

Experimental developments for measuring the initiation of mine fires

E. Querol *Laboratorio Oficial Madariaga. Universidad Politécnica de Madrid, Spain*

J. García Torrent *Laboratorio Oficial Madariaga. Universidad Politécnica de Madrid, Spain*

C. Grima Olmedo *Laboratorio Oficial Madariaga. Universidad Politécnica de Madrid, Spain*

A. Ramos Millán *Laboratorio Oficial Madariaga. Universidad Politécnica de Madrid, Spain*

Abstract

A scale model of a dead end gallery has been developed. After heated air flow was introduced, the increase in temperature and gases evolution were monitored. The ventilation was increased and the temperature was elevated to produce an ignition process.

Obtained data have shown significant measures of the self ignition mechanism, bringing a valuable tool to predict and early detect the process.

1 Principles and practices of spontaneous combustion

Spontaneous combustion means combustion without any externally applied heat source from a spark or a pilot flame, so that the departure of the internal temperature profile from being flat is due entirely to the material's own heat release by reason of chemical reaction.

Coal can interact with oxygen contained in the air at ambient temperatures liberating heat, which, if allowed to accumulate, would enhance the rate and ultimately, lead to fires known as spontaneous combustion of coal. At ambient temperatures the reaction is so slow that passes unnoticed. Although according to Arrhenius law an increase of the temperature makes the reaction rate to increase exponentially.

$$v = c_r \cdot c_o \cdot A \cdot e^{-\frac{Ea}{R \cdot T}} \quad (1)$$

where:

v = Reaction rate

c_r = Combustible concentration

c_o = Oxygen concentration

A = Arrhenius Frequency Factor

Ea = Activation Energy (J mole⁻¹)

R = Universal gas constant = 8.314 J mole⁻¹ K⁻¹

T = Temperature (K).

Obviously, the liberation of heat from coal due to interaction with oxygen is not enough; the physical conditions must satisfy heat accumulation situations for the initiation of spontaneous heating phenomenon. Thus, spontaneous heating would be facilitated in conditions where a large mass of coal is involved and ventilation is neither too little to restrict coal – oxygen interaction nor too big to dissipate away all the heat generated from above. Under such conditions, part of the coal mass may heat up to the stage of ignition after the lapse of a certain period of time. This time, between which the coal was first subjected to favourable conditions to spontaneous heating to the point of reaching ignition, is usually known as Incubation Period.

If however, conditions do not permit accumulation of heat, the heat liberated from coal oxygen interaction would be dissipated away. Soon, the coal, or more accurately, the affected coal surface reaches the stage of

saturation where no further interaction with oxygen, at ambient temperature, can occur. It is then said that the coal has become weathered. Such weathered coal is poor in calorific value and cooking properties.

The interaction of oxygen with coal is superficial and it is called adsorption. Porous solids may absorb a gas or a liquid or a substance in solution. This process of taking up of a substance by the solids is generally termed as sorption. If the accumulation occurs mainly at the surface of the solid, it is called adsorption, and is distinguished from absorption, meant for uniform penetration in the bulk of the solid.

The process of adsorption is always associated with the evolution of heat (exothermic) and is rather rapid, at least in its initial stage. To what extent a certain substance will be absorbed on the solid depends on the physical and chemical nature of both.

The reason for the adsorption phenomena has been attributed to the presence of a residual field of force at the surface of the absorbent solid, and thereby giving the surface a tendency for its free energy to decrease. Depending on the nature of operative forces, between the solid surface and the substance adsorbed (e.g. gas), two main categories of adsorption phenomena have been recognised. The processes where physical forces like inter – molecular attraction are responsible, are termed as physical adsorption or Van Der Waals' adsorption, but when operative forces are chemical in nature and are almost as strong as those existing in stable stoichiometric compounds, are called chemisorption or activated – adsorption.

The equilibrium between the solid and the gas in the case of physical adsorption is reversible and is associated with smaller heats of adsorption, e.g. 20 kJ/mole or less. But the forces responsible for chemisorption are generally irreversible or reversible with great difficulty. They are normally associated with much larger heat changes (bond energies), on the order of 80 kJ/mole to 400 kJ/mole.

Generally, physical adsorption predominates at low temperatures while chemisorption occurs at high temperatures. Chemisorption process has a very low rate at low temperature.

2 Experimental techniques to measure spontaneous combustion susceptibility of coals

Nowadays several techniques are employed in the characterization of the self-combustion behaviour of dusts (García Torrent, 2000). The fundamental ones used at Laboratorio Oficial Madariaga (García Torrent, 2000) are: Maciejask index, Volatile emission temperature, minimum ignition temperature (dust layer and dust cloud), self ignition temperature (isothermal oven), thermogravimetry (TG) and differential scanning calorimetry (DSC).

A single characterization index based in fast and reliable techniques, such as TG and DSC, to allow a preliminary classification with little amount of substances in a brief period of time is now possible following two procedures (García Torrent et al. 2004): TGO and Ea.

