature is very high in the flames of the propane burner and the cone calorimeter. Even for the cone calorimeter before ignition the temperature is high and increasing. By contrast, the temperature above the smouldering fire is quite constant and not significantly higher than the ambient room temperature. This means that the change in $U_{breakdown}$ due to changed air density does not come into play for the smouldering fire in the same way as it does for the propane burner and the cone calorimeter. On the other hand the results show that increased temperature, due to removed radiation shield, is not the supreme parameter affecting $U_{breakdown}$. For example, in Figure 30, $U_{breakdown}$ does not start to decrease significantly at 20 s when the radiation shield is removed, but rather at \sim 75 s when the pyrolysis gases, as measured by the SPR, start to appear. This is in contrast to the results in Figure 29 where the decrease in $U_{breakdown}$ starts immediately at the time of shield removal, but where also the SPR starts to increase at the time of shield removal. Furthermore the correlation between temperature (or density) and $U_{breakdown}$ is not trivial, as discussed at the end of Section 4.2.2.1.1.

Although measurement of smouldering fires did not succeed in this project this does not mean that there is no hope for using the electrodes for this purpose. There are many possible refinements possible for the method as will be discussed below.

5 Conclusions

It has been shown that the signal to noise ratio of DC current measurements can be greatly improved by careful shielding and grounding of the measurement equipment. This enables more sensitive detection of the ignition phase. It was also shown that the current can straightforwardly be translated into electric conductivity which is a property that better lends itself to a description of the status of the gas between the electrodes.

It was not possible to detect a current above the noise level for the pyrolysis phase, neither by increasing the applied voltage to 1000 VDC nor by increasing the size of the electrodes. The explanation for this is probably that the concentration of electrons and ions is much lower for the pyrolysis gases than for the flame front. In order to measure pyrolysis gases with the electrodes another property was investigated, the breakdown voltage, $U_{breakdown}$.

The breakdown voltage correlated with HRR and SPR before and at ignition. After ignition the correlation was poor. This shows that, given the simple equipment used in this report, is possible to use the pilot ignition electrodes to detect pyrolysis gases and ignition. Indeed, this is possible to do at the same time as the electrodes perform the additional role of pilot ignition. In other words, it is possible to perform measurements of $U_{breakdown}$ without compromising with the ISO 5660 standard. In fact, according to the standard the spark igniter should be removed after ignition. In other words the low correlation after ignition is of no relevance if the standard is followed. The drop in $U_{breakdown}$ is not as distinct as the current pulses that appear using the DC measurements. However, this was only a first test of measuring $U_{breakdown}$ and there is clearly a potential for improvement of the methodology.

6 Future Work

Further research should aim at improving the response of the methods to weakly ionized gases such as pyrolysis gases and especially smoke from smouldering fire. The latter has not yet been measurable be any of the two methods tested.

The voltage divider probe did not give the same result as the commercial voltage probe. This is probably due to the relative high inductance of the voltage divider. The inductance will affect the probes accuracy when measuring dynamic processes. The performance of the voltage divider could be improved by either adding a compensating network or changing the resistors. An improved probe should be calibrated against known high voltage pulses and not against a commercial probe since the latter can give incorrect results for the type of demanding measurements performed in this study (high voltage, fast processes, EMC problems...).

One proposal for improving the response of the system is to study the time lag between the applied voltage and resulting current. This can be done quite straightforwardly with the method of electric breakdown as has been described in this report but an improved voltage probe and an appropriate current probe are required. For the DC measurements (without electric breakdown) it is clearly not possible to measure a time lag since the voltage is constant. Therefore a signal generator producing AC voltages would be required. When the atmosphere between the electrodes changes there will be a change in the capacitance, and therefore also a change in the the time lag. Measuring the change in time lag (capacitance) instead of the current (conductivity) can also be described as measuring electric dipoles instead of electric monopoles (free charges). The change in abundance of dipoles can be expected to vary more than the change of free charges since the latter require ionization or emission of electrons from the cathode. Changes in dipole concentration can occur more easily due to non-ionized chemistry in the pyrolysis of the fuel, in the flames, or in the smoke gases.

Electric flame diagnostics is not limited to the cone calorimeter. One interesting project would be to conduct a similar study to the one presented here but applied to the smoke box method [28] where under-ventilated combustion is studied.

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