2.1 Thermogravimetry in oxygen flow (TGO)

Due to the oxygen stream used, the behaviour of the sample changes dramatically giving a curve profile (Figure 1) characterized mainly by a temperature in which the lost of weight is almost the whole weight lost of the sample (a very fast combustion of the product).

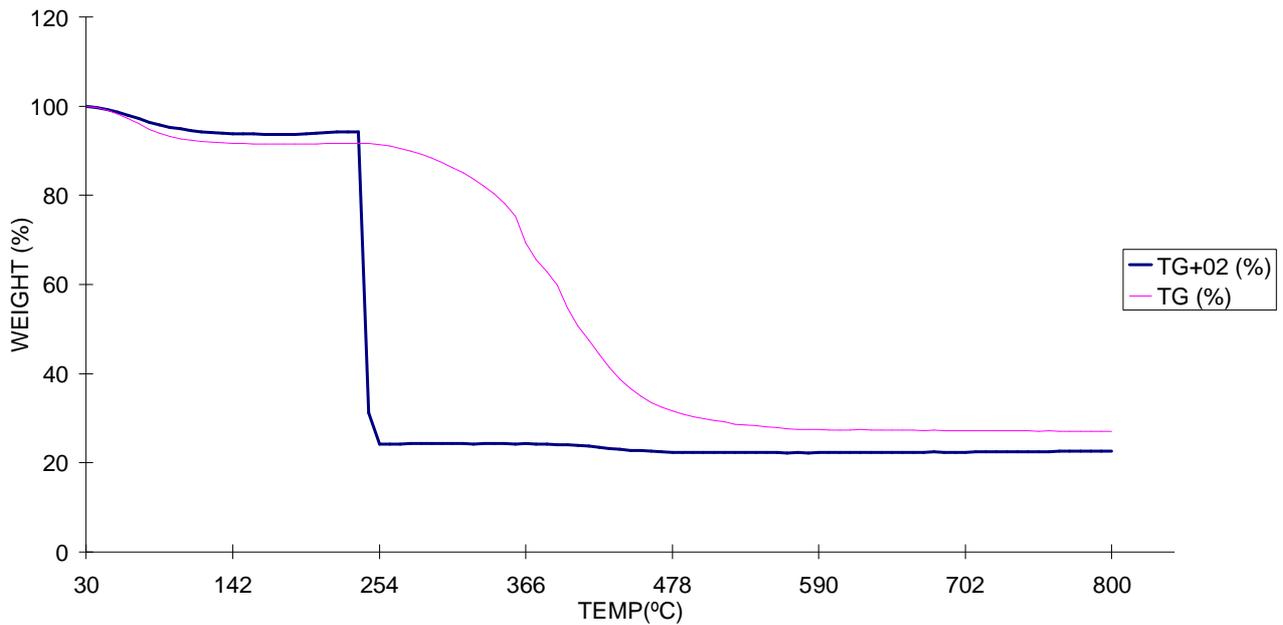


Figure 1 Comparison between TG and TGO (TG +O2).

2.1 Activation energy (Ea)

The Cummings kinetic model (Cumming, 1984) based on the loss of weight produced during heating coal samples gave as a result a relationship between the activation energy Ea and the rate of weight loss:

$$\ln\left(-\frac{1}{w} \cdot \frac{dw}{dt}\right) = \ln A - \frac{Ea}{RT} \quad (2)$$

where:

w = weight of unburned combustible

dw/dt = instantaneous rate of weight loss.

Thermogravimetry is used as the fundamental technique. Dust samples are subjected to a heating ramp, increasing the temperature at a constant rate, measuring the loss of weight. After recording the weight loss rate, a rather simple algorithm can be used to fit a line to the experimental points in the region of the maximum rate, obtaining a sort of apparent activation energy, used to compare the behaviour of substances.

During heating of samples, the loose of weight produced can be measured. The activation energy Ea and the rate of weight loose are related through the Cummings kinetic model already presented by equation (2).

3 Experimental set-up of a laboratory model

In order to study the influence of a heated air stream on coal, a simple model of a dead end typical in Spanish coal mines formed by a main gallery and a cross gallery was developed. A schematic view of this model is given in Figure 2.

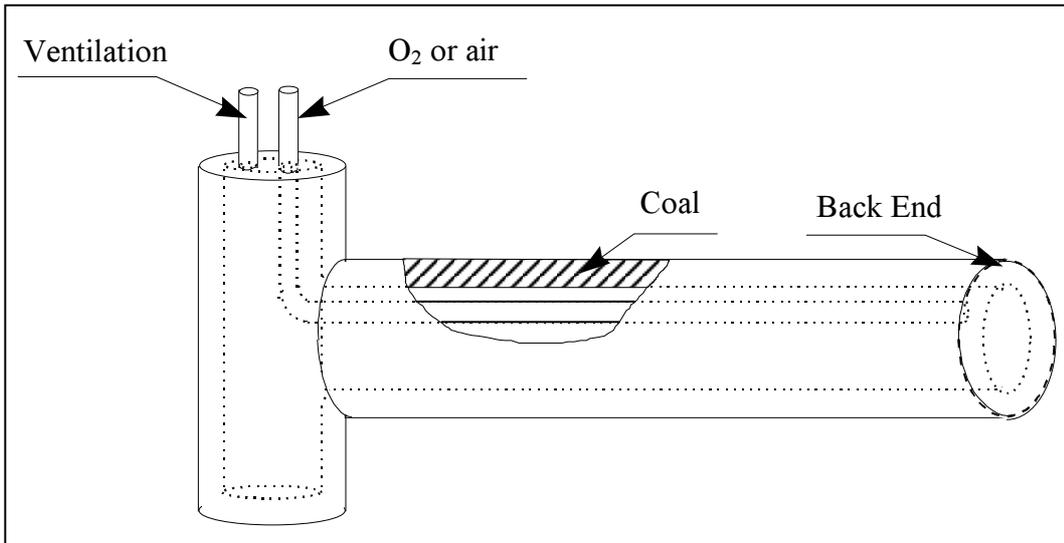


Figure 2 Laboratory model

Two metal cylinders are used to obtain a scale model from the shaft and the cross gallery. Inside both cylinders and concentric with them is placed a wire mesh. The space between the cylinders and the wire mesh is filled with a coal sample. Another two small cylinders allow the introduction of air or O₂ at different temperatures.

The tests were carried out with subbituminous coal from the mine “María y Regina”, whose composition is shown in table 1 and its characteristic parameters are presented in table 2.

Sample	Humidity (%)	Ash (%)	Volatiles (%)	CO ₂ (%)	C (%)	H (%)	S (%)
IMV-2	17,50	12,45	30,15	0,03	50,57	5,23	5,30

Table 1 Chemical composition of coal sample

Sample	MIT _L (°C)	MIT _C (°C)	MEC (g/m ³)	MIE (mJ)	Pmax (bar)	Kst (bar.m/s)
IMV-2	17,50	12,45	30,15	0,03	50,57	5,23

Table 2 Flammability and explosibility data

A general view of this model is given in figure 3, and the tests arrangements showing the position of thermocouples in figure 4.

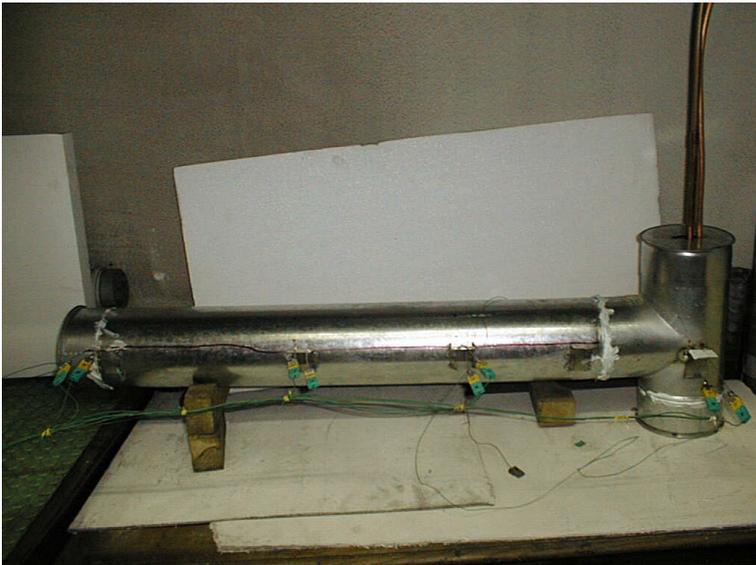


Figure 3 General view of the laboratory model

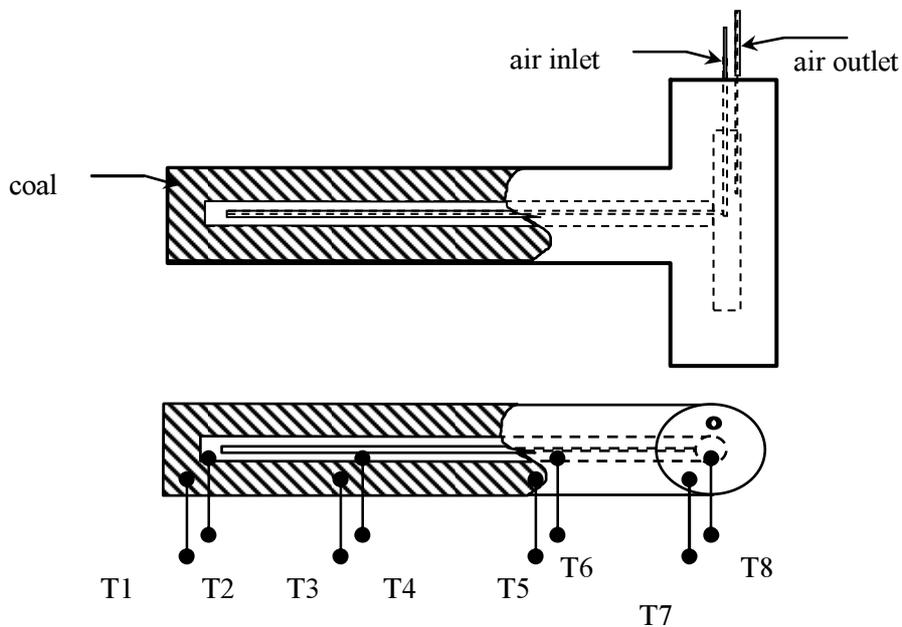


Figure 4 Position of thermocouples

Eight thermocouples, type K, are placed for temperature registration. They are placed in four groups. In each group one thermocouple is situated at the sample and the other one in the main air flow. So it is possible to record the temperature evolution in the sample and in the air by means of a data acquisition equipment.

4 Results and discussion

Figure 5 shows the construction of the physical model. At the beginning of the testing experimental procedure, an inert matter has been used just to check the heating and the adequate recording of the measurements. Figure 6 shows the temperature plot obtained during a test with sand.

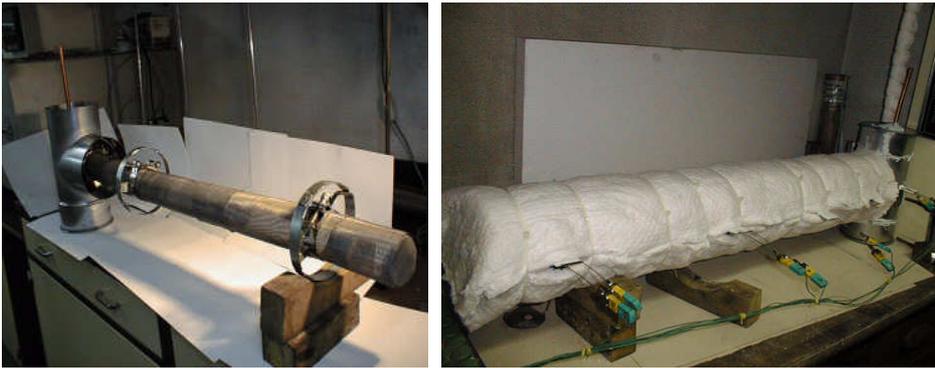


Figure 5 Construction of the physical model

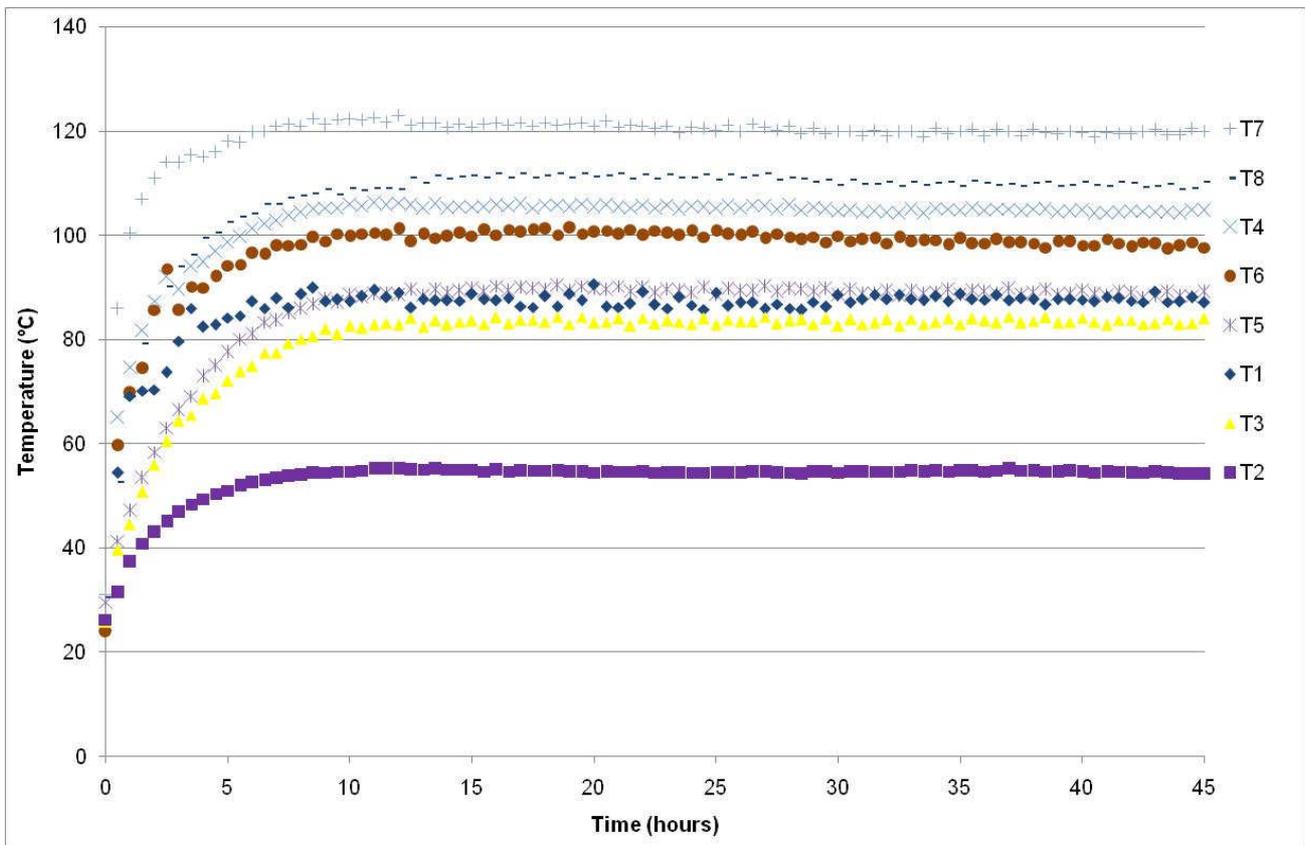


Figure 6 Temperature profile with sand with a hot air inlet

Several experiments were conducted increasing the air velocity from 40 l/min to 53 l/min. For lower air velocities, a general heating of the coal mass was observed in some experiments, but no ignition was obtained in any case. Figures 7 and 8 show the temperature recordings after 35 hours of test and an infrared image of the model obtained during heating.

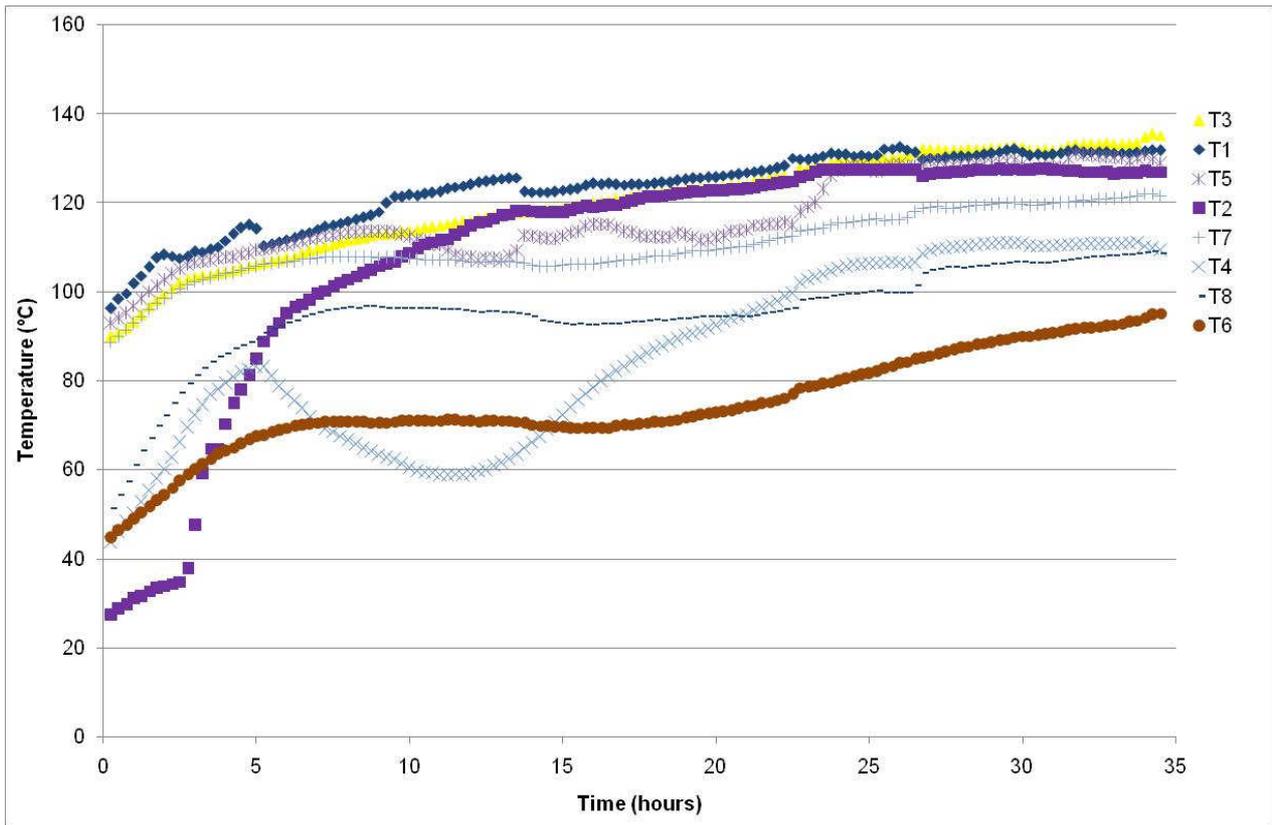


Figure 7 Temperature recording in the scale model

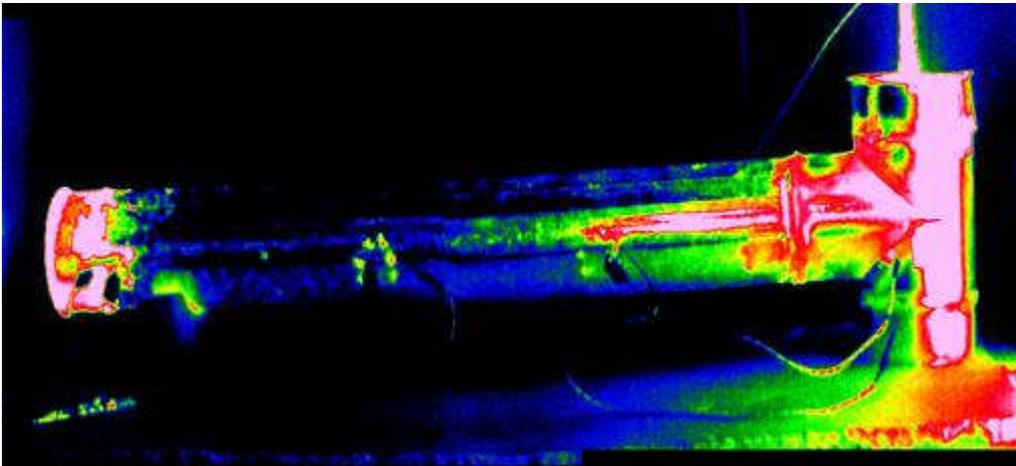


Figure 8 Infra-red temperature image of the scale model

As can be seen in this IR photograph, a perceptible heating is produced at the right, in the inlet area and also in the left area of the photo, which corresponds to the “dead end” of the simulated gallery.

Also, gas analyzers were connected to the air exhaust to detect any increase in the gases evolving from the coal mass. Figure 9 shows the results obtained in a non-ignition test. In this test series only a slight increase in CO was observed just after stopping the air circulation. Since the coal temperature only increased up to an apparent constant level and did not surpass the inlet air temperature, we could not assume any self-heating, but perhaps the increase in the CO gas was an evidence of the initiation of the coal-oxygen interaction.

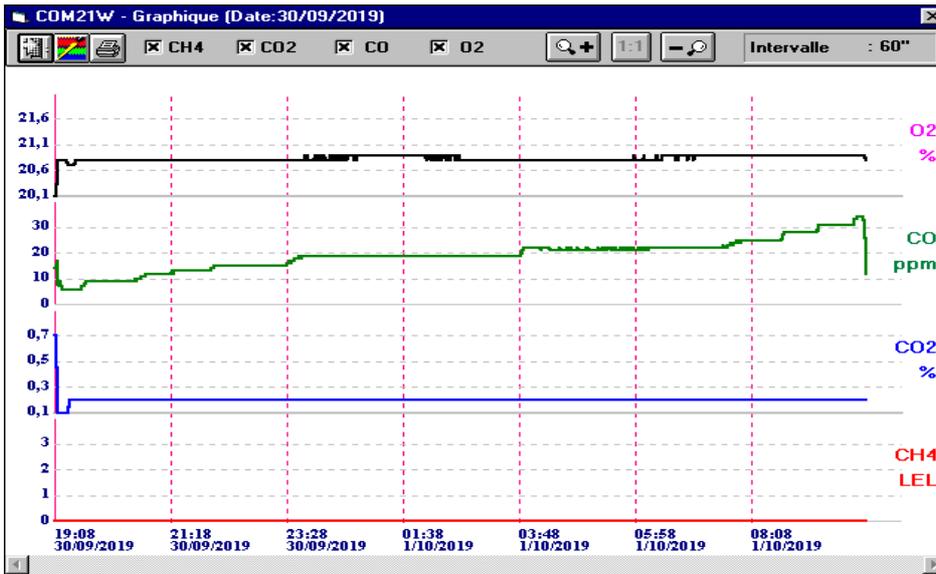


Figure 9 Gas analysis during testing

The inlet air was heated when it went through a pipe coil installed inside the drying oven heated at its maximum temperature. In order to reach higher inlet temperatures, the length of the coil was successively increased up to obtain the desired temperature in the inlet air flow.

Finally, for an initial temperature of 150°C the ignition of the coal was observed after 4 hours. Figures 10 and 11 represent the temperature and gas recordings, showing an obvious ignition of the sample: there is a clear output of CH₄ after some 240 minutes, together with the strong production of CO and CO₂, and coinciding with a decrease in the oxygen level.

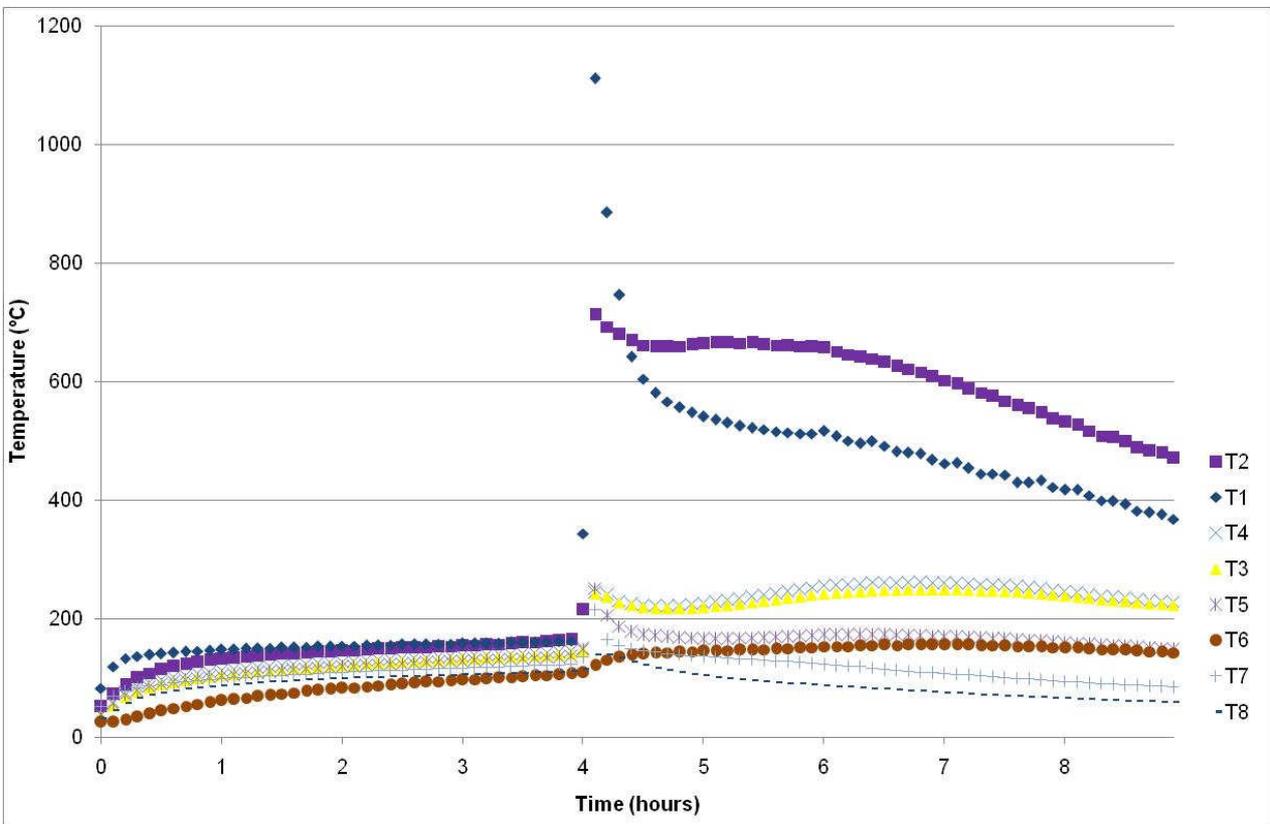


Figure 10 Temperature profile during a test with ignition at 240 minutes

It is important to remark that a clear discontinuity is observed in the four plots at 240 minutes time. However, in the CO plot it is also possible to see a slow but constant increase in the percentage of this gas after 60 minutes, and more clearly after 120 min. This important result confirms that CO can be detected in the first stages of the self heating, before the high velocity oxidation takes place and before the ignition appears. Thus, CO detection could be used in the model to predict the spontaneous combustion of the coal sample.

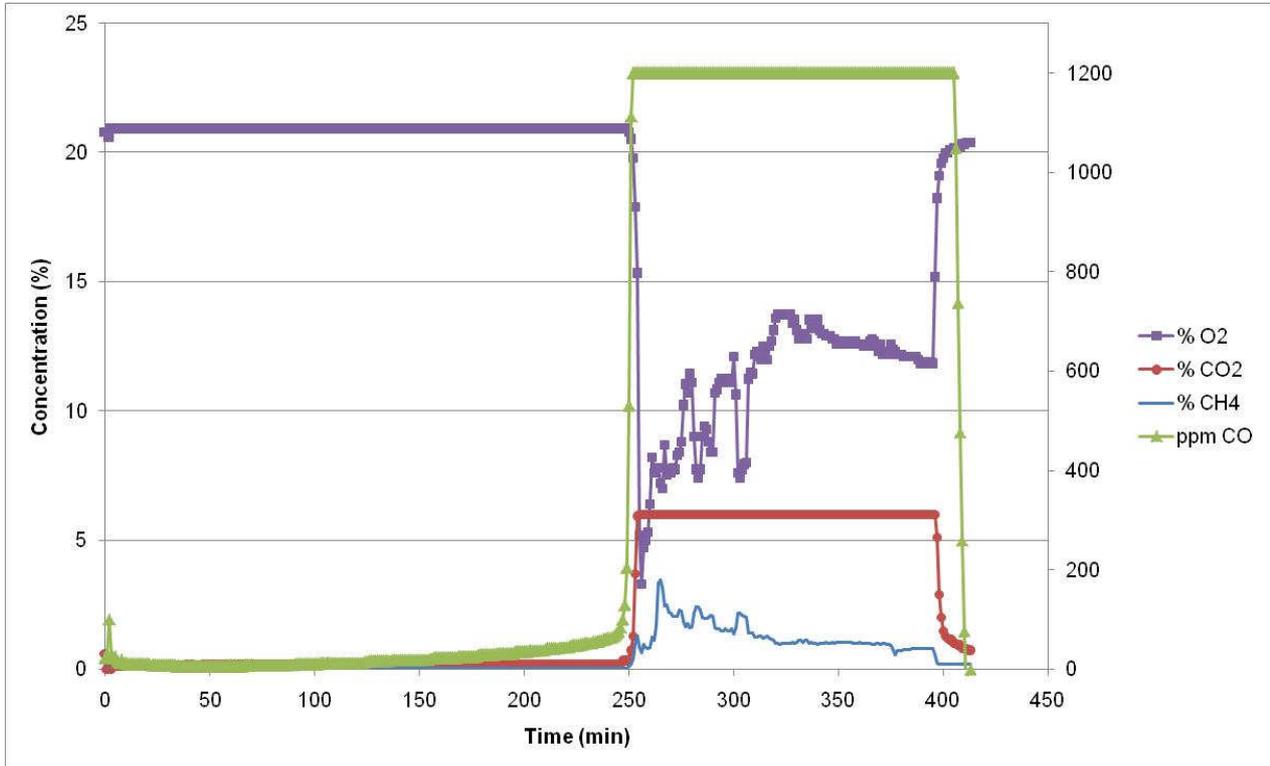


Figure 11 Gas analysis during testing

5. Conclusions

Several theoretical models can be applied to the process of self heating of a coal mass and the development of a self ignition phenomenon. Also, a great number of different experimental methods and practical procedures exist to obtain different parameters which can be used to quantify the self-heating tendency of coals (and other combustible substances).

Most techniques consist of a certain procedure to heat up a coal sample and to study the consequences, recording the evolution of a physical variable.

There are classical techniques more used in the characterization of the flammability of solids, especially dusts, which can produce valuable data. However, the most significant data are obtained when the sample is subjected to a programmed heating.

Two types of techniques have proved their reliability and strength: thermogravimetry and isothermal oven tests. Both have been extensively used to diverse types of coals.

The original approaches of this study to well known techniques are two in the case of the TG method. Firstly the attack of the coal sample with pure oxygen, obtaining a unique characteristic temperature, and secondly, the development of a very simple routine to obtain apparent activation energies from TG plots.

In the case of oven techniques, several options have been analysed, obtaining promising results, which are in the line of the standardisation of a laboratory methodology. The main disadvantages of these techniques, as

compared as TG analysis, are the duration of the tests and the big amount of coal sample required. Once results are obtained, extrapolation can be easily done by determined algorithms.

Thus, TG tests could be recommended in a first stage of a self ignition study, while oven tests could be applied afterwards, when more accurate results are needed, mainly for dealing with big accumulations of coal.

A predictive criterion has been derived, giving an indication of a possible method to establish a classification of coals based on their intrinsic propensity to exothermically react with air. Future application to different types of coals is needed to prove it.

The scale model has shown how a gallery-shaped coal block reacts to heated air. The results showed different ways for the temperature to rise, with or without reaching the ignition conditions. The analysis of the gases produced proved that gas monitoring, especially of CO, can be a very effective means for early detection of mine fires.

Acknowledgements

A research project on self ignition of coals was partly funded by the European Coal and Steel Community as a part of the contract ECSC 7220 AC/009.

References

García Torrent J., (2000), ECSC Project 7220 – AC/009: ‘Improved Mine Ventilation and Climate Control, Self ignition of coals’. CECA

García Torrent J., Querol Aragón E., Cámara Rascón A., (2000), ‘Spontaneous Combustion Testing, Safety Seminar on Explosion Prevention’, www.safetynet.de

García Torrent, J.; Medic Pejic, L.; Querol Aragón, E. (2004) ‘A self-combustion characterisation index based in thermogravimetric and differential scanning calorimetry techniques’. V International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions. Krakow. Poland.

Cumming J., (1984), ‘Reactivity assessment of coals via a weighted mean activation energy’, FUEL, October Vol63, Elsevier, p1